Bundesamt für Energie BFE

Forschung Juni 2013

Programm Photovoltaik Ausgabe 2013

Überblicksbericht, Liste der Projekte Jahresberichte der Beauftragten 2012

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BFE-Vertrags- und Projektnummer: SI/500020-03

Für den Inhalt und die Schlussfolgerungen ist ausschliesslich der Autor dieses Berichts verantwortlich.

Titelbild: *1982 – 2012: im Oktober 2012 feierte an der SUPSI in Canobbio die älteste netzgekoppelte Photovoltaik-Anlage in der Schweiz und Europas ihr 30-jähriges Jubiläum und die Solarmodule funktionieren weiterhin, wenngleich mit reduzierter Leistung (Bildquelle NET).*

Programm Photovoltaik Ausgabe 2013 Forschung

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Überblicksbericht 2012

Forschungsprogramm Photovoltaik

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Office fédéral de l'énergie OFEN

Titelbild:

Neue und konventionelle Photovoltaik-Technologien an einer Gebäudefassade

Mikromorphe Dünnschicht (10,8 kW, links) und multikristalline (11,3 kW, rechts) Photovoltaik-Module bilden eine Fassadenanlage bei der Firma Lippuner in Grabs (SG). Die Unterkonstruktion inkl. Glashalterung für eine schraubenlose Modulmontage wurde von der Firma Jansen entwickelt, Module von Schüco, Lieferant des Gesamtsystems ist ebenfalls Jansen, Oberriet (Bildquelle: Jansen).

BFE Forschungsprogramm Photovoltaik
Überblicksbericht 2012

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Einleitung

Die Photovoltaik erfährt in der aktuellen nationalen und internationalen Energiedebatte eine immer grössere Beachtung. Dabei wird diese sehr dynamische Energietechnologie sowohl aus wissenschaftlich-technischer Sicht, als auch industriell und marktbezogen viel diskutiert. Vor dem Hintergrund einer rasch wachsenden, global orientierten Industrie findet weltweit eine intensive Forschung statt, welche als Hauptziel eine weitere Kostenreduktion und die rasche Industrialisierung der Photovoltaik verfolgt. In den technologisch besonders wichtigen Ländern wie Deutschland, Japan und den USA werden die Photovoltaikforschung intensiviert und ambitiöse Ziele formuliert [1, 2]. Ähnlich ist Europa mit der Solar Europe Industry Initiative bestrebt, weiterhin eine führende Rolle auf diesem Gebiet zu spielen. Parallel dazu findet marktseitig eine weiterhin rasante Kostenreduktion statt, welche einerseits die Wettbewerbsfähigkeit der Photovoltaik mit anderen Energieformen laufend erhöht, andererseits innerhalb der Photovoltaikindustrie zu einem stark verschärften Wettbewerb führt.

In der Forschung geht es um die anhaltende Weiterentwicklung der bestehenden Photovoltaik-Technologien sowie die Entwicklung neuer Materialoptionen und Konzepte. Nebst dem Kerngebiet der verschiedenen Solarzellen-Technologien beinhaltet die Photovoltaikforschung auch technologiespezifische Themen auf der Systemebene, z. B. der Gebäudeintegration, der elektrischen Systemtechnik oder der Umweltindikatoren und des Recyclings. Mit der derzeit anhaltenden Kostenreduktion bilden System-übergreifende Aspekte wie die Netzintegration, die Speicherung oder energetische Konzepte im Gebäude immer wichtigere Themen der Forschung. Neue Erkenntnisse und Resultate aus der Forschung werden möglichst rasch in die Industrie übergeführt.

Die Photovoltaik als möglicher wesentlicher Pfeiler einer nachhaltigen Stromversorgung hat in relevanten Szenarien inzwischen ihren festen Platz: Die im Jahr 2010 publizierte Photovoltaik-Roadmap der Internationalen Energieagentur IEA [3] spricht bis 2050 von einem möglichen Beitrag von mehr als 10 % zur weltweiten Stromversorgung. In aktuellen Schweizer Energieszenarien wird von der Photovoltaik bis 2050 ein Beitrag von mindestens 10 TWh Elektrizität als möglich erachtet [4]. Zunehmend verlagert sich die Diskussion angesichts der raschen Kostendegression auf die Frage, wie rasch die Photovoltaik ihren Beitrag leisten kann und soll.

In den letzten 25 Jahren hat sich eine starke Schweizer Position in verschiedenen Gebieten der Photovoltaikforschung herausgebildet: Im Vordergrund stehen die Entwicklungen von verschiedenen Dünnschicht-Technologien, welche schon immer den Schwerpunkt der Schweizer Photovoltaikforschung bildeten. Ausgehend von Arbeiten an neuen Solarzellen-Konzepten wurden diese sukzessiv in die industrielle Umsetzung übergeführt. Heute findet neben der Forschung an Instituten und Hochschulen auch seitens der Industrie eine intensive Technologieentwicklung statt, welche mittlerweile zu einer entlang der ganzen Wertschöpfungskette der Photovoltaik bedeutenden Schweizer Industrie geführt hat. Dabei bleibt auch die Schweizer Photovoltaik Industrie vom intensiven weltweiten Wettbewerb nicht verschont.

Laufene Aktivitäten in Forschung und Entwicklung sowie Projekte im Bereich von Pilot- und Demonstrationsanlagen umfassen im Berichtsjahr 2011 rund 70 Projekte, wobei alle der Programmleitung bekannten Projekte mit einer Förderung der öffentlichen Hand berücksichtigt sind. Nebst den durch das Bundesamt für Energie (BFE) geförderten Projekten und den Schwerpunkten einzelner Hochschulen und Forschungsinstitute spielen Projekte mit Unterstützung der Kommission für Technologie und Innovation (KTI) sowie zahlreiche EU-Projekte im Forschungsprogramm *Photovoltaik* des BFE eine tragende Rolle.

Das Forschungsprogramm *Photovoltaik* des BFE verfolgte in der Periode 2008–2012 die folgenden Ziele [5, 6]:

- Senkung der Kosten der Solarzellen und -module;
- Steigerung des Wirkungsgrades (Solarzellen);
- Senkung des Material- und Energieeinsatzes;
- Vereinfachung und Standardisierung der elektrischen Systemtechnik; Steigerung der Lebensdauer und Zuverlässigkeit von Wechselrichtern;
- Erhöhung der Verfügbarkeit und der Vielfalt industrieller Produkte.

IEA Klassifikation:	3.1.2 Photovoltaics
Schweizer Klassifikation:	2.1.2 Photovoltaik

Programmschwerpunkte

Das Forschungsprogramm *Photovoltaik* ist in folgende fünf Bereiche aufgeteilt (die in Klammern angegebene Klassifizierung bezieht sich auf die Liste der Projekte, Seite 13 ff.):

Solarzellen (1a-e):

Verschiedene materialspezifische Ansätze zu Dünnschichtsolarzellen stellen hier den wichtigsten Schwerpunkt dar (Silizium, Verbindungshalbleiter, organische Materialien). Verstärkt werden Hocheffizienz-Zellen mit Heteroübergängen zwischen Dünnschicht- und kristallinem Silizium vorangetrieben. Organische und Polymersolarzellen als mögliche langfristige Technologieoptionen gewinnen an Bedeutung. Ausserdem werden in der Grundlagenforschung fortgeschrittene Konzepte mit Photonen-Management erforscht.

Module und Gebäudeintegration (2a-e):

Das Gebiet der Solarmodule ist im Forschungsprogramm *Photovoltaik* eng mit der Anwendung der Gebäudeintegration verbunden. Im Vordergrund stehen Modultechnologien, welche mit den in der Schweiz entwickelten Solarzellen einhergehen.

Elektrische Systemtechnik (3):

Bei der elektrischen Systemtechnik steht die Qualitätssicherung von Modulen und Wechselrichtern im Vordergrund, einschliesslich entsprechender Normen. Ein in Zukunft wichtiger werdendes Thema ist die Wechselwirkung mit dem elektrischen Netz und die Integration der Photovoltaik ins Netz.

Begleitende Themen (4):

Zum einen geht es hier um relevante technische und nicht technische Themen zur Marktentwicklung (z. B. Hilfsinstrumente, Monitoring, Umweltaspekte). Andererseits sind hier auch auf andere Energiethemen übergreifende Projekte (z. B. Gebäude, Mobilität, Speicherung) angesiedelt.

Institutionelle internationale Zusammenarbeit (5):

Sie erfolgt einerseits projektbezogen auf allen Gebieten und andererseits im Rahmen des Implementing Agreements Photovoltaic Power System Programme (PVPS) der Internationalen Energieagentur (IEA), der Europäischen Photovoltaik-Technologieplattform, der europäischen PV-ERA-Net-Kooperation (ERA: European Research Area), der neuen Solar Europe Industry Initiative (SEII) im Rahmen des SET-Plans und der Normen festlegenden Internationalen Elektrotechnischen Kommission (IEC).

Rückblick und Bewertung 2012

Gemessen an der Anzahl laufender Projekte mit öffentlicher Finanzierung und der gesamthaft gemeldeten Forschungsprojekte [7] kann eine anhaltende Verstärkung der Forschungsaktivitäten beobachtet werden. Diese Erhöhung ist in erster Linie auf Erfolge mit KTI- und EU-Projekten zurückzuführen. Die zur spezifischen Förderung der Photovoltaik verfügbaren Forschungsmittel des BFE sind im Jahr 2012 beschränkt aber konstant geblieben, nachdem sie in den letzten 10 Jahren kontinuierlich reduziert werden mussten. Die Mittel für Pilot- und Demonstrationsprojekte konnten leicht erhöht werden mit Aussicht auf einen deutlichen Anstieg 2013, wobei hier keine für die Photovoltaik spezifischen Mittel reserviert sind. Inhaltlich sind programmübergreifend drei wesentliche Trends zu erkennen, i) die verstärkte Fokussierung auf kurz- und mittelfristig relevante Fragestellungen der Industrie (anhaltende Kostensenkung und Effizienzsteigerung), ii) die waschsende Bedeutung von systemrelevanten Aspekten (z. B. Gebäude- und Netzintegration) sowie iii) langfristige Optionen in der Grundlagenforschung. Für die Photovoltaikindustrie hat der Wettbewerb im letzten Jahr weiter zugenommen und eine ausgeprägte weltweite Konsolidierungsphase mit zahlreichen Insolvenzen eingeleitet. Dennoch zeichnet sich gleichzeitg ab, dass die technologische und industrielle Entwicklung rasch weiter geht und international eine Beschleunigung von Forschung und Innovation stattfindet.

Ausblick

Die Herausforderung der Schweizer Photovoltaikforschung und -industrie für die kommenden Jahre liegt darin, international an vorderster Front mithalten zu können. In der Schweiz zeichnet sich ab 2013 im Rahmen des Aktionsplans Koordinierte Energieforschung insgesamt eine Verbesserung der Situation ab, indem die Mittel für Forschung wie für P&D-Projekte generell zunehmen werden. Es gilt, diesen Zeitraum optimal zu nutzen, um die Photovoltaikforschung als innovative Kompetenz-Grundlage der Schweizer Photovoltaikindustrie zu positionieren und in dieser Hinsicht weiter zu verstärken. Optimal wird dies mittels einer Stärkung der Forschung und der institutionellen Kapazitäten zur raschen Umsetzung von Forschung in die Industrie erreicht. Das im Jahr 2013 konkret werdende Photovoltaik-Kompetenzzentrum am Centre Suisse d'Electronique et de Microtechnique (CSEM) soll hier wesentliche Beiträge leisten.

Highlights aus Forschung und Entwicklung

Seit vielen Jahren setzt sich das Forschungsprogramm *Photovoltaik* zum Ziel, zu den einzelnen Teilbereichen Kompetenzzentren mit nationaler und internationaler Ausstrahlung zu fördern. Im Jahr 2012 sind dies das Photovoltaik-Labor (PV-Lab) an der Eidgenössischen Technischen Hochschule Lausanne (EPFL) in Neuchâtel (Silizium-Dünnschicht-Solarzellen), das Institut of chemical sciences and engineering (ISIC) an der EPFL in Lausanne (Farbstoff-Solarzellen), die Empa in Dübendorf (Verbindungshalbleiter- und organische Solarzellen), die Scuola universitaria professionale della Svizzera italiana (SUPSI) in Lugano (Solarmodule und Gebäudeintegration) und die Berner Fachhochschule Technik und Informatik (HTI) in Burgdorf (elektrische Systemtechnik).

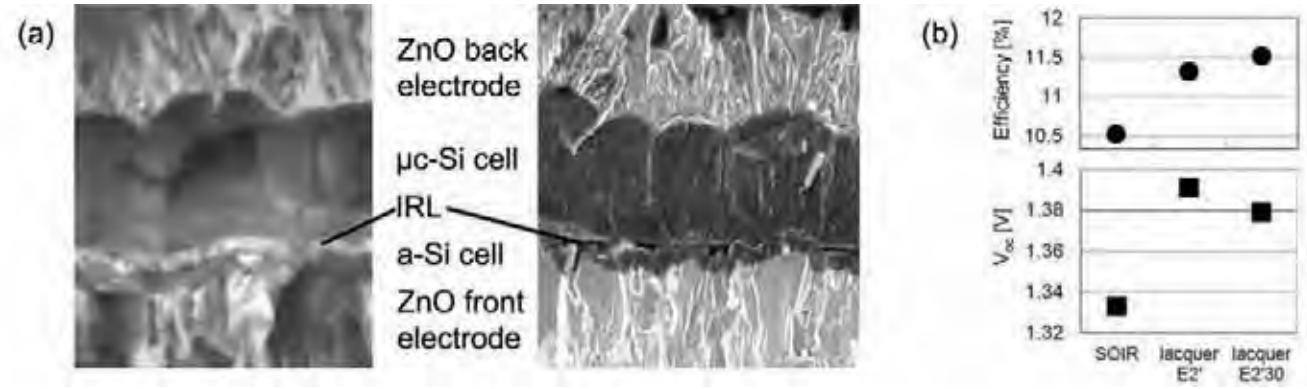
Forschung und Entwicklung auf kristallinen Solarzellen ist in der Schweiz weit gehend Sache der Industrie. Ein Grossteil der öffentlichen Photovoltaikforschung befasst sich mit neuen Solarzellen auf der Grundlage von Dünnschicht-Technologien. Die wesentlichen Technologieansätze betreffen Dünnschicht-Silizium (zur Hauptsache am PV-Lab der EPFL) sowie Dünnschicht-Verbindungshalbleiter CIGS und CdTe (Empa). Die rasche Kostenreduktion bei den kristallinen Solarzellen zwingt die Vertreter der Dünnschicht-Technologien, ihre Konzepte kosten- und effizienzmässig noch schneller weiter zu entwickeln. Dabei gewinnt auch das Konzept der hocheffizienten Solarzellen mit Heteroübergängen zwischen amorphen und kristallinen Zellen rasch an Bedeutung.

Fortgeschrittene Solarzellenforschung bedeutet immer mehr auch Materialforschung mit neusten Ansätzen, neuen Materialkombinationen und neuen Prozessen. Dabei spielen feinste Schichten und Strukturen im Nanometerbereich eine zunehmende Rolle. Nebst den etablierten Photovoltaik-Kompetenzzentren befassen sich weitere akademische Institute an Universitäten und Fachhochschulen vermehrt mit Fragestellungen im Zusammenhang mit der Photovoltaik.

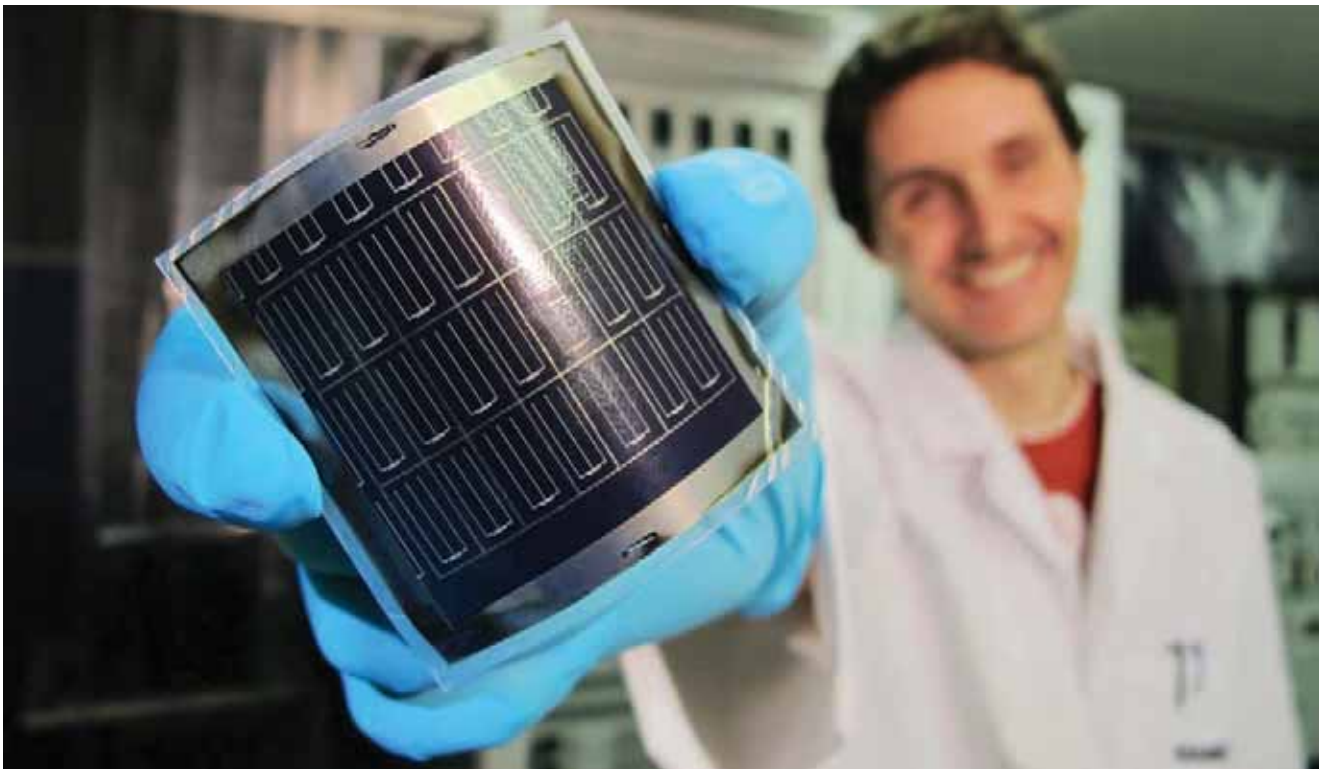
Die Qualitätssicherung hat seit vielen Jahren ihren festen Stellenwert in der Photovoltaik-Forschungslandschaft. Die Prüfung von Solarmodulen und deren Verhalten bei unterschiedlichen Betriebsbedingungen ist die Kernkompetenz des Istituto sostenibilità applicato all'ambiente costruito (ISAAC) an der SUPSI. Komplementär dazu wird an der Fachhochschule HTI in Burgdorf das Verhalten von Wechselrichtern und Systemen untersucht. Beide Institute betreiben Prüflabors, in welchen Solarmodule oder Wechselrichter gemäss gängigen Normen geprüft werden können.

Dünnschicht Silizium und CIGS – mit neuen Konzepten zu höchsten Wirkungsgraden

Das PV-Lab an der EPFL in Neuchâtel bearbeitet in einer Anzahl von eng verwandten Projekten aktuelle Fragestellungen zur weiteren Entwicklung von Silizium-Dünnschichtsolarzellen auf verschiedenen Substraten. Zur Optimierung dieser Solarzellen in ihren verschiedenen Ausprägungen stehen zahlreiche Parameter zur Verfügung. Neben Material, Art, Anzahl und Umfang der aktiven Schichten, welche zur Hauptsache aus amorphem und mikrokristallinem Silizium bestehen, spielen Dotierung, Fenster- und Zwischenschichten, Art der Deposition, Struktur, usw. wichtige Rollen. Ziel der laufenden Optimierung und neuer Ansätze ist es letztlich, den Wirkungsgrad der Solarzellen zu erhöhen. Durch Simulation und systematische sowie kontrollierte Variation der experimentellen Parameter wird das Verständnis der in der Solarzelle stattfindenden Prozesse gefördert, was einen wesentlichen Schlüssel zur weiteren Entwicklung darstellt. Eine wachsende Rolle spielen kontrollierte Strukturen und Zwischenschichten im Nanometerbereich. An diesen Zwischenschichten wird die Lichtabsorption optimiert, sodass möglichst viele Photonen in Ladungsträ-



Figur 1: a) Elektronenmikroskopischer Querschnitt durch eine mikromorphe Solarzelle mit einer glättenden Zwischenreflektorschicht durch Spray-Deposition von Zn-Acetat (links, grau) und Spin-coating und Ätzen (rechts, schwarz). b) Wirkungsgrad und Voc von mikromorphen Zellen mit einer glättenden SiOx Zwischenreflektorschicht oder einer Zwischenreflektorschicht durch Ätzen (Bildquelle: PV-Lab, EPFL).



Figur 2: Hocheffiziente und flexible CIGS Solarzellen auf Polyimidfolie entwickelt mit einem neuen Prozess erreichen einen neuen Weltrekord-Wirkungsgrad von 20,4 % (Bildquelle: Empa).

ger umgewandelt werden. Durch eine bessere Materialqualität kann sodann sichergestellt werden, dass möglichst wenige dieser Ladungsträger wieder rekombinieren und für die Energieumwandlung weiter zur Verfügung stehen. Entsprechend komplex ist der Weg zu verbesserten Solarzelleneigenschaften, welche auch noch den Anforderungen an grossflächige industrielle Prozesse gerecht werden müssen.

Die Übertragbarkeit der Forschungsergebnisse auf den industriellen Massstab sowie industrielle Prozesse bildet eine zentrale Aufgabe, bei welcher eine zunehmende Anzahl von Industrieunternehmen mit dem PV-Lab zusammenarbeitet. Damit wachsen auch die Anforderungen an eine leistungsfähige Labor-Infrastruktur, welche in der Lage sein muss, rasch reproduzierbare Resultate zu liefern. Ab 2013 wird hierzu am CSEM mit massgeblicher Unterstützung des Bundes ein industrieorientiertes Photovoltaik-Kompetenzzentrum aufgebaut. Es wird erwartet, dass die industrieorientierte Forschung dadurch nachhaltig gestärkt werden kann.

Im Berichtsjahr begann am PV-Lab mit Unterstützung des BFE eine neue Projektphase, welche sich den Kernthemen und Lösungsansätzen des PV-Lab zu Silizium-Dünnschichtsolarzellen und -modulen widmet. Das Projekt ist in sechs komplementäre Aufgabenbereiche strukturiert (Einfluss der Plasmaeigenschaften auf die Siliziumschichten, neue Materialien und Schichten, Lichteinfang, Mehrfachübergänge, Zuverlässigkeit und Charakterisierung sowie allgemeine Infrastruktur). Im ersten Projektjahr konzentrierten sich die Arbeiten auf fundamentale Aspekte der Technologie. Dabei wurde zum einen das analytische Verständnis des Mechanismus des Lichteinfangs durch Fensterschichten verbessert, zum anderen Wege zu besseren Materialeigenschaften von amorphem und mikrokristallinem Silizium erforscht. Daraus resultierten amorphe Schichten mit reduzierter Lichtdegradation und mikrokristalline Schichten mit höherer Klemmenspannung Voc. Mit glättenden Zwischenschichten konnte die Kopplung zwischen den einzelnen Sub-Zellen verbessert werden. Durch die Kombination der verschiedenen Ansätze wird erwartet, den Wirkungsgrad der Silizium-Dünnschichtmodule auf über 12 % erhöhen zu können (Figur 1). In insgesamt vier EU-Projekten (PEPPER, N2P, SILICON_LIGHT und FAST TRACK) werden diese Ansätze am PV-Lab auch praxisorientiert weiter vertieft. Es zeigt sich hier ebenfalls, dass durch gezielte Verbesserung der Materialeigenschaften und Prozesse, z. B. Reduktion der Defektzonen im mikrokristallinen Silizium hervorgerufen durch schlechte Front-Kontakte, bessere Wirkungsgrade erzielt werden können.

Das Konzept von Hocheffizienz-Solarzellen mit einem Heteroübergang zwischen verschiedenen Schichten aus kristallinem und amorphem bzw. mikrokristallinem Silizium gewinnt unter dem aktuellen Kostendruck durch die marktübliche kristalline Technologie rasch an Bedeu-

Figur 3: Outdoor Messstand mit 11 verschiedenen Dünnschicht PV-Modulen und 2 kristallinen Silizium-Modulen zur Vergleichsmessung (Bildquelle: ISAAC SUPSI).

tung. Im EU-Projekt 20PLUS erreichte das PV-Lab hierzu einen Wirkungsgrad von 21,4 % auf p-Typ Wafern, bzw. 22,1 % auf n-Typ Wafern.

Wesentliche Industriekooperationen des PV-Lab erfolgen mit TEL-Solar (der früheren Oerlikon Solar), Meyer Burger, Roth & Rau sowie mit verschiedenen weiteren in- und ausländischen Unternehmen.

Die derzeit wichtigsten Vertreter der Verbindungshalbleiter-Solarzellen sind CIGS und CdTe. Letztgenannte Technologie hat sich in den vergangenen Jahren als weltweit führende Dünnschichttechnologie etabliert mit einer Produktion im GW-Massstab (First Solar) und ist der Referenzwert für die Wettbewerbsfähigkeit von Dünnschicht-Solarzellen. CIGS-Solarzellen werden erst in kleinerem Umfang produziert, bergen aber ein grosses Effizienzpotenzial. Nebst diesen Hauptvertretern der Verbindungshalbleiter-Solarzellen werden weltweit neue Materialvarianten erforscht, insbesondere in der Materialklasse der Kesteriten.

In der Schweiz hat sich auf diesem Gebiet das Labor für Dünne Schichten und Photovoltaik an der Empa als leistungsfähige Forschungseinheit etabliert. Das Labor arbeitet im Rahmen von BFE-, EU-, KTI- und weiteren Projekten an unterschiedlichen Fragestellungen zu CIGS-Solarzellen. Dabei interessieren auch bei dieser Technologie die Materialeigenschaften, Depositionsprozesse und -temperaturen (sowohl unter Vakuum, als auch bei Atmosphärendruck), die notwendigen Pufferschichten und die Substratwahl. Von besonderem Interesse sind flexible Solarzellen auf Kunststoffsubstraten. Hier erfolgt eine intensive Zusammenarbeit mit dem Empa-Spin-off-Unternehmen FLISOM. Im Berichtsjahr erzielte das Team an der Empa einen weiteren Erfolg: Beim jüngsten Rekord gelang es den Forschern, die Eigenschaften der Licht absorbierenden CIGS-Schicht, die bei reduzierten Prozesstemperaturen aufgetragen wird, weiter zu optimieren. Der Rekord-Wirkungsgrad einer CIGS-Solarzelle auf Kunststoff von 20,4 % wurde vom Fraunhofer-Institut für Solare Energiesysteme (ISE) in Freiburg (Deutschland) verifiziert – und übersteigt damit den Rekordwert von 20.3 % für CIGS-Solarzellen auf Glas (Figur 2). Gegenüber dem letztjährigen Empa-Rekord für flexible CIGS-Solarzellen von 18,7 % stellt dies eine markante Steigerung dar. Damit entspricht der Wirkungsgrad von CIGS-Dünnschichtsolarzellen nun sogar demjenigen von multikristallinen Siliziumzellen.

Ein neues, vom BFE unterstütztes Projekt an der Empa befasst sich mit dem Aufbau einer pilotmässigen Anlage zur mehrstufigen Abscheidung von CIGS-Solarzellen auf Kunststofffolien in einem roll-to-roll Prozess. Damit soll die Übertragung der im Labor erzielten Forschungsresultate auf industrienahe Verhältnisse erreicht werden. Im Berichtsjahr standen Konzept und Design der Anlage im Vordergrund.

In verschiedenen EU-Projekten (HIPO-CIGS, NOVA-CIGS, R2R-CIGS und dem neuen Grossprojekt SCALENANO) verfolgt die Empa-Gruppe ihre Projektaktivitäten auch international erfolgreich weiter.

Dünnschichtmodule – Resultate aus praxisnahen Messungen

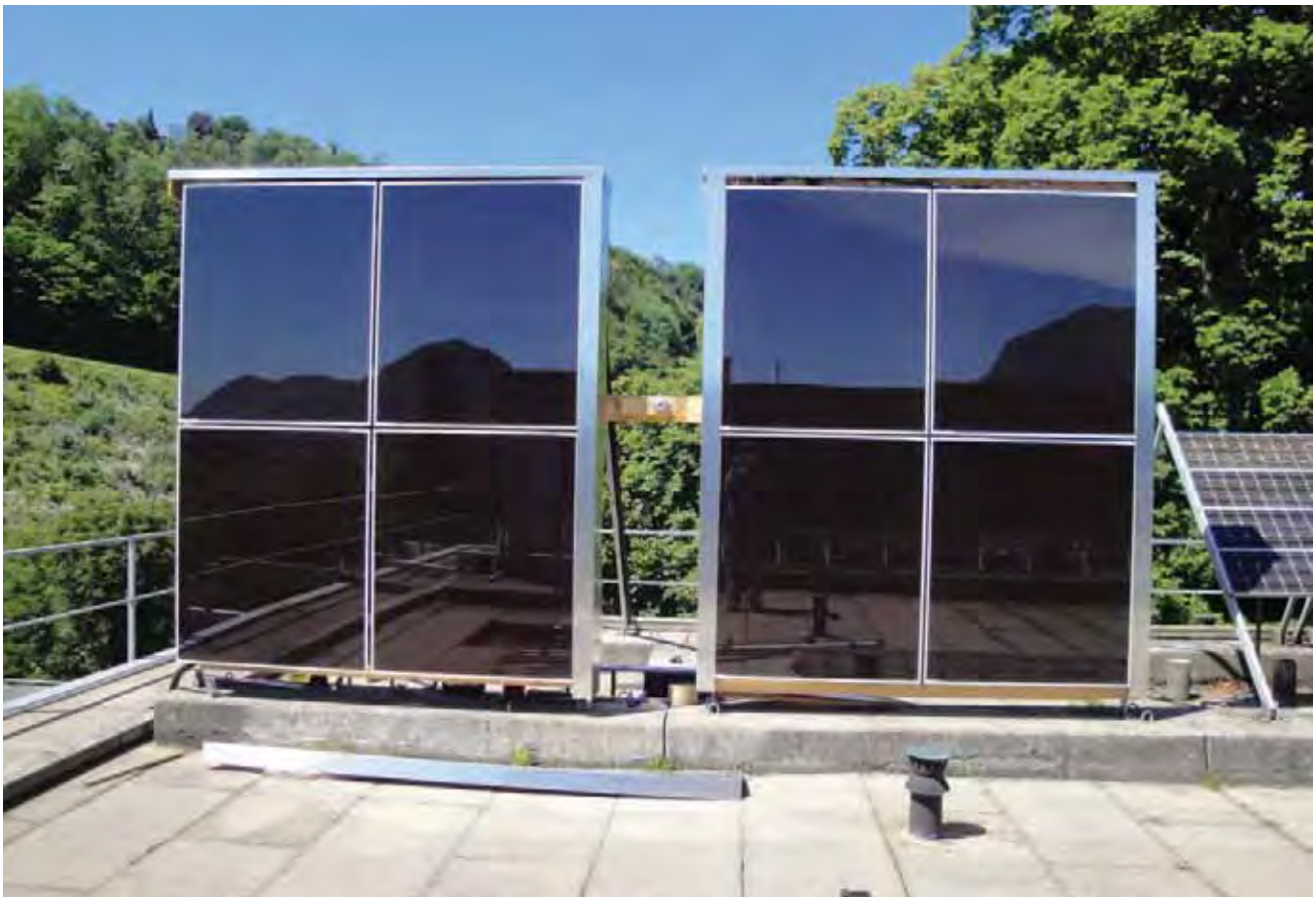
Während für kristalline Silizium Solarmodule langjährige Erfahrungen und Resultate in der Charakterisierung und normierten Messung vorliegen, bestehen für Dünnschichtmodule immer noch grössere methodische Ungenauigkeiten, welche auch mit dem komplexen und unterschiedlichen Aufbau dieser Module (z. B. verschiedene Materialien, unterschiedliche spektrale Empfindlichkeiten, mehrere Schichten, usw.) zusammen hängen. Dies bedingt bei der Messung dieser Module häufig eine Vorkonditionierung, um zu besser vergleichbaren Resultaten zu gelangen.

Am ISAAC der SUPSI wird in einem neuen, vom BFE unterstützten Projekt die Methodik zur Messung von Dünnschichtmodulen verfeinert. Im Berichtsjahr wurden dazu die Messstände sowohl im Labor wie für die Aussenmessung um Geräte zur Berücksichtigung der spektralen Empfindlichkeit von mehrschichtigen Dünnschichtmodulen ergänzt. Aufgrund des Farbspektrums des verwendeten Solarsimulators kann durch Vergleichsmessungen die geeignete Referenzzelle für ein bestimmtes Solarmodul bestimmt werden. Auf dem Aussenprüfstand (Figur 3) wurden Messungen an 11 verschiedenen Dünnschichtmodulen durchgeführt (a-Si, 2 a-Si/a-Si, 4 a-Si/μc-Si, 1 CdTe, 1 CIS, 1 CIGS und 1 CIGSS). Die ersten Resultate zeigen eine grosse Bandbreite der normierten STC-Leistung (Standard Test Conditions) bzw. der Anfangsdegradation.

Figur 4: Zustand von schneebedeckten PV-Modulen an einem Februar-Tag mit unterschiedlichen Lösungen zur Schneeentfernung (von vorne: Eulektra, Freso, Solutronic (X2) und Bosch als Referenz) (Bildquelle: Planair).

Nebst der Leistung wird auch die spezifische Energieproduktion (in kWh/kWp) der verschiedenen Technologien erfasst. Diese hängt naturgemäss ausgeprägt vom gewählten Referenzwert der STC-Leistung ab. Um zu besseren Aussagen zu gelangen, wurden im Berichtsjahr Arbeiten zur spektralen Modellierung für die unterschiedlichen Modultechnologien durchgeführt. Diese zeigen auf, wie gross die spektralen Effekte für die einzelnen Technologien sind und führen zu deutlich besseren Genauigkeiten der Vorhersage.

Zusammen mit weiteren Testmethoden (z. B. Defektanalysen durch Elektrolumineszenzmessungen), der Teilnahme am DURSOL CCEM-Projekt zur Erforschung der Dauerhaftigkeit von Dünnschichttechnologien und dem akkreditierten Swiss PV Module Test Centre bestehen am ISAAC der SUPSI umfangreiche Erfahrungen und Infrastruktur zur Messung von Photovoltaik Modulen. Das ISAAC konnte im Berichtsjahr in einem Festakt 30 Jahre Forschung an Photovoltaikmodulen feiern und seine frühe Pionierrolle auf diesem Gebiet erfolgreich demonstrieren.



Figur 5: Feldtest von Prototypen aus dem Projekt PV Foamglas beim ISAAC SUPSI: Vorgehängte PV-Testfassade (links), geklebte PV-Testfassade (rechts) (Bildquelle: Basler & Hofmann).

Pilot- und Demonstrationsprojekte

P&D-Projekte können sowohl Prozesse, Produkte als auch Anlagen umfassen. Im Bereich der P&D-Anwendungen stehen als Schwerpunkt neue Ansätze im Bereich der Photovoltaik Gebäudeintegration im Vordergrund. Typische Themen sind hier der Unterbau und das Montagesystem, der Aufbau des Solarmoduls, ein hoher Integrationsgrad oder Zusatzfunktionen am Bau. Photovoltaik-Indachsysteme übernehmen neben der Stromproduktion die Funktion der Wasser führenden Dachhaut. Eine wichtige Aufgabe von P&D-Projekten ist zudem die Erfolgskontrolle von neuen Produkten und Konzepten in der Praxis (Figur 4).

Das ISAAC an der SUPSI hat zum Thema der Photovoltaik-Gebäudeintegration einen Schwerpunkt gesetzt und erarbeitet in mehreren übergreifenden Projekten umfassende Analysen und Lösungsansätze. Dieses Wissen wird im BRENET-Netzwerk (Nationales Kompetenznetzwerk Gebäudetechnik und Erneuerbare Energien) weiter entwickelt. Mit der Homepage www.bipv.ch werden aktuelle Produkte und Lösungen einem breiten Publikum vorgestellt.

Ästhetische und funktionale Gebäudeintegration

Die folgenden Beispiele von P&D-Projekten stellen aktuelle Ansätze der PV-Gebäudeintegration dar, bei welchen funktional und ästhetisch neue, sowie wirtschaftlich aussichtsreiche Lösungen erarbeitet und in der Praxis getestet werden.

Im BFE-Projekt PV-Foamglas geht es darum, dass die Photovoltaikmodule neben der Stromproduktion und der Funktion der Dachhaut auch die Wärme- und Schalldämmung übernehmen. Dieser Ansatz stellt insbesondere in Bezug auf das thermische Verhalten der Photovoltaikanlage eine Herausforderung dar. Hierzu erarbeiten die Partner Basler & Hofmann und Pittsburgh Corning Schweiz geeignete Lösungen, welche anschliessend in einer Demonstrationsanlage realisiert werden sollen. Im Berichtsjahr wurden konkrete technische Lösungen des geklebten Verbunds zwischen Glas-Glasmodulen und dem

Figur 6: Erste Prototypen von farbigen Dünnschicht-PV-Modulen aus dem Projekt Archinsolar (Bildquelle: PV-Lab, EPFL).

Foamglas-Dämmstoff realisiert und klimatisch wie in Bezug auf die Haftung geprüft (Figur 5). In einem ersten Feldtest wurden Fassadenelemente mit und ohne Dämmstoff in Bezug auf die elektrische Produktion und Performance verglichen. Diese ersten Erkenntnisse sollen in einer grösseren Pilotanlage weiter vertieft werden.

Einen grundlegenderen Ansatz verfolgt das P&D-Projekt Archinsolar, welches verschiedene Partner und Förderorganisationen (BFE, SwisselectricResearch, SIG, CCEM) vereint. Es geht darum, Silizium-Dünnschichtsolarmodule mittels kolorierten Interferenzfiltern so zu gestalten, dass unterschiedliche Farben möglich werden (Figur 6). Damit soll eine neue und energetisch effizientere Art der Farbgebung von Solarmodulen erzielt werden. Im Berichtsjahr wurden verschiedene farbige und grossflächige Demonstrationsmodule sowie Dachziegel hergestellt. Dabei wurde der Verbundaufbau variiert und in Bezug auf Materialien, Funktionalität, Haftung, Dichtheit, Kosten sowie Umweltaspekte analysiert.

Nationale Zusammenarbeit

Im Berichtsjahr wurde die vielfältige nationale Zusammenarbeit in verschiedenen, zum Teil übergreifenden Projekten weiter gepflegt. Damit findet innerhalb der Schweizer Photovoltaik-Gemeinschaft aus Forschung, Industrie und Anwendung ein reger Austausch statt. Die Zusammenarbeit mit Industrieunternehmen konnte weiter intensiviert werden, sowohl in neuen Projekten mit Unterstützung der KTI, als auch in der Form von direkten Mandaten der Industrie an ausgewählte Forschungsinstitute. Als wichtigstes neues Element ist das CSEM Photovoltaik-Kompetenzzentrum zu erwähnen, welches anfangs 2013 seinen Betrieb aufnimmt. Es soll die industrienahe Forschung mit allen wichtigen Schweizer Photovoltaik-Kompetenzzentren nachhaltig stärken.

Auf Programmebene wurde die Zusammenarbeit mit vielen Stellen des Bundes, der Kantone und der Elektrizitätswirtschaft weiter gepflegt. Auf der strategischen Ebene wurde die Umsetzung des neuen Forschungskonzeptes der Eidgenössischen Energieforschungskommission (Commission fédérale pour la recherche énergétique CORE) 2013–2016 [8] vorbereitet. Hierzu soll auch der im Entwurf bestehende Masterplan Photovoltaik weiter voran getrieben werden. Mit dem Aktionsplan Koordinierte Energieforschung, dem erwähnten CSEM Photovoltaik-Kompetenzzentrum mit Unterstützung des Bundes und der Erhöhung der BFE-Mittel für P&D-Projekte haben sich wesentliche Randbedingungen für die beschleunigte Entwicklung und Umsetzung der Forschung positiv entwickelt.

Internationale Zusammenarbeit

Die institutionelle Zusammenarbeit innerhalb der IEA, der IEC und der europäischen Netzwerkprojekte wurde im Berichtsjahr kontinuierlich fortgesetzt. Auf der Projektebene konnte die Zusammenarbeit innerhalb der EU in bestehenden und neuen Projekten sehr erfolgreich fortgesetzt werden. Im Jahr 2012 waren es 21 Projekte im 7. Rahmenforschungsprogramm der EU bzw. zwei Grundlagen-Projekte mit Unterstützung des European Research Council.

Die Beteiligung am Photovoltaikprogramm der IEA (Implementing Agreement PVPS) wurde im Berichtsjahr fortgesetzt, sowohl auf der Projektebene als auch im Executive Committee (ExCo) [9]. Im Berichtsjahr wurde die 4. Phase dieses Programms abgeschlossen und für die 5. Phase eine neu ausgerichtete Strategie erarbeitet.

Die Firma Nova Energie vertritt die Schweiz in Task 1 des Implementing Agreements (IA) PVPS der IEA, welcher allgemeine Informationsaktivitäten zur Aufgabe hat. Im Berichtsjahr wurde ein weiterer nationaler Bericht über die Photovoltaik in der Schweiz bis 2011 [10] ausgearbeitet. Auf dieser Grundlage wurde die 17. Ausgabe des jährlichen internationalen Berichtes (Trends Report) über die Marktentwicklung der Photovoltaik in den IEA-Ländern erstellt [11].

Im Rahmen der interdepartementalen (SECO, DEZA, BAFU, BFE) REPIC Plattform zur Förderung der erneuerbaren Energien und der Energieeffizienz in der internationalen Zusammenarbeit [12] leistet das Beratungsunternehmen Entec den Schweizer Beitrag zum IA PVPS Task 9 über die Photovoltaik-Entwicklungszusammenarbeit. Dieses Projekt befasst sich mit der nachhaltigen Verbreitung der Photovoltaik in Entwicklungsländern und thematisiert auch Aspekte der solaren Wasserversorgung. Im Berichtsjahr wurde dazu unter Schweizer Leitung eine neue Publikation mit Empfehlungen zur Nachhaltigkeit von solaren Wasserversorgungsprojekten fertiggestellt [13].

ESU Services bzw. die im Berichtsjahr daraus heraus gegründete Treeze vertritt die Schweiz im IA PVPS Task 12 zu Umwelt-, Sicherheits- und Gesundheitsaspekten der Photovoltaik. In diesem Projekt sollen industriell möglichst aktuelle, relevante und international abgeglichene Informationen zu diesem bedeutenden Thema aufgearbeitet und publiziert werden.

TNC vertritt die Schweiz im IA PVPS Task 13 zu Performance und Zuverlässigkeit von Photovoltaikanlagen, welcher in der Schweiz durch den IEA PVPS Pool (aktuell getragen von ewz., Gesellschaft Mont Soleil und Swissolar) gefördert wird. Im Berichtsjahr hat TNC eine internationale Datenbank für Photovoltaik bereitgestellt, mit welcher weltweit Erfahrungen und Resultate aus vermessenen Photovoltaik-Anlagen gesammelt und analysiert werden können [14]. Im Projekt werden zudem Methoden zur Charaktierisierung und normierten Messung von Photovoltaikmodulen entwickelt sowie entsprechende Erfahrungen, z. B. zu Fehlverhalten von Modulen, ausgetauscht. In diese Aktivität ist auch das ISAAC SUPSI mit seinen relevanten Aktivitäten eingebunden. An der 27. Europäischen Photovoltaik Konferenz in Frankfurt fand dazu ein vielbeachteter Workshop statt.

Eine Arbeitsgruppe unter Leitung von Planair vertritt die Schweiz im IA PVPS Task 14 zur hohen Penetration von PV-Anlagen in elektrischen Netzen. Auch dieser Schweizer Beitrag wird durch den IEA PVPS Pool unterstützt. Das Projekt gewinnt aufgrund des starken Wachstums der Photovoltaik in einzelnen Ländern bzw. Regionen rasch an Bedeutung

und stösst damit auf grosses internationales Interesse. Erste Projektresultate betreffen hier Vorhersagemodelle und Fallstudien zu hoher Photovoltaik-Netzpenetration.

Das Unternehmen Meteotest und die Groupe Energie an der Universität Genf erbringen zusammen den Schweizer Beitrag zum Task 46 Solar resource assessment and forecasting. Task 46 folgt dem ähnlichen Task 36 und ist Bestandteil des IA Solare Wärme und Kälte (SHC) der IEA [15], inhaltlich ist es jedoch für alle Solartechnologien relevant. Dementsprechend erfolgt eine Zusammenarbeit mit den weiteren IA zur Solarenergie (IA PVPS und IA SolarPACES). In diesem Projekt werden die Auswirkungen von Strahlungsänderungen und Vorhersagen auf die solare Energieproduktion bei hoher Dichte von Solaranalgen sowie die Verfügbarmachung der entsprechenden Daten bearbeitet.

Ähnlich erfolgt im Task 41 [16] Solar Energy and Architecture des IA SHC eine Mitwirkung der Schweiz durch die HSLU (CCTP) und das ISAAC an der SUPSI. Auch hier finden Photovoltaik-relevante Aktivitäten statt. Dieses Vorhaben wurde im Berichtsjahr abgeschlossen.

Basler & Hofmann vertritt die Schweiz im Auftrag von Swissolar im TC 82 der IEC zu Photovoltaik-Normen [17].

Das von verschiedenen Ländern seit 2010 selbst getragene Projekt PV-ERA-Net, welches Programmkoordinationsstellen und verantwortliche Ministerien unter dem ERA-Net-Schema zusammengeführt hatte, wurde am Ende des Berichtsjahrs durch das neue SOLAR-ERA.NET Projekt [18] abgelöst. Dieses neue EU-Projekt umfasst nebst der Photovoltaik auch die konzentrierende solarthermische Energie und soll die Umsetzung der Solar Europe Industry Initiative unterstützen. Das Projekt umfasst rund 20 nationale und regionale Forschungs- und Innovationsprogramme. Das Projekt wird durch die Schweiz (Programmleitung *Photovoltaik*) koordiniert.

Die Schweiz ist zudem in der Europäischen Photovoltaik-Technologie-Plattform sowohl im Steuerungsausschuss, als auch in der Mirror Group vertreten [19].

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Laufende und im Berichtsjahr abgeschlossene Projekte

(* IEA-Klassifikation)

THIN LAYERS FOR HIGH-EFFICIENCY SILICON SOLAR CELLS THROUGH IDEAL COUPLING OF INDIVIDUAL COMPONENTS

R&D (1a) 3.1.2*

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	BFE
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2012–2014

Abstract: The project focuses on the increase in efficiency of thin film silicon devices, and also contributes to developments that can be implemented for high efficiency crystalline heterojunction solar cells. The final objective is to bring new findings to the research field that provides new routes for increased module efficiencies for similar costs, without impacting the reliability.

DEMONSTRATION OF HIGH PERFORMANCE PROCESSES AND EQUIPMENTS FOR THIN FILM SILICON PHOTOVOLTAIC MODULES (PEPPER)

R&D (1a) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	EU
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2010–2013

Abstract: The FP7 EU PEPPER project aims at achieving high efficiency (11 %) micromorph (amorphous/microcrystalline silicon tandem) modules at low cost (CoO ≤ 0.5 €/Wp) while reducing the environmental impact of fabrication processes.

FLEXIBLE PRODUCTION TECHNOLOGIES AND EQUIPMENT BASED ON ATMOSPHERIC PRESSURE PLASMA PROCESSING FOR 3D NANO STRUCTURED SURFACES (N2P)

R&D (1a) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	EU
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2008–2012

Abstract: The overall objective of the project "N2P" (Nano to Production) is to develop and substantially enhance the position of Europe in the science, application and production technologies of surface 3D nano-structuring.

IMPROVED MATERIAL QUALITY AND LIGHT TRAPPING IN THIN FILM SILICON SOLAR CELLS (SILICON_LIGHT)

R&D (1a) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	EU
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2010–2012

Abstract: The project Si-Light is devoted to the investigation of n-i-p solar cells on flexible substrates with focus on material quality, interface properties, and light management.

ACCELERATED DEVELOPMENT AND PROTOTYPING OF NANO-TECHNOLOGY-BASED HIGH-EFFICIENCY THIN-FILM SILICON SOLAR MODULES (FAST TRACK)

R&D (1a) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	EU
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2012–2015

Abstract: The main project goals are the development of innovative photovoltaic cell processes and their up-scaling to the level of pilot lines. These goals should be reached in terms of stable device efficiency higher than 14% and a prototype module with stable efficiency higher than 12 %.

INTERFACE TEXTURING FOR LIGHT TRAPPING IN SOLAR CELLS

R&D (1a) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	SNF
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2009–2013

Abstract: The project is devoted to a fundamental understanding of the light trapping process in solar cells.

A NEW LOW ION ENERGY BOMBARDMENT PECVD REACTOR FOR THE DEPOSITION OF THIN FILM SILICON FOR SOLAR CELL APPLICATIONS.

R&D (1a) 3.1.2

Lead:	EPFL CRPP	Funding:	KTI
Contact:	Hollenstein Christoph christophe.hollenstein@epfl.ch	Period:	2008–2012

Abstract: A novel electrode configuration is proposed for improved plasma-enhanced chemical vapour deposition of films such as amorphous silicon and micro-crystalline silicon.

ZWEIDIMENSIONALE NANOSTRUKTUREN FÜR SILIZIUM-SOLARZELLEN

R&D (1a) 3.1.2

Lead:	PSI Paul Scherrer Institut	Funding:	BFE
Contact:	Gobrecht Jens jens.gobrecht@psi.ch	Period:	2008–2012

Abstract: Optical gratings can be used to increase the light absorption in thin film solar cells. The main goal of the project is the development of efficient numerical methods to solve the Maxwell equations in order to calculate the optical properties of crossed gratings rigorously.

NOVEL REFLECTIVE LAYER ALLOWING A CONTROL OF THE QUALITY OF THE MICROCRYSTALLINE SOLAR CELL IN THIN FILM MICROMORPH DEVICES

R&D (1a) 3.1.2

Lead:	HE-ARC	Funding:	KTI
Contact:	Keppner Herbert herbert.keppner@he-arc.ch	Period:	2011–2013

Abstract: The project aims to create an innovative smoothening reflective layer SRL that will be inserted between the top and bottom cell of a Micromorph tandem device deposited on as-grown thick highly textured LPCVD ZnO layer.

HISOCEL: IMPROVEMENT OF FRONT CONTACTS MORPHOLOGY FOR ENHANCEMENT OF EFFICIENCY IN THIN FILM SILICON SOLAR CELLS

R&D (1a) 3.1.2

Lead:	CSEM	Funding:	KTI
Contact:	Dadras Massoud massoud.dadras@csem.ch	Period:	2012–2013

Abstract: The aim of this project is to improve the front contacts of tandem microcrystalline & amorphous silicon solar cells to reach an efficiency of 13% by producing denser and nearly defect free silicon layers.

HIGH EFFICIENCY TRIPLE JUNCTION THIN FILM SILICON SOLAR CELLS IMPLEMENTING AMORPHOUS SILICON GERMANIUM ALLOY (TRIGGER)

R&D (1a) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	KTI
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2012–2015

Abstract: Advanced triple junction solar cell will be developed to further enhance the conversion efficiency of thin film silicon solar cells. High quality silicon germanium alloys will be synthesized on textured substrates, and implemented in the triple junction solar cells. Record devices will be developed on state-of-the-art substrates as well as on advanced electrodes.

20 PERCENT EFFICIENCY ON LESS THAN 100 µM THICK INDUSTRIALLY FEASIBLE C-SI SOLAR CELLS (20PLµS)

R&D (1b) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	EU
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2010–2013

Abstract: The guiding principle of the 20PLµS project is to develop new and innovative process steps for wafer fabrication and solar cell and module manufacturing, taking into consideration the transfer of the processes to a pilot production line.

ELECTROPLATED FRONT GRID FOR CRYSTALLINE SI HETERO JUNCTION SOLAR CELL

R&D (1b) 3.1.2

Lead:	NTB	Funding:	KTI
Contact:	Gutsche Martin martin.gutsche@ntb.ch	Period:	2010–2012

Abstract: The challenge of this project is to deposit the front grid metallization directly on a transparent conductive ITO layer with excellent adhesion, specified electrical performance, and good long-term reliability.

DEVELOPMENT OF THIN HIGH-EFFICIENCY LARGE-AREA INTERDIGITATED BACK CONTACT SILICON HETEROJUNCTION SOLAR CELLS FOR MASS PRODUCTION (HET-IBC)

R&D (1b) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	KTI
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2012–2014

Abstract: The HET-IBC project aims at the development of an industrial process for the manufacture of high efficiency large-area interdigitated back contact silicon heterojunction solar cells on thin Si wafers. This type of device is amongst the most promising ones for ultra-high conversion efficiencies, low production costs and easier assembly into solar modules.

NODHID

R&D (1b) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	Axpo Naturstrom
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2011–2013

Abstract: Entwicklung von kristallinen Silizium-Solarzellen und -modulen mit höherem Wirkungsgrad und besserer Energieausbeute

CIGS MULTI-STAGE INLINE DEMONSTRATION

R&D (1c) 3.1.2

Lead:	EMPA Dübendorf	Funding:	BFE
Contact:	Tiwari Ayodhya N. ayodhya.tiwari@empa.ch	Period:	2011–2013

Abstract: The goal of the project is to develop and demonstrate a CIGS deposition system where the innovative multi-stage co-evaporation process developed in the lab for small area substrates in static positions can be scaled up for coating on in-line moving large area substrates.

HIPOCIGS – NEW CONCEPTS FOR HIGH EFFICIENCY AND LOW COST IN-LINE MANUFACTURED FLEXIBLE CIGS SOLAR CELLS

R&D (1c) 3.1.2

Lead:	EMPA Dübendorf	Funding:	EU
Contact:	Tiwari Ayodhya N. ayodhya.tiwari@empa.ch	Period:	2010–2012

Abstract: The HIPO-CIGS project aims at the development of cost efficient flexible solar cells and modules based on the compound semiconductor CIGS.

NOVA-CI(G)S – NON-VACUUM PROCESSES FOR DEPOSITION OF CI(G)S ACTIVE LAYER IN PV CELLS

R&D (1c) 3.1.2

Lead:	EMPA Dübendorf	Funding:	EU
Contact:	Tiwari Ayodhya N. ayodhya.tiwari@empa.ch	Period:	2010–2013

Abstract: NOVA-CI(G)S proposes alternative, non-vacuum deposition processes for thin film CI(G)S photovoltaic cells. The low capital intensive, high throughput, high material yield processes are expected to deliver large area uniformity and optimum composition of cells.

ROLL-TO-ROLL MANUFACTURING OF HIGH EFFICIENCY AND LOW COST FLEXIBLE CIGS SOLAR MODULES (R2R-CIGS)

R&D (1c) 3.1.2

Lead:	EMPA Dübendorf	Funding:	EU
Contact:	Tiwari Ayodhya N. ayodhya.tiwari@empa.ch	Period:	2012–2015

Abstract: The aim of R2R-CIGS is to develop efficient flexible solar modules by implementing innovative cost-effective processes such that production costs below 0.5€/Wp can be achieved in large volume factories with annual capacity of 500MWp in future.

DEVELOPMENT AND SCALE-UP OF NANOSTRUCTURED BASED MATERIALS AND PROCESSES FOR LOW COST HIGH EFFICIENCY CHALCOGENIDE BASED PHOTOVOLTAICS (SCALENANO)

R&D (1c) 3.1.2

Lead:	SUPSI ISAAC	Funding:	EU
Contact:	Virtuani Alessandro alessandro.virtuani@supsi.ch	Period:	2012–2015

Abstract: This project will exploit the potential of chalcogenide based thin film photovoltaic technologies for the development and scale-up of new processes based on nano-structured materials for the production of high efficiency and low cost photovoltaic devices and modules compatible with mass production requirements.

DURSOL – EXPLORING AND IMPROVING DURABILITY OF THIN FILM SOLAR CELLS

R&D (1d) 3.1.2

Lead:	EMPA	Funding:	diverse
Contact:	Nüesch Frank frank.nuesch@empa.ch	Period:	2011–2013

Abstract: The project's objectives are focused towards the understanding of fundamental degradation phenomena in thin film solar cells and enhancement of lifetime.

NEUARTIGE SENSIBILISATOREN FÜR FARBSTOFFSOLARZELLEN: SQUARAIN- UND HEPTAMETHINFARBSTOFFE MIT EINER GROSSEN SPEKTRALEN VIELFALT OBERHALB 700 NM

R&D (1d) 3.1.2

Lead:	EMPA Dübendorf	Funding:	KTI
Contact:	Nüesch Frank frank.nuesch@empa.ch	Period:	2009–2012

Abstract: Was für die Pflanzen bzw. für die Photosynthese die komplexen Chlorophyllmoleküle sind, sind für Solarzellen heutzutage photosensitive anorganische und organische Materialien, die in gleicher Weise wie das Chlorophyll effizient Licht absorbieren und in Energie umwandeln können. Die Entwicklung solcher organischer Materialien für Farbstoffsolarzellen ist das Ziel des Projektes.

DYE SENSITISED NANOCRYSTALLINE SOLAR CELLS

R&D (1d) 3.1.2

Lead:	EPFL ISIC-LPI	Funding:	diverse
Contact:	Graetzel Michael michael.graetzel@epfl.ch	Period:	2000-

Abstract: Key activities concerning dye sensitised nanocrystalline solar cells at EPFL.

ESCORT – EFFICIENT SOLAR CELLS BASED ON ORGANIC AND HYBRID TECHNOLOGY

R&D (1d) 3.1.2

Lead:	EPFL ISIC-LPI	Funding:	EU
Contact:	Graetzel Michael michael.graetzel@epfl.ch	Period:	2010–2013

Abstract: The project's objectives are to exploit the joint leadership of the top European and Indian academic and industrial Institutions to foster the wide-spread uptake of Dye-Sensitized Solar Cells technology, by improving over the current state of the art by innovative materials and processes.

MOLESOL – ALL-CARBON PLATFORMS FOR HIGHLY EFFICIENT MOLECULAR WIRE-COUPLED DYE-SENSITIZED SOLAR CELLS

R&D (1d) 3.1.2

Lead:	EPFL ISIC-LPI	Funding:	EU
Contact:	Graetzel Michael michael.graetzel@epfl.ch	Period:	2010–2013

Abstract: The proposed project comes with a visionary approach, aiming at development of highly efficient molecular-wire charge transfer platform to be used in a novel generation thin film dye-sensitized solar cells fabricated via organic chemistry routes. The proposed technology combines the assembled dye monolayer's, linked with organic molecular wires to semiconducting thin film deposited on optically transparent substrates.

SANS – SENSITIZER ACTIVATED NANOSTRUCTURED SOLAR CELLS

R&D (1d) 3.1.2

Lead:	EPFL ISIC-LPI	Funding:	EU
Contact:	Graetzel Michael michael.graetzel@epfl.ch	Period:	2011–2013

Abstract: Plastic electronics and solution-processable inorganic semiconductors can revolutionise the photovoltaic industry due to their relatively easy and low cost processability (low embodied energy). The project aims at achieving significant progress in the materials for this type of solar cells.

FARBSTOFF-SOLARZELLEN AUF SEFAR PRÄZISIONSGEWEBEN

R&D (1d) 3.1.2

Lead:	EPFL ISIC-LPI	Funding:	KTI
Contact:	Graetzel Michael michael.graetzel@epfl.ch	Period:	2012–2014

Abstract: The project aims to enhance market readiness of dye sensitized solar cells (DSC) by developing electrodes based on transparent and conductive precision fabrics.

ORDERED INORGANIC-ORGANIC HYBRIDS USING IONIC LIQUIDS FOR EMERGING APPLICATIONS (ORION)

R&D (1d) 3.1.2

Lead:	Solaronix SA	Funding:	EU
Contact:	Meyer Toby toby.meyer@solaronix.com	Period:	2009–2013

Abstract: The ORION project puts together a multidisciplinary consortium of leading European universities, research institutes and industries with the overall goal of developing new knowledge on the fabrication of inorganic-organic hybrid materials using ionic liquids.

FIRST PRINCIPLES SIMULATIONS OF THE ELECTRON DYNAMICS IN DYE SENSITIZED SOLAR CELLS

R&D (1d) 3.1.2

Lead:	ETH Zürich	Funding:	SNF
Contact:	VandeVondele Joost joost.vandevondele@mat.ethz.ch	Period:	2011–2016

Abstract: The research focus is on the development of new methods to enable ab initio molecular dynamics simulations of complex systems with modern density functional theory. New methods, implemented for massively parallel computers, are applied to a wide range of systems such as radicals in clusters and the condensed phase, surface physics, and interfacial systems such as dye sensitized solar cells.

MESOLIGHT – MESOSCOPIC JUNCTIONS FOR LIGHT ENERGY HARVESTING AND CONVERSION

R&D (1d) 3.1.2

Lead:	EPFL	Funding:	EU
Contact:	Vaccaro Luciana luciana.vaccaro@epfl.ch	Period:	2010–2015

Abstract: Research will focus on the generation of electric power by mesoscopic solar cells. The target is to increase the photovoltaic conversion efficiency from currently 11 to over 15 percent rendering these new solar cells very attractive for applications in large areas of photovoltaic electricity production.

UPCON – ULTRA-PURE NANOWIRE HETEROSTRUCTURES AND ENERGY CONVERSION

R&D (1d) 3.1.2

Lead:	EPFL	Funding:	EU
Contact:	Vaccaro Luciana luciana.vaccaro@epfl.ch	Period:	2010–2014?

Abstract: This proposal is devoted to the synthesis of ultra pure semiconductor nanowire heterostructures for energy conversion applications in the photovoltaic domain.

TRANSPARENT ELECTRODES FOR LARGE AREA, LARGE SCALE PRODUCTION OF ORGANIC OPTOELECTRONIC DEVICES

R&D (1d) 3.1.2

Lead:	EMPA Dübendorf	Funding:	EU
Contact:	Nüesch Frank frank.nuesch@empa.ch	Period:	2011–2015

Abstract: TREASORES will demonstrate the production of large area organic electronics using high throughput manufacturing technologies based on roll-to-roll (R2R) wet deposition processes.

NUMERICAL SIMULATION, DESIGN AND FABRICATION OF EXTREMELY THIN ABSORBER SOLAR CELLS

R&D (1d) 3.1.2

Lead:	ZHAW, EMPA Thun	Funding:	BFE
Contact:	Loeser Martin loma@zhaw.ch	Period:	2011–2012

Abstract: This joint research focuses on combining both numerical and experimental methods to analyze and improve the optical efficiency of extremely thin absorber (ETA) solar cells.

CARACTÉRISATION DES MODULES PHOTOVOLTAÏQUES À COLORANT DE L'ENTREPRISE G2E (SWISS SOLAR POWER)

R&D (1d) 3.1.2

Lead:	HEIG-VD	Funding:	BFE
Contact:	Affolter Jean-François jean-francois.affolter@heig-vd.ch	Period:	2012–2014

Abstract: A solar simulator for measuring the performance of solar panels based on dye sensitised solar cells is going to be realized. The panels will be installed in real conditions and monitored over a complete year, in order to characterize and have the necessary perspective on this new technology and product.

NANOSPEC – NANOMATERIALS FOR HARVESTING SUB-BAND-GAP PHOTONS VIA UPCONVERSION TO INCREASE SOLAR CELL EFFICIENCIES

R&D (1e) 3.1.2

Lead:	Universität Bern, Dep. Chemie & Biologie	Funding:	EU
Contact:	Krämer Karl karl.kraemer@iac.unibe.ch	Period:	2010–2013

Abstract: Fundamental loss mechanisms limit the maximum achievable efficiency: around 20% of the incident power is lost, because photons with energies below the band-gap are transmitted. Upconversion of two low energy photons into one usable photon reduces these losses. In this project we will realize upconversion with the help of nanostructures and nanotechnoloy-based materials and show a significant improvement in solar cell efficiency.

NANODESIGNED ELECTROCHEMICAL CONVERTER OF SOLAR ENERGY INTO HYDROGEN HOSTING NATURAL ENZYMES OR THEIR MIMICS (SOLHYDROMICS)

R&D (1e) 3.1.2

Lead:	Solaronix SA	Funding:	EU
Contact:	Meyer Toby toby.meyer@solaronix.com	Period:	2009–2012

Abstract: The main objective is to leapfrog current limitations of third-generation PV devices through a drastic improvement of the materials used for assembling XSCs.

INNOVASOL – INNOVATIVE MATERIALS FOR FUTURE GENERATION EXCITONIC SOLAR CELLS

R&D (1e) 3.1.2

Lead:	Solaronix SA	Funding:	EU
Contact:	Meyer Andreas andreas.meyer@solaronix.com	Period:	2009–2012

Abstract: The main objective is to leapfrog current limitations of third-generation PV devices through a drastic improvement of the materials used for assembling excitonic solar cells.

OPTIMIZED METHODS FOR INCREASED PERFORMANCE PHOTOVOLTAIC CELLS BY NANOPARTICLES INTEGRATION (OPTINOGEN)

R&D (1e) 3.1.2

Lead:	EIA-FR	Funding:	Sciex
Contact:	Niederhaeuser Elena Lavinia Elena-Lavinia.Niederhaeuser@hefr.ch	Period:	2011–2013

Abstract: The project targets the optimization and the development of new improved methods for enhancing of the overall performance and stability of nanocomposite solar cells (NSC) by introducing new physical principles.

DIAMOND: DISCOVERY AND INSIGHT WITH ADVANCED MODELS OF NANOSCALE DIMENSIONS

R&D (1e) 3.1.2

Lead:	ETH Zürich	Funding:	ERC
Contact:	VandeVondele Joost joost.vandevondele@mat.ethz.ch	Period:	2011–2016

Abstract: Generating knowledge about new materials and obtaining insight in their properties at the nano-scale level are highly relevant to the scientific objectives of the EU. Here, it is proposed to advance the current state of the art in atomistic modeling of complex systems. The goals are providing and establishing new tools that will allow for the description of large multi-component/multi-phase systems at experimental temperature and pressure with predictive power and controlled error.

ENTWICKLUNG NEUARTIGER POLYMERE FÜR DIE POLYMERPHOTOVOLTAIK

R&D (1e) 3.1.2

Lead:	ZHAW -ICBC	Funding:	diverse
Contact:	Hinderling Christian hicr@zhaw.ch	Period:	2010–2012

Abstract: Projektziel ist die Herstellung und Erprobung von neuartigen Polymeren für den Einsatz in Polymersolarzellen. Geeignete Polymere enthalten Cyaninfarbstoffe als aktive Komponente und zeichnen sich insbesondere dadurch aus, dass sie sich aus einer Lösung heraus z.B: durch spin-coating verarbeiten lassen. Ein weiteres Projektziel ist die Erprobung solcher Polymere in homo-junction devices.

PYRITE-BASED SOLAR CELL

R&D (1e) 3.1.2

Lead:	HE-ARC	Funding:	diverse
Contact:	Keppner Herbert herbert.keppner@he-arc.ch	Period:	20010–2012

Abstract: The overall objective of this project is the achievement of a "diode kind" behavior of a full <p> pyrite / <n> ZnO heterojunction device ready for electronic characterization (current-voltage, spectral response, etc.) and further optimization.

LIGHT-IN, LIGHT-OUT: CHEMISTRY FOR SUSTAINABLE ENERGY TECHNOLOGIES (LILO)

R&D (1e) 3.1.2

Lead:	Uni Basel (Institut für Anorganische Chemie)	Funding:	ERC
Contact:	Constable Edwin Charles Edwin.Constable@unibas.ch	Period:	2011–2016

Abstract: The project is concerned with a coordinated approach to the development of of novel chemical strategies for light harvesting by photovoltaic cells and light generation using light emitting electrochemical cells.

ENTWICKLUNG VON LUMINESZENZKONZENTRATOREN

R&D (1e) 3.1.2

Lead:	ZHAW IEFE	Funding:	diverse
Contact:	Brühwiler Dominik dominik.bruehwiler@zhaw.ch	Period:	2011–2015

Abstract: Das hier untersuchte Konzept von Lumineszenzkonzentratoren baut auf der Grundlage der Förster Resonance Energy Transfer (FRET) Frequenzverschiebung auf. Hierzu werden geeignete Materialien mit den gewünschten Eigenschaften entwickelt.

UNIQUE AND INNOVATIVE SOLUTION OF THIN SILICON FILMS MODULES BUILDING INTEGRATION (ARCHINSOLAR)

P&D (2a) 3.1.2

Lead:	CSEM	Funding:	BFE, SER, CCEM
Contact:	Perret-Aebi Laure-Emmanuelle laure-emmanuelle.perret@csem.ch	Period:	2010–2013

Abstract: This project aims to develop and test a new generation of photovoltaic building elements based on thin film silicon technology (single amorphous and tandem amorph/microcrystalline cells).

NOVEL PRODUCTION EQUIPMENT FOR NOVEL PHOTOVOLTAIKC MODULE DESIGNS USING NEW ENCAPSULANTS

R&D (2a) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	KTI
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2012–2014

Abstract: The main target of this project is the development and the market launch of novel laminating lines optimized for the production of PV modules based on novel module designs using new encapsulants.

ADVANCED LASERS FOR PHOTOVOLTAIC INDUSTRIAL PROCESSING ENHANCEMENT (ALPINE)

R&D (2a) 3.1.2

Lead:	Oclaro (Switzerland) AG	Funding:	EU
Contact:	Schmid Manuel www.oclaro.com	Period:	2009–2012

Abstract: ALPINE aims to push forward the European research and development of fiber laser systems for the scribing of photovoltaic modules, joining together two exciting challenges: the fiber laser development for advanced industrial processing and the solar energy exploitation.

PRODUKTENTWICKLUNG SOLAR DEVICE

R&D (2a) 3.1.2

Lead:	NTB	Funding:	KTI
Contact:	Gutsche Martin martin.gutsche@ntb.ch	Period:	2010–2012

Abstract: In diesem Projekt wird die Technologie der hocheffizienten textilen Photovoltaik bis zur Produktionsreife weiterentwickelt. Diese Produktentwicklung wird die Markteinführung von textiler Photovoltaik beschleunigen.

TEXTILE PHOTOVOLTAICS: INTEGRATION OF MINIATURIZED SOLAR MODULES ON TEXTILES BY EMBROIDERY TECHNIQUES

R&D (2a) 3.1.2

Lead:	NTB	Funding:	KTI
Contact:	Gutsche Martin martin.gutsche@ntb.ch	Period:	2010–2012

Abstract: Im Projekt Textile Photovoltaik werden durch die Kombination von bestehenden Techniken miniaturisierte Solarmodule hergestellt und mittels Sticktechnik zu einem neuen Gewebeverbund verarbeitet. Die erarbeiteten Techniken erlauben es zum ersten Mal, vollflexible Flächengebilde mit photovoltaischer Funktion zu erzeugen.

LOW-COST PV BITUMINOUS-MODIFIED ROOFING MEMBRANE WITH FULL INTEGRATION OF FLEXIBLE THIN-FILM SILICON PV MODULES (PV-GUM)

R&D (2a) 3.1.2

Lead:	VHF Technologies SA	Funding:	EU
Contact:	Fischer Diego diego.fischer@flexcell.com	Period:	2010–2013

Abstract: The PV-GUM project aims at developing new manufacturing technologies and equipments which will produce a low cost highly efficient flexible BIPV solar cell on a bituminous roofing membrane.

LARGE AREA SOLAR SIMULATOR INTEGRATING POWER LIGHT EMITTING DIODES FOR PERFORMANCE MEASUREMENT OF NEW GENERATIONS OF PHOTOVOLTAIC MODULES (SUNSIM)

R&D (2b) 3.1.2

Lead:	EPFL STI IMT-NE PV-LAB	Funding:	KTI
Contact:	Ballif Christophe christophe.ballif@epfl.ch	Period:	2010–2012

Abstract: High precision solar simulators will become crucial to characterize the next generation of low cost PV modules. In this project, a new large area characterization tool, satisfying criteria on homogeneity, spectrum, and temporal stability will be developed, prototyped and tested.

OPTIMIZATION OF THIN FILM MODULE TESTING AND PV MODULE ENERGY RATING AT SUPSI

R&D (2c) 3.1.2

Lead:	SUPSI ISAAC	Funding:	BFE
Contact:	Friesen Gabi gabi.friesen@supsi.ch	Period:	2011–2014

Abstract: This project aims to improve the measurment accuracy for thin film technologies throgh th definition of new test procedures and the up-grade of the test equipment.

DEFEKTANALYSEN AN PV MODULEN MIT ELETTROLUMINISENZAUFNAHMEN UND DEREN KLASSIFIZIERUNG

R&D (2c) 3.1.2

Lead:	SUPSI ISAAC	Funding:	KTI
Contact:	Friesen Thomas thomas.friesen@supsi.ch	Period:	2011–2012

Abstract: The project aims to improve the quality control of PV module production. The quality control is performed after the soldering of the string and before the lamination process. This step allows the repair of strings with soldered cracked cells replacing them with new ones and the final quality of the PV module increase.

PHOTOVOLTAIK IM VERBUND MIT DÄMMSTOFF FOAMGLAS

P&D (2d) 3.1.2

Lead:	Basler & Hofmann AG	Funding:	BFE
Contact:	Bucher Christof christof.bucher@baslerhofmann.ch	Period:	2010–2013

Abstract: The scope of this project is the development and realisation of building integrated photovoltaic (BIPV) including the feature of thermal insulation. A pilot plant with modules combined of photovoltaic modules and Foamglas insulation shall be build.

SOLAR BRICK: INNOVATIVE PHOTOVOLTAIC AND THERMAL INSULATING BUILDING MATERIALS

R&D (2d) 3.1.2

Lead:	SUPSI ISAAC	Funding:	KTI
Contact:	Rudel Roman roman.rudel@supsi.ch	Period:	2011–2013

Abstract: The goal of this project is to develop a photovoltaic and thermal insulating building material and in parallel to plan and construct a prototype installation including said material.

PV-CARPORTS PUBLIKUMSWIRKSAME PHOTOVOLTAIKANLAGE

P&D (2d) 3.1.2

Lead:	ZHAW IEFE	Funding:	diverse
Contact:	Baumgartner Franz franz.baumgartner@zhaw.ch	Period:	2011–2012

Abstract: Es wird die Nutzung von mit Photovoltaik überdachten Parkplätzen im Zusammenhang mit der Elektromobilität untersucht. Anhand von konkreten Fallstudien wird das Potenzial dieser Anwendung abgeschätzt.

APPLICATION DE MODULES PV FLEXIBLES SUR LE SITE DE PRODUCTION FLEXCELL

P&D (2d) 3.1.2

Lead:	VHF Technologies SA	Funding:	BFE
Contact:	Fischer Diego diego.fischer@flexcell.com	Period:	2009–2012

Abstract: The goal of this project to develop, install and monitor various building integrated PV products and installation solutions based on Flexcell's technology on buildings of Flexcell's production site in Yverdon.

LANGZEIT-MESSUNG VON PV-ANLAGEN

R&D (3) 3.1.2

Lead:	BFH Burgdorf	Funding:	KTI
Contact:	Muntwyler Urs urs.muntwyler@bfh.ch	Period:	2012–2016

Abstract: Das PV Labor führt Langzeit-Messungen an unterschiedlichen PV-Anlagen durch und dokumentiert damit das längerfristige Verhalten dieser Anlagen.

PHOTOVOLTAÏQUE ET NEIGE: HORIZON DES SOLUTIONS POUR L'INSTALLATION SUR LES TOITS DANS LES RÉGIONS ENNEIGÉES

P&D (3) 3.1.2

Lead:	Planair SA	Funding:	BFE
Contact:	Perret Lionel lionel.perret@planair.ch	Period:	2011–2014

Abstract: Seven different photovoltaic fields and three snow clearing solutions were implemented. Measures on different parameters such as production and consumption of each field will occurre during the winters of 2012, 2013 and 2014. The evaluation of the measures will enable to determine snow impact and compare different photovoltaic technologies and snow clearing solutions.

POTENTIAL VON PHOTOVOLTAIK AN SCHALLSCHUTZWÄNDEN ENTLANG DER NATIONALSTRASSEN (ASTRA)

R&D (3) 3.1.2

Lead:	TNC Consulting AG	Funding:	ASTRA
Contact:	Nordmann Thomas nordmann@tnc.ch	Period:	2010–2013

Abstract: Das Projekt prüft das Anwendungspotential der Kombination von Photovoltaik und Schallschutz ausgehend vom kurz- und mittelfristigen Realisierungsumfang bestehender und neuer Schallschutzvorhaben in der Schweiz entlang von Nationalstrassen.

MOBILES PV MESSSYSTEM

P&D (3) 3.1.2

Lead:	ZHAW IEFE	Funding:	diverse
Contact:	Baumgartner Franz franz.baumgartner@zhaw.ch	Period:	

Abstract: Ein Messsystem für PV-Module ist auf einem Kleinbus montiert und erlaubt so Messungen von PV-Modulen an einem beliebigen Ort. Damit können langwierige Transporte von grösseren Mengen von zu testenden Modulen vermieden werden.

ALTERNATIVE AUFSTÄNDERUNG FÜR PV-MODULE

R&D (3) 3.1.2

Lead:	ZHAW	Funding:	KTI
Contact:	Koller Christoph kolc@zhaw.ch	Period:	2011–2012

Abstract: The world's first solar ski lift has a 60 kW PV system that is tracked in one axis. The robust design of the mechanical system requires less material than usual: less than 100kg of steel per kW nominal PV module. To achieve this goal the steel cables function as the support structure for the PV modules.

PV TESTANLAGE DIETIKON

P&D (3) 3.1.2

Lead:	ZHAW IEFE	Funding:	diverse
Contact:	Baumgartner Franz franz.baumgartner@zhaw.ch	Period:	0

Abstract: Die Arbeiten an der PV Testanlage EKZ Dietikon wurden weitergeführt, mit der jährlichen Flasher Messungen aller etwa hundert Module mit dem EKZ ZHAW Flasherbus und der Ausweitung der Feinanalyse des Netzgekoppelten Systems. Dabei wurde in diesem Jahr der Fokus auf die DC und AC Performance der Inverter, die Gewichtungsfaktoren des Euro-Wirkungsgrades, aber auch den Wirkungsgradverlaufes an klaren und bewölkten Tagen für die fünf unterschiedlichen PV Modultechnologien gelegt.

SIMULATION APPROACH TO INVESTIGATE THE IMPACT OF DISTRIBUTED POWER GENERATION WITH PHOTOVOLTAICS ON A POWER GRID (PV ERA NET PROJECT PV+GRID_06_DPVG)

R&D (3) 3.1.2

Lead:	Basler & Hofmann AG	Funding:	BFE
Contact:	Bucher Christof christof.bucher@baslerhofmann.ch	Period:	2010–2013

Abstract: Simulation Approach to Investigate the Impact of Distributed Power Generation with Photovoltaics on a Power Grid. The project addresses the important topic of grid integration of variable production from phovoltaics.

DIGITALER LICHTBOGENDETEKTOR FÜR PV-WECHSELRICHTER

R&D (3) 3.1.2

Lead:	BFH Burgdorf	Funding:	KTI
Contact:	Muntwyler Urs urs.muntwyler@bfh.ch	Period:	2012

Abstract: In diesem Projekt besteht die Innovation in der Entwicklung eines digitalen Lichtbogen-Detektionsalgorithmus und der Industrialisierung eines Lichtbogendetektors für dessen Integration in einen Wechselrichter.

RESOURCE- AND COST-EFFECTIVE INTEGRATION OF RENEWABLES IN EXISTING HIGH-RISE BUILDINGS (COST-EFFECTIVE)

R&D (4) 3.1.2

Lead:	Emmer Pfenninger Partner AG	Funding:	EU
Contact:	Emmer Andreas andreas.emmer@eppag.ch	Period:	2008–2012

Abstract: The main focus of the project is to convert facades of existing "high-rise buildings" into multifunctional, energy gaining components. This goal will be achieved by: development of integrated building concepts, development of new multi-functional façade components and development of new business and cost models.

POTENTIALANALYSE HYBRIDE PV-ANLAGE MIT THERMISCHER NUTZUNG

R&D (4) 3.1.2

Lead:	NTB	Funding:	KTI
Contact:	Bertsch Stefan stefan.bertsch@ntb.ch	Period:	2011–2012

Abstract: Es soll eine Potenzialanalyse eines hybriden Sonnenkollektors zur parallelen Erzeugung von Strom über Photovoltaik und Warmwasser über Solarthermie erstellt werden. Der Fokus liegt in einem Mehrfachnutzen einer PV-Anlage mit einer Erdwärmensonden-Beheizung.

NORMENARBEIT FÜR PV SYSTEME

WTT (4) 3.1.2

Lead:	Basler & Hofmann AG	Funding:	BFE
Contact:	Toggweiler Peter peter.toggweiler@baslerhofmann.ch	Period:	2007-

Abstract: Normen sind ein wichtiges Instrument zur Qualitätssicherung sowie zum sicheren und zuverlässigen Betrieb von PV-Anlagen. Das Projekt umfasst den Schweizer Beitrag zu den entsprechenden Arbeiten im IEC Technischen Kommittee 82.

SCHWEIZER BEITRAG IEA PVPS TASK 1 – EXCHANGE AND DISSEMINATION OF INFORMATION ON PHOTOVOLTAIC POWER SYSTEMS

R&D (5) 3.1.2

Lead:	Nova Energie GmbH	Funding:	BFE
Contact:	Hüsser Pius pius.huesser@novaenergie.ch	Period:	2012

Abstract: IEA PVPS Task 1 befasst sich mit Informationsaufgaben zum Stand der Photovoltaik in den Mitgliedländern des IEA PVPS Programms. Dazu leistet dieses Projekt den Schweizer Beitrag, insbesondere zur Entwicklung von Industrie und Markt sowie des regulatorischen Kontextes.

SCHWEIZER BEITRAG IEA PVPS TASK 12 – PV ENVIRONMENTAL HEALTH & SAFETY ISSUES

R&D (5) 3.1.2

Lead:	Treeze GmbH	Funding:	BFE
Contact:	Frischknecht Rolf frischknecht@treeze.ch	Period:	2012

Abstract: IEA PVPS Task 12 befasst sich mit Umweltaspekten der Photovoltaik ausgehend von Analysen in den Mitgliedländern des IEA PVPS Programms. Dazu leistet dieses Projekt den Schweizer Beitrag, insbesondere zur Lebenszyklusanalyse (LCA) von PV-Systemen.

SCHWEIZER BEITRAG IEA PVPS TASK 13 – PERFORMANCE AND RELIABILITY OF PV SYSTEMS

R&D (5) 3.1.2

Lead:	TNC Consulting AG	Funding:	IEA PVPS Pool
Contact:	Nordmann Thomas nordmann@tnc.ch	Period:	2011–2012

Abstract: IEA PVPS Task 13 befasst sich mit Performance und Zuverlässigkeit von PV-Kompenten und PV-Anlagen in den Mitgliedländern des IEA PVPS Programms. Mit diesem Projekt wird der Schweizer Beitrag zu diesem neuen internationalen Vorhaben vorbereitet.

SCHWEIZER BEITRAG IEA PVPS TASK 14 – HIGH PENETRATION OF PV SYSTEMS IN ELECTRICITY GRIDS (SWISS CONTRIBUTION)

R&D (5) 3.1.2

Lead:	Planair	Funding:	IEA PVPS Pool
Contact:	Renaud Pierre pierre.renaud@planair.ch	Period:	2010–2014

Abstract: The main purpose of Task 14 is to analyze the role of grid connected PV as an important source in electric power systems on a high penetratin level where additional efforts may be necessary to integrate the dispersed generation in an optimum manner. The aim of these efforts is to reduce the technical barriers to achieve high penetration levels of distributed renewable systems on the electric power system.

SCHWEIZER BEITRAG IEA SOLAR HEATING & COOLING PROGRAMME, TASK 46 – SOLAR RESOURCE MANAGEMENT

R&D (5) 3.1.2

Lead:	Meteotest	Funding:	BFE
Contact:	Kunz Stefan stefan.kunz@meteotest.ch	Period:	2005–2010

Abstract: In the framework of IEA Solar Heating and Cooling (SHC) Task 46, Meteotest investigates the possibilities and quality of global radiation forecast, the trend of recent global radiation data and distribution of atmospheric aerosols.

Solarzellen

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THIN LAYERS FOR HIGH-EFFICIENCY SILICON SOLAR CELLS THROUGH IDEAL COUPLING OF INDIVIDUAL COMPONENTS

Annual Report 2012

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Project- / Contract Number	SI500750 / SI500750-01
Duration of the Project (from – to)	01.01.2012 – 31.12.2014
Date	16.12.2012

ABSTRACT

The project focuses on the increase in efficiency of thin film silicon devices, and also contributes to developments that can be implemented for high efficiency crystalline heterojunction solar cell. It is divided in six axis, ranging from a better understanding of the key parameters of the fabrication processes (notably the plasma deposition of the silicon layers) to the improvement of the efficiency, of the reliability and of the characterization/understanding of the obtained devices. Developing new layers, improving the light trapping and the opto-electrical coupling of multi-junction devices complete the panel, with also a part dedicated to updating and improving the infrastructure park. The final objective is to bring new findings to the research field that provides new routes for increased module efficiencies for similar costs, without impacting the reliability.

In the first year of this 3-year project, the focus was put on acquiring new knowledge on fundamental aspects of the technology, and setting the basis of novel concepts. A clarification of the mechanism governing light scattering was obtained, with the assessment of the potential of several light trapping structures. Parasitic absorption was notably identified as the main challenge to face to this respect. Also, routes towards better amorphous and microcrystalline absorber layers were sketched. For amorphous cells, exploring various deposition conditions permitted to target a regime giving a promising stability with only 8% of light induced degradation. On the microcrystalline side, a passivating interfacial layer was shown to enable 600mV of Voc to be reached

On the device side, the coupling between sub-cells could be significantly improved by introducing a smoothening interlayer. A new method to fabricate a highly transparent and low-index layer enabling transverse conduction of electrical carriers was developed. Improvements in stable efficiency are expected with this layer which enables both a boost of the top-cell current and an increase of the electrical quality and compactness of the microcrystalline material. Also continuous improvement of base processes, including more transparent electrodes and doped layers, lead to a noteworthy 11.8% stable efficiency, obtained by solely employing ZnO electrodes and thin Si layers (< 1.5 µm total thickness), to large area (> 1 cm2) 10.4% microcrystalline cells. In synergy with other projects triple junction with up to 12.5% in substrate configuration could also be demonstrated

Finally, this project tackles all the most challenging aspects of the technology and should contribute to push the efficiency of thin-film silicon modules to 12% and above.

Introduction

In 2012, the industrial crisis that thin-film silicon companies had been facing for a couple of years continued, with many thin-film silicon manufacturers in a difficult position. The global production overcapacity of modules (mostly crystalline) put a strong pressure on thin-film silicon manufacturers. Yet, many large industrial players still invest in this technology, as demonstrated by the recent purchase of Oerlikon solar by TEL and the strong research and development effort made all around the world by leading large companies (as evidenced by the new world-record efficiency of 13.4% from LG electronics for a triple junction cell). This R&D effort is still necessary in the strongly competitive photovoltaics market to further lower the cost of thin-film silicon installations, through improved efficiencies to limit BOS penalties or cheaper manufacturing processes. The attractivity of the thin-film silicon solution remains robust for the energy sector, notably due to its ideal suitability for low-cost building integration, and for a large deployment of utility-scale photovoltaics in warm places. In particular, the possibility to reach unsubsidized module manufacturing costs in the range of 0.35-0.4€/W, without any constraint on the supply chain continues to make this a long term choice technology.

Project goals

By **aiming at improving the efficiency of thin-film silicon modules**, this project fits the present main challenge of the technology. A combination of improvements in material deposition techniques, in layer – but also interface – properties, and in light trapping is thought to be necessary to bring thin-film silicon devices one step further. Yet, this is not enough as a key challenge still to be addressed is the coupling of the sub-cells in a multi-junction device. Mastering all these aspects is needed to push upwards the efficiency and bring the technology to its full potential.

Short project description (2012-2014)

The project aims at obtaining high-efficiency thin-film silicon solar cells, through an ideal coupling of optimized individual sub-cells in a multi-junction device. As sketched in Figure 1, the fulfilling of this task goes through improvements in three major areas:

- Impact of plasma conditions on layers quality (defect density and their metastability in aSiH, self passivated and dense µc-Si:H material even on rough substrates)
- Doped layers, buffers and new materials (more transparent, diffusion barriers, more absorbing active materials)
- Light trapping (higher light in-coupling, new light trapping mechanisms)

To help in these tasks, two other areas complete the view. The first one concerns reliability and characterization, which are the key bases of scientific progress, and the second one is updating of the infrastructure to maintain an adequate technology park for future developments.

For 2012, the major objectives have been to:

- Quantify the light trapping capacity of our existing structures and determine the most promising routes towards improved light management.
- Develop reliable methods to obtain smoothening interlayers between the top and bottom sub-cell.
- Improve the understanding of microcrystalline material.
- Valorise results from previous project with high efficiency devices.
- Set up reliable characterization of individual components in tandem devices.

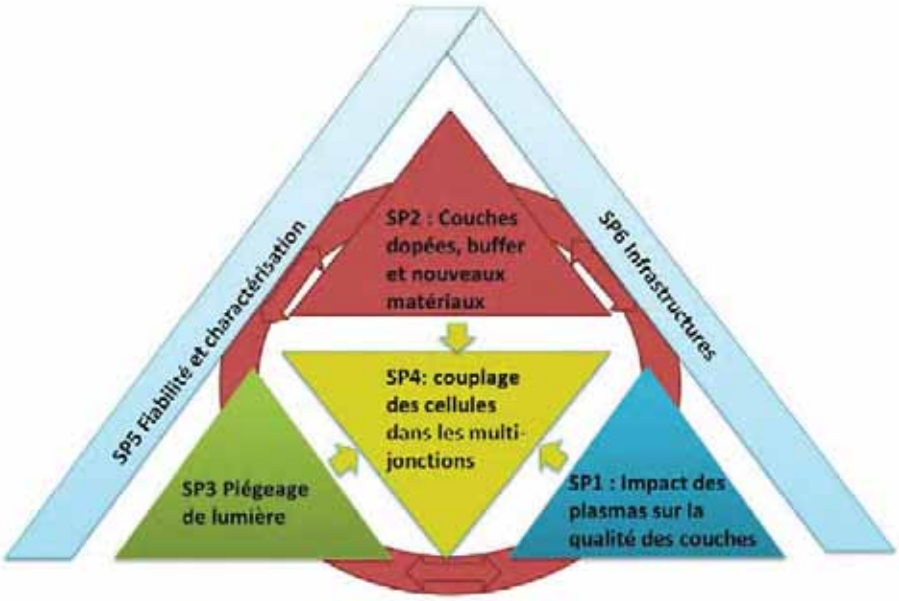

Figure 1: *Summary of work packages of SFOE-EPFL PV-Lab project 2012-2014.*

Eventually, many of the processes and layers developed for the thin film silicon technology can also be applied to the field of silicon heterojunction cells (SHJ), where the a-Si/c-Si interfaces dictate in large part the device behaviour. Hence this project also provides bases for preparing next generation layers and processes for SHJ devices.

The detailed scientific results are reported in the publications listed in the references at the end of the report, which the reader is invited to consider.

Work performed and results achieved in 2012

In the first part of this three-year project, the emphasis was put on fundamental aspects of the afore-mentioned areas. A better understanding of the basic mechanism causing losses in the conversion efficiency will set the basis for improvement in next years. Yet, improvements in the record efficiency of several devices are reported following the findings obtained during previous project.

1. Impact of plasma conditions on the quality of silicon thin films

1.1 Understanding of the origin of the M1 (bulk) and M2 (porous) phases

For the first time, a fine 3-D tomographic reconstruction of a µc-Si solar cell was performed. A 3-D dataset was created by alternating milling steps with a focus ion beam (FIB) column (to obtain a smooth cross section of the sample), with imaging the milled face (with a scanning electron micro-scope (SEM) column). By proceeding by steps of some nanometers, a 3-D dataset was created. A clear view of the 2-D interconnected network formed by the local nano-porous / low quality material areas can for example be obtained, as shown in Fig. 1.1. This result was obtained in collaboration with Prof. Hebert's CIME in EPFL. The localization of pinching points, particularly detrimental for multi-junctions, could also be determined. Such tomographic imaging thus appears as a valuable technique to provide insights into the µc-Si microstructure [1].

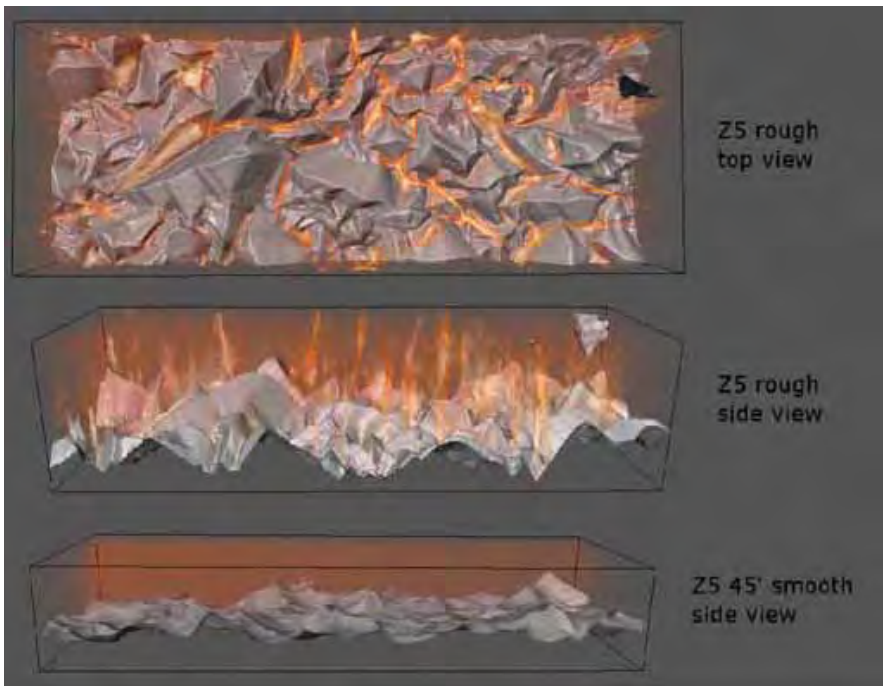

Figure 1.1: *Reconstructed top and side view of the porous areas (cracks, appearing in orange here) in a micro-crystalline cell deposited on a rough (Z5) or smooth (Z5 45') ZnO electrode. The bulk silicon was numerically hidden, revealing the interconnected 2-D network of porous, defective area [1].*

The development of this nano-porous 2-D network was shown to be much more dramatic when the deposition rate was increased, enabling the development of a simple qualitative model describing how plasma processes act on the properties of µc-Si:H material and on the related solar cell performances. It has been published in Advanced Functional Material [2]. The degradation induced by water vapour ingress in this porous material has also been clearly evidenced, indicating that further adapting the interplay between substrate morphology and the growth dynamic is necessary to improve the film compactness and the device stability.

1.2 Development of new a-Si materials and study of their stability

Thanks to the extended range of process parameters of the Octopus tool, an extensive study of the process parameters on the properties of intrinsic amorphous silicon layers have been made. Three main plasma regimes have been explored: a standard very-high frequency (VHF) regime with low pressure and low power (40 MHz, 0.2 mbar, 13 mW/cm^2 of excitation frequency, pressure and power); a protocrystalline-like regime (13 MHz, 2.5 mbar, 13 mW/cm^2); and a polymorphous-like regime (13 MHz, 9 mbar, 90 mW/cm^2). For the first time, these different a-Si:H materials could be synthetized in the same laboratory and in the same PECVD system. They were also studied in layers and in high efficiency base-line cells. For all deposition regimes, both a hydrogen dilution series and a temperature series were made, while cell deposition was carried out on substrates with varying roughness (from untreated rough LPCVD ZnO to fully flat substrate). A large variety of materials could be obtained: high band-gap material was obtained for high dilution and low temperature in the protocrystalline regime, with potential application in triple junction devices; an extremely low light-induced-degradation of only 8% was observed in the polymorphous regime for a reasonably good cell (7.1% stabilized efficiency); and a solid base-line process was identified in the standard-VHF regime with the achievement of an 8.7%-stable-efficiency device with no anti-reflective coating (typically for > 9 % stable efficiency after device optimization). First demonstration of a reduced resilience of the cell electrical performance to the substrate roughness was also evidenced for high H_2 dilution processes (i.e. high V_{OC} cells). Further analysis of the layers and correlation between material quality and solar cell properties is ongoing.

1.3 Conformality of the a-Si layers

The deposition of the a-Si top cell modifies the initial morphology of the electrode surface, and typically generates pinches that favor the formation of cracks in the bottom cell. The influence of the deposition conditions of the a-Si layer on the pinching has been studied. In collaboration with CSEM, case-study substrates were developed, consisting of self-ordered nanopillars, to quantify the conformality of

the a-Si layers for various deposition conditions and thicknesses. Favorable regimes, leading to a conformal growth were developed. In particular, lowering the hydrogen dilution and increasing the temperature was shown to improve the conformality of the layers. The suitability of the developed process for high-efficiency devices was confirmed with 10.4% initial (8.3% stable) efficiency single junction a-Si cells.

1.4 Annealing and plasma post treatments

A major input towards higher efficiencies in µc-Si:H single junctions and µc-Si-based multi-junction solar cells has been the implementation of a post deposition hydrogen plasma, with typical gains of up to 20-30 mV of Voc and 3% (absolute) of FF both for single-junction and micromorph cells, the biggest improvements being on the roughest substrate (Fig. 1.2 left). Note that the gain in FF depends on the doping of the electrode and can thus be made even larger. Lately, very promising gains in Voc and FF (but for the latter to a lower extent than with H2 plasma) have been also observed with annealing under vacuum if temperature is high enough. With this plasma post-treatment, a record 10.4% efficiency was obtained for a 1cm^2 single-junction microcrystalline device (Fig. 1.2 right), which is currently in the process of being certified by Fraunhofer institute.

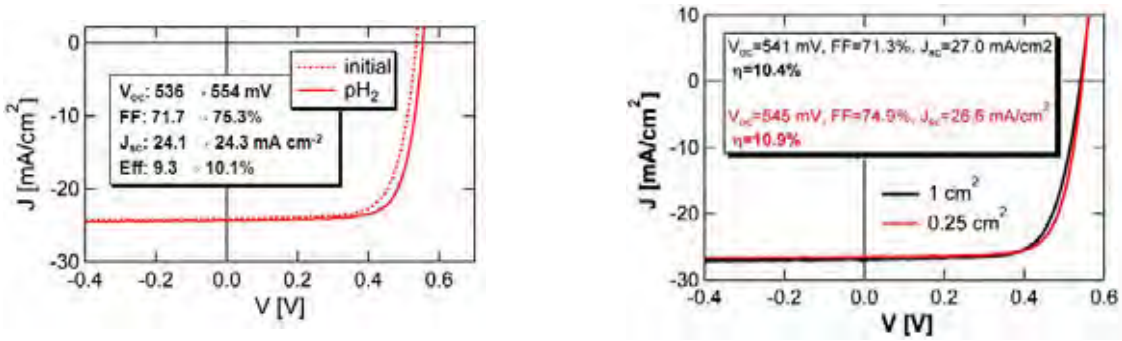

Figure 1.2: *Left: IV characteristics of a microcrystalline cell as deposited, and after a H_2 post-deposition plasma treatment, with the IV properties before and after the treatment. Right: Record microcrystalline single junction devices of 0.25 cm^2 and 1 cm^2.*

2. New doped layers and buffers

2.1 Novel window layer in amorphous silicon cells

By combining a lower deposition temperature and adapted gas flows, a strong gain in transparency could be obtained for the window layer of amorphous cells (Fig. 2.1 left). By using a low-temperature p-doped layer (150°C compared to 200°C), a ~0.2 mA/cm^2 gain could be observed, thanks to an improved EQE in the 380 nm – 520 nm wavelength range. This apparently small gain is nevertheless of great interest when implementing this cell as the top cell of a micromorph device, as it is directly transferred into top-cell current gain without impacting the bottom cell current.

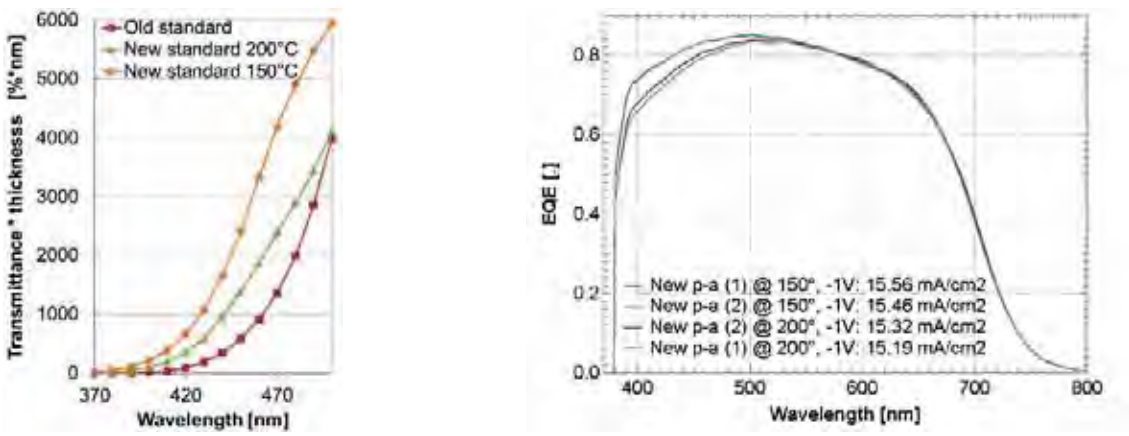

Figure 2.1: *left: transmittance-thickness product of three P-doped window layers for amorphous silicon cells. Right: EQE of an amorphous cell with two different p-doped window layers deposited at two different temperatures.*

2.2 Passivating layers for high-Voc microcrystalline cells

By using the synergy between thin-film-silicon and silicon-heterojunction technologies, a passivating interlayer was introduced at the i-n interface in p-i-n microcrystalline silicon cells. For thin devices (~500nm), that are particularly sensitive to the interfaces, Voc values above 600mV have been obtained by implementing this interlayer in state-of-the-art devices. For the first time, such a high Voc could be maintained even for crystallinity values up to 70% by only employing PECVD processes for the deposition of the silicon layers, and was obtained together with a FF above 75%. This result brings new insights in the understanding of the present limitations of microcrystalline silicon devices, and brings new prospects for high-efficiency microcrystalline-based solar cells. A noteworthy Voc value of 1.53V could be demonstrated in a micromorph tandem cell by combining this microcrystalline cell with a high-gap amorphous silicon top cell. Future work will focus on improving the current of these high-voltage devices.

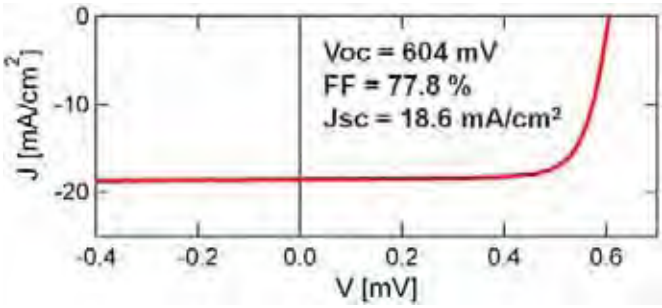

Figure 2.2: *IV characteristic of a high-Voc microcrystalline cell implementing a passivating interlayer.*

2.3 Impact of SiO layers in substrate-type cells (n-i-p)

An SiO window layer was also successfully transferred to single-junction a-Si:H n-i-p solar cells. An 80 mV Voc enhancement, compared to a µc-Si:H “standard” p-layer, was observed. A numerical modeling was performed to identify the origin of this gain. Both the higher work function of this p-layer and the increased conduction band offset at the i/p interface were introduced in the model. As the built-in voltage of the cells – probed with the differential temperature method – were shown to be similar with the two different p-layers, the improvement of the Voc could be attributed mostly to the reduction of recombination at the i/p interface, originating from the higher conduction-band offset. This new window layer enabled a stabilized efficiency of 8.4% to be reached for an amorphous silicon cell (Voc > 900mV), with a total silicon thickness of 300 nm on an opaque substrate [3].

2.4 Insights on the quality of the passivation of SHJ cells with sputtered TCO layers

A damaging of the hydrogenated amorphous/crystalline silicon interface passivation during the sputtering of the transparent conductive oxide was observed with lifetime measurements. This damage was notably shown to be at least partially caused by luminescence of the sputter plasma. Even though low-temperature annealing was demonstrated to allow a complete recovery of the electronic interface properties, infra-red absorbance spectra indicated that the silicon-hydrogen configuration of the amorphous silicon film is permanently changed; the passivation quality was however not affected. Sputtered TCO can therefore be used in high-efficiency devices without inducing a drop in the Voc [4].

3. Light trapping

3.1 Fundamentals of light trapping

New insights about the light trapping capacity of our current devices were obtained. By applying a model developed during previous projects, we could determine that the photonic structures presently used in state-of-the-art devices do not provide a Lambertian light scattering in silicon layers (which is considered to be the ideal light scattering distribution). Yet, scaling laws that are derived from the model enable to find a simple geometrical modification of morphology that would enable such a light scattering distribution. According to this prediction, smaller features but with a higher inclination are preferable for ideal light scattering. This theoretical prediction is an important first step towards improved random light scattering in thin-film silicon solar cells [5].

Pushing further the analysis, an intuitive analytical model for light management in solar cells was developed. An accurate reproduction of light absorption in each layer of a microcrystalline solar cell could be obtained. Based on this model, we could identify the origin of the light losses in present devices. In particular, it was shown that the angular distribution of scattered light in the solar cell evoluates from the initial angular distribution dictated by the rough electrode-silicon interface towards a Lambertian distribution as light experiences multiple total internal reflections. Therefore, the non-Lambertian light scattering induces extra-escaping of light only for the first few passes compared to an ideal case. Another major result was that the main cause of light loss between ideal and present state-of-the-art light management schemes comes from parasitic absorption rather than sub-optimal light scattering. Present light trapping schemes were indeed shown to enable the reaching of above 30 mA/cm^2 (compared to around 25 mA/cm^2 presently) in a 1-µm-thick microcrystalline cell by suppressing parasitic absorption [6].

Continuing the collaboration with Stanford university, a paper published in ACS nano showed unambiguously how carefully designed periodic structures can rival with state-of-the-art random structures in providing well-suited superstrate for high-efficiency amorphous silicon solar cells [7]. The importance of designing nanophotonic scattering features with a smooth morphology was also evidenced by comparing nanocones, nanodomes and nanopillars approaches. This was published in Advanced Energy Materials [8].

3.2 Post-treatments for high-transparency ZnO layers

A hydrogen plasma post-deposition treatment was developed for ZnO layers, to improve their electrical properties. An improvement of mobility was observed for all standard electrodes, which surpasses the improvement observed when a simple annealing step was performed (Fig. 3.1). A strong boost was notably observed for the non-intentionally-doped (n-i-d) samples (+70%), with mobility values up to 60 cm^2/V/s for 2-µm-thick layers. This high mobility, combined to a low carrier density, enables a high transparency to be maintained for these layers together with sufficient conduction for solar cell applications [9][10].

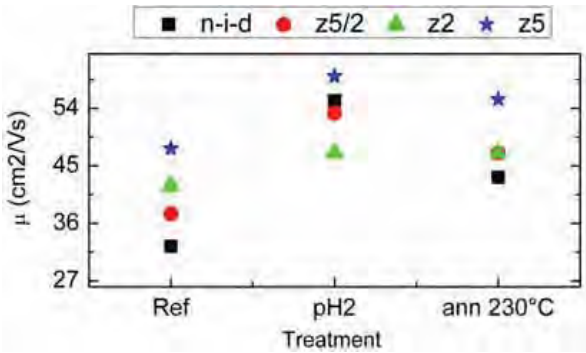

***Figure 3.1**: Mobility of four different LP-CVD ZnO layers, as deposited, or after a H_2 plasma treatment, or after annealing under vacuum at 230°C.*

3.3 Two-step growth to adapt the morphology of ZnO layers

ZnO multi-layers were developed to provide a surface of which the roughness is directly adapted (*i.e.* smooth enough) to enable the growth of high-quality silicon layers, without the need of the post-deposition smoothening treatment. Such multi-layers are obtained with a two-step growth: a standard rough layer is first deposited and then its sharp valleys are filled with a second deposition step, enabling a smooth layer to be obtained. On such electrodes, and without post-deposition smoothening treatment, micromorph cells of equally good properties as on state-of-the-art electrodes (requiring a post-deposition smoothening treatment) could be obtained. Such new electrodes are particularly attractive for industrial applications, by suppressing one step which is delicate to upscale in the fabrication of micromorph modules [11][12].

3.4 Plasmonic v.s. metallic grating

In the continuation of the collaboration with Prof. Jürgen Brugger's group, a direct assessment of the potential of plasmonics, compared to metallic gratings, to provide light trapping in thin-film silicon solar cell was performed. For that, we fabricated amorphous silicon n-i-p solar cells with two types of nanopatterned back reflectors using stencil lithography. One of the reflectors has a plasmonic grating, embedded in the ZnO layer; the other one has a metallic grating patterned on top of the Ag layer. Similar morphologies are thus obtained for the silicon layers, with an additional plasmonic effect in the first case due to the isolation of the silver particles. This allows thus a fair comparison of the two light coupling mechanisms. A 14% and 19% short-circuit current density enhancement for the plasmonic and for the metallic grating, respectively, were obtained compared to a flat reference. This indicates that pure grating coupling is more efficient in coupling guided modes in the intrinsic layer than metallic nanodots through localized surface plasmon effects [13].

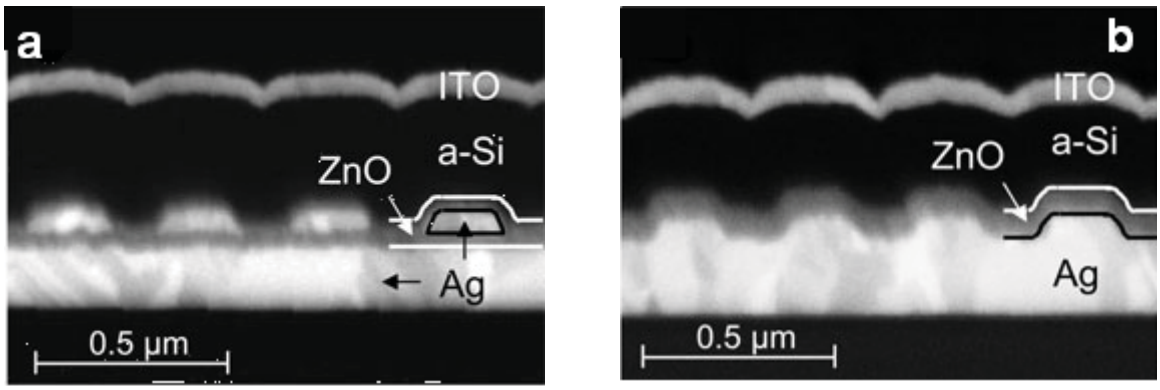

Figure 3.2: *SEM cross-section images of an a-Si cell deposited on a) a plasmonic grating and b) a metallic grating. Identical morphology is obtained in both cases at the surface of the a-Si cell.*

3.5 External geometrical light trapping

An anti-escape light trapping system was developed, to prevent light from escaping the device. It uses a microlenses array, coupled to an array of apertures in a highly reflective silver layer. Based on geometric optics, a reduction by a factor of five of the share of light escaping the device can be achieved, at the cost of a reduction by the same factor of the solid angle of acceptance. Even though this reduction of the solid angle of acceptance prevents any efficiency gain in outdoor conditions without a tracking system, such a tool can be used to boost by a factor of five the light trapping capacity of a device in standard test conditions (i.e. with collimated light). With 85% coverage of microlenses at the surface and two more glass-air interfaces, inducing 20% of reflection losses, we experimentally observed a strong improvement of the EQE in the wavelength range of weak absorption for microcrystalline silicon, by up to 45% for wavelengths above 1000 nm. Extrapolating this to 100% coverage of the microlenses, a 10% current gain could be obtained. This system can be used as a tool to probe the influence of parasitic absorption for very good light-trapping conditions. By doing so, we could highlight the need for very low parasitic absorption in order to take advantage of an excellent light trapping scheme to achieve a high current density.

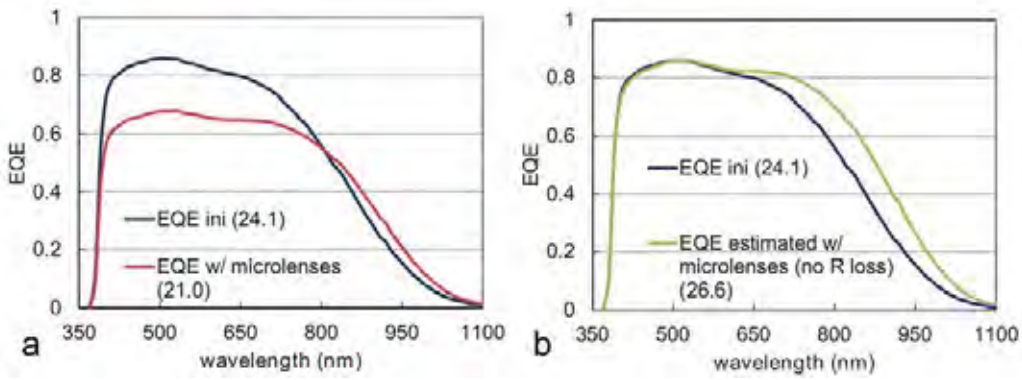

Figure 3.3: *a) Measured and b) extrapolated EQE of a microcrystalline device with and without microlenses setup in front.*

3.6 High-current microcrystalline devices

In the substrate configuration, 2-D gratings were implemented in thin microcrystalline devices, to provide a stronger light scattering while preserving a morphology suitable for the growth of high-quality silicon layers. A 9.9% efficiency single junction device could be obtained, with a short-circuit current density of 24.4mA/cm^2, for a thickness of 900 nm. This result is amongst the first experimental proofs that a periodic texture can combine excellent light trapping performances together with a suitable morphology, leading to an efficiency surpassing reference random textures.

4. Coupling in multijunction

4.1 Micromorph record device in superstrate configuration

A novel record efficiency was obtained in micromorph configuration, by combining all findings from previous project. By using industrially compatible processes only, an 11.8% stable efficiency micromorph device was obtained, with 13.7% initial efficiency (Fig. 4.1). The application of an advanced anti-reflective coating (ARC) enabled a notable increase of the initial efficiency by 5%, compared to 3% for conventional ARC. This device ended up being top limited in the degraded state (i.e. with a lower current in the top cell than in the bottom cell), explaining the heavy 14% degradation. This result confirms that our process has the potential to enable above 12% efficiency devices with a more efficient intermediate reflecting layer [14]. The record initial efficiency remains the 14.1% value obtained on a multi-scale textured electrode architecture, which was published this year [15]. This approach is still investigated in the framework of this project, and set the basis for a large European project “Fast Track” which started this year.

	$J_{SC\ top}$ (mA/cm^2)	$J_{SC\ bottom}$ (mA/cm^2)	V_{OC} (V)	FF (%)	Eff. (%)
Initial state no ARC	12.85	13.06	1.395	72.5	13
Initial state w. ARC	13.6	13.4	1.395	73.5	13.7
Stabilized state after 1000 h LID, w. ARC	13.05	13.3	1.36	66.4	11.8

Figure 4.1: *Detailed performances of the new record micromorph device in superstrate configuration.*

4.2 Multi-junction devices in substrate configuration

Improvements in the light-trapping / morphology trade-off for rough silver back reflector on flexible substrates lead to a new record stabilized efficiency of 9.2% in a-Si / a-Si tandem configuration [16]. Also, the flat light scattering substrate approach introduced during previous project for microcrystalline silicon cells [17] has been extended to a-Si / µc-Si / µc-Si triple devices. In addition, high efficiency µc-Si:H n-i-p devices could be rapidly synthetized by using processes developed for record p-i-n cells. By combining the advanced “flat” light trapping scheme with the high quality µc-Si:H layers, a 12.5% stable efficiency device [18] could be demonstrated: this lies amongst the highest reported values for this technology. It must be further noted that such result could be achieved with only few depositions, so that higher efficiencies should be in hand with proper device optimization.

4.3 Planarization of the a-Si cell

The concept of smoothening intermediate reflecting layers (IRLs) has been explored in details during this year. The aim of such structures is to provide a well suited surface morphology on which to grow good electrical quality microcrystalline silicon, especially in Micromorph devices including a rough front electrode enabling good light scattering. We could validate this concept by showing a 50mV *V*oc enhancement when employing a polished SiOx-based IRL (using chemo-mechanical polishing, CMP) compared to a non-polished one [19]. Shunting of the top cell due to the irregular surface of the random rough electrode and additional reflection losses (-0.7mA/cm^2 in the bottom cell) due to the resulting flat interfaces show the limitations of this technique, highlighting the need to smoothen without completely flattening.

A strong focus was therefore put on liquid-based deposition of IRLs. Good smoothening was shown to be achieved with spray coating of ZnO from Zn-acetate, but this method was abandoned because the deposition temperature (>250°C) required for complete decomposition was too high and damaging the top cell. A new technique was then developed to enable the use of highly transparent – but isolating – UV-curable lacquer thanks to selective etching: since the lacquer preferentially settles in the bottoms of the structure rather than at the tips, a short dry-etching can unveil the tips of the surface, enabling electrical conduction. Smoothening of the surface of the top cell was demonstrated with this technique, with a *V*oc boost of up to 50mV compared to a standard IRL. A strong top cell current boost was also shown, of up to 2.3mA/cm^2 (20% relative), compared to 1.8mA/cm^2 with a standard IRL. Adjusting the volume of lacquer composing this advanced interlayer was shown to enable a fine tuning of its opto-electrical properties [20]. A cross-section view of a micromorph device including such an IRL can be seen in Fig. 4.2, as well as micromorph cell performances.

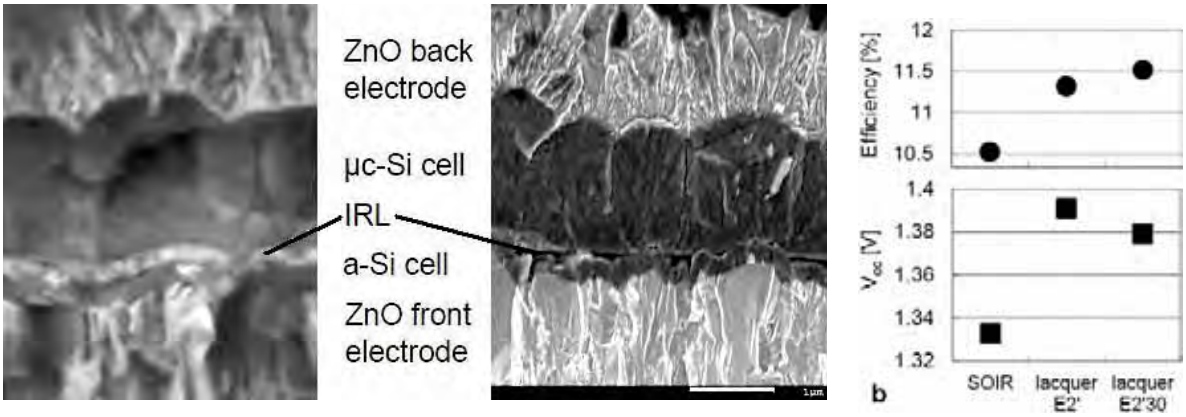

Figure 4.2: *a) Cross-section view of a micromorph device including a smoothening intermediate reflector made from left) spray-deposition of Zn-acetate (appearing in light gray) and right) spin-coating + etching of lacquer (appearing in black). b) Efficiency andVoc of micromorph cells including a SiOx-based IRL, or an IRL made out of lacquer etched for 2 minutes or 2minutes and a half.*

5. Reliability and Characterization

5.1 Damp-heat tests in microcrystalline cells

Dark degradation of microcrystalline cells has been identified as one of the main issue for long-term stability of this material. Water vapour ingress was previously shown to be responsible for this metastability (similarly to light-induced degradation, this effect is reversible after annealing). A process to hasten this long-term degradation has been developed in an in-house damp-heat chamber in which a 100% humidity and 50°C atmosphere can be set. Similar degradation can be obtained after 2 days in this chamber compared to 2 months in ambient air storage, enabling a much faster probing of the stability of microcrystalline devices.

5.2 Encapsulation

A new design for compressive-shear testing of polymer layers bonded to rigid substrates was developed to characterize real interfacial adhesion of ethylene-vinyl acetate (EVA) and polyvinyl-butyral (PVB) to a glass substrate, both before and after degradation in damp-heat. Results from this technique showed that a peak-force based metric wass unable to capture the evolution of adhesion through degradation. For a better representation, new metric based on the elastic strain energy of the encapsulant was suggested. Moreover, it was shown that PVB adhesion to glass was much more affected by damp-heat exposure where polymer saturation takes place, in comparison with the adhesion of EVA to glass. This characterization protocol is therefore believed to be a powerful tool to contribute in assessing the reliability of an encapsulant facing specific degradation conditions [21].

5.3 Voc and FF separation in micromorph devices

To probe the quality of each sub-cell when combining single junctions in micromorph tandem devices, setups aiming at Voc separation, FF analysis and complete IV separation are now operational. A novel method for probing the Voc of individual sub-cells was suggested, as well as a novel IV separation technique [22]. The latter was shown to enable a more precise characterization than other existing techniques, as illustrated in Fig. 5.1 [23]. For IV separation, different methods were compared in [24], the most promising one being the use of “fake-aSi” filtered microcrystalline cells, which was developed during previous project. This method reproduces efficiently both the morphology and the optical filtering of the a-Si cell in a micromorph configuration (Fig. 5.1) [25].

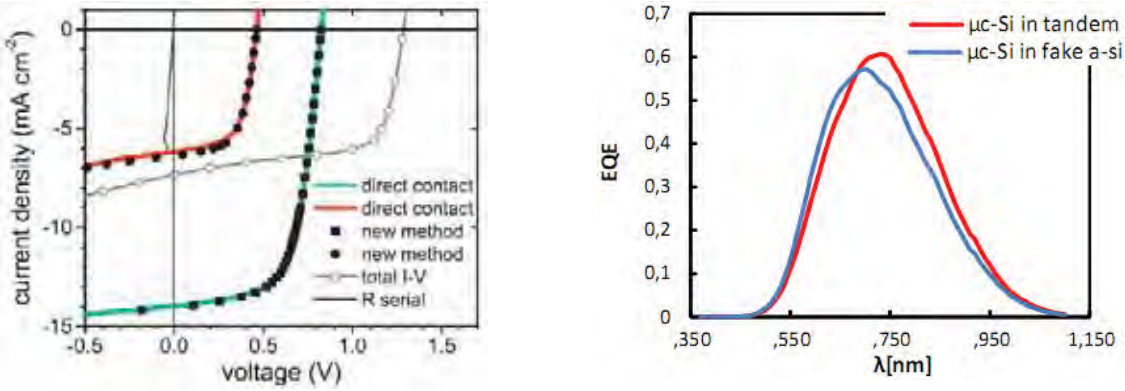

Figure 5.1: *Left: illustration of the IV separation method, showing the IV curves of a micromorph device including a conductive interlayer, the curves obtained with the IV separation method for both sub-cells, and the IV curves measured for both sub-cells in direct contact with the conductive interlayer. Right: Illustration of the optical filtering provided with the “fake a-Si” method, which corresponds well to the filtering of a top cell in micromorph conditions.*

5.4 Accelerated degradation with 3-sun illumination system

The 3-sun illumination system, for accelerated degradation has been mounted and first tests were made. Minor hardware adjustments are still being made and software is under final development, for a start-up beginning of next year.

6. Infrastructure

6.1 PE-CVD cluster tool

The Octopus cluster tool is now fully operational, with standard recipes available. It has been used for different deposition series with a good reliability and reproducibility. With the installation of new heating units in all chambers, the temperature can now be maintained for all process ranges, including high flow regimes. The variety of plasma conditions offered by this tool has been exploited to explore deposition conditions that were not accessible with other equipment. Promising regimes for depositing high-quality amorphous silicon layers have been identified, with single single-junction amorphous silicon cells with initial and stable efficiency of 10.4% and 8.7%, lying amongst the highest values observed in PV-lab.

6.2 Germanium development

The Octopus cluster is notably used for developments involving germane that started this year. A germane gas line has been installed and connected to the system with adequate security adjustments. Amorphous silicon-germanium alloy layers could successfully be deposited in a dedicated chamber, with no contamination of other processes observed. An efficient incorporation of Germanium in the amorphous silicon films was observed, with a subsequent decrease of the electronic gap of the obtained material. The PECVD system is therefore now operational for developing µc-SiGe:H layers and solar cells.

6.3 Octopus II

The Octopus II tool is being installed, with a start-up planned for January 2013. All hardware is in place, and vacuum chambers have been successfully tested. A base pressure below 10^{-6} mbar has been assessed and transfers between chambers are in operation. Final electrical power adjustments are being performed with first plasma tests in early December 2012.

6.4 Large area ZnO LP-CVD and high temperature LP-CVD systems

The large-area LP-CVD ZnO system is now fully operational, and the deposition of standard layers is now done in this system in batches of up to 40 samples. A homogeneous deposition (+/-5% of thickness, roughness and conductivity) can be obtained on a 30x40 cm^2 area. All processes were successfully transferred to this new system that allows a higher throughput and reproducibility compared to previous deposition tools.

6.5 Sputtering system

A new high-performance sputtering system was purchased. This Clusterline 200 II tool from Oerlikon will enable a reliable deposition of various high-quality layers, both for optical applications and for electrode applications. Its installation is planned for beginning of 2013.

National and international collaborations

Regular academic contact/scientific and sample exchanges continued to be maintained throughout the project both with national and international entities (ETH Zürich, Zürich University of Applied Sciences, CSEM Neuchâtel, Forschungszentrum Jülich, Friedrich-Schiller Universität Jena, Helmoltz Zentrum Berlin, Academy of Science Prague, University of Delft, Energy Research Center Netherlands, University of Utrecht, Stanford University, Caltech, National University of Singapore, AIST Japan…).

PV-Lab continues to be involved in several European projects (Fast Track, N2P, Silicon Light, Pepper, 20 plus) as well as national projects (Dursol, Axpo, Archinsolar, Velux in collaboration with CSEM) and benefits from the support of the National Science Foundation. This variety of interests in several aspects of the technology creates a strong synergy between all these projects ant this running SFOE project. In addition, national and industrial collaborations with industrial partners are ongoing, either in the frame of CTI projects or through direct mandates, e.g. with Oerlikon Solar (now TEL Solar), Roth & Rau Switzerland (now Roth & Rau Research AG), 3S Photovoltaics, Pasan, Metalor, Solneva, Essemtech, Indeotec, IBM, Air Liquide,...

Evaluation of 2012 and perspectives for 2013

In 2012, new insights about fundamentals of light trapping were unveiled, leading to a better understanding of the most limiting parameters in present devices. Another key result comes from the development of promising techniques to integrate smoothening IRL in micromorph devices. Also, in the continuity of the efforts from previous project, further improvement in stable efficiency were obtained in micromorph configuration, with an 11.8% efficiency, contributing to filling the gap between lab-record and world-record values from industrial labs (12.3%) for tandem junctions. Many scientific findings were valorized through journal and conference papers, ensuring a strong visibility for PV-lab's activities. This visibility was strengthened by several invited presentations in the key international conferences, confirming the status of PV-lab as leading laboratory in the thin-film silicon field. Another prestigious recognition has been the attribution of the Zeno Karl Schindler Price 2012 to Dr. Corsin Battaglia.

Two major directions could be derived from the results obtained this year towards improved multi-junction devices. One aspect comes from intrinsically better amorphous and microcrystalline cells, with better bulk material or advanced interfaces. The high-Voc microcrystalline device and the low-degradation amorphous silicon cell are two key results towards improvements in this direction. The other route goes through improving the coupling of the amorphous and microcrystalline cells in the tandem device. The preliminary results obtained when using a newly developed smoothening intermediate reflecting layer confirmed the strong potential of this approach. A 1% absolute gain in efficiency is within reach by mastering this technique. Such a gain would be strongly beneficial towards an economically viable industrialization of this technology, due to the pressure of higher-efficiency technologies. Another 1% gain from sub-cell improvement, leading to 14% lab-size cells, would allow for 13% stable efficiency modules representing an attractive low-cost technology.

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DEMONSTRATION OF HIGH PERFORMANCE PROCESSES AND EQUIPEMENTS FOR THIN FILM SILICON PV MODULES PRODUCED WITH LOWER ENVIRONMENTAL IMPACT AND REDUCED COST AND MATERIAL (PEPPER)

Annual Report 2012

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Project- / Contract Number	PEPPER / 249782
Duration of the Project (from – to)	01.09.2010 – 31.08.2013
Date	16.12.2012

ABSTRACT

The FP7 EU PEPPER project aims at achieving high efficiency (11%) micromorph (amorphous/ microcrystalline silicon tandem) modules at low cost (CoG ≤ 0.5 €/W_p) while reducing the environmental impact of fabrication processes. The project thus includes development of a new generation of Plasma Enhanced Chemical Vapor Deposition (PECVD) reactors for high rate deposition (up to 15 Å/s) of intrinsic µc-Si:H thin films. PVLAB participates in assessing the most favorable process parameters space for high rate deposition and also contributes, together with the University of Patras, Greece, to the development of a model linking layer quality to deposition parameters and plasma dynamics (work package WP3). In addition, PVLAB is leader of WP2, which focuses on the development of advanced transparent conductive oxide (TCO).

In this latter, PVLAB has shown that the defective zones density (cracks) in µc-Si:H as induced by inappropriate front contact roughness could be reduced by smoothening the front ZnO by other means that Argon plasma. Several approaches have been tested among which use of an ethanol based cap layer to smoothen the surface of the TCO film or exploration of new growth regimes leading to improved surface features morphologies.

In WP3, the second year of the project was focused on further improving the material quality and device efficiency by further decreasing the inter-electrode distance of PVLAB KAI-M PECVD reactor. Conversion efficiency of 9.3% at 15 Å/s and 9.6% at 10 Å/s could thus be achieved for 1 µm thick single-junction µc-Si:H solar cells. Still, µc-Si:H material deposited at high rate was shown to be very ensitive to substrate morphology, rapidly developing zones of porous material (cracks). Thus, implementing this high rate material in bottom cells of micromorph devices, where the deposition of the amorphous to cell typically leads to pinching, was revealed as more critical than with low rate µc-Si:H.

Indeed, initial micromorph conversion efficiencies up to 12.7% could be obtained with the bottom cell i-layer deposited at 12 Å/s but light induced degradation (LID) experiments have demonstrated a higher relative degradation than expected, probably consequent to ambient air (dark) degradation linked to oxygen incorporation in the porous zones. However, first tests of solar cell encapsulation have shown promising results in reducing such additional degradation leading the path to higher stable efficiency.

Aims of the project

The global goal of the project is to demonstrate and partially implement cost-effective high efficiency processes to prove the feasibility of thin film micromorph (amorphous/microcrystalline silicon tandem) module production. Its objectives are to:

- Increase the module power to 157 W_p stabilized (corresponding to 11% conversion efficiency)
- Maintain low Cost of Ownership (CoO) for micromorph module fabrication at 0.5 €/W_p
- Reduce the environmental impact of the fabrication process with the target of 20% lower energy payback time

For the second year of the project, specific milestones and deliverables were the following:

- **WP2**

➢ M2.1 Layers with nanomorphology allowing reduced crack density by a factor 2 as compared to the current process at OS (M2.1 was achieved first last year, see previous report)

➢ D2.2 First Solar cell deposition on one of the most promising LPCVD ZnO layers as defined on D2.1 with efficiency >11%

Both the milestone M2.1 and the deliverable D2.2 were successfully achieved.

- **WP3**

➢ M3.1b Solar cell with 11% stable at 1.2 nm/s in medium area reactor (M24)

➢ D3.1b Report on layer properties and rates, exploration of parameter space, cells results on medium area

The deliverable D 3.1b was achieved but the milestone M3 3.1b has yet not been fulfilled, with present best stable micromorph efficiencies with bottom i-layer at > 1 nm/s being of the order of 10-10.5%.

Description of the project

An optimized TCO front contact is a prerequisite to cost-effective and efficient micromorph modules. Two requirements should be fulfilled: (1) the electrode (substrate) should be rough enough to enable good light scattering (high solar cell current) while, at the same time, still allowing high quality silicon growth. During the first year, different deposition concepts and regimes have been evaluated in order to improve the transparency/conductivity tradeoff of front electrode. During this second year, different concepts have been tested in order to reduce the defect density in µc-Si: cells in relation with the ZnO front contact morphology. The most promising approaches will be later selected and the possibility of their industrial transfer will be studied in more detail for the end of the project.

Regarding plasma processes and high deposition rates development for µc-Si:H silicon, the first year was focused on studying the impact of the inter-electrode distance of a KAI-M Plasma Enhanced Chemical Vapor Deposition (PECVD) reactor on the process parameter space for high rate deposition of µc-Si:H. In, 2012, we further studied the impact of the inter-electrode distance (d_{gap}) on the process parameter space for µc-Si high rate deposition by further reducing d_{gap} from 11 mm to 8 mm in our medium-size PECVD KAI reactor (KAI-M, VHF = 40.68 MHz). We could thus confirm the trends already observed in 2011: the narrower the gap the higher the pressure achievable (in powder free conditions), leading to improved bulk material quality of the deposited intrinsic µc-Si films and enhanced solar cell performances at higher deposition rates R_d. A notable conversion efficiency of 9.3% in µc-Si:H single-junction solar cell with 1 µm of i-layer deposited at 15 Å/s could be achieved.

Work carried out and results achieved

➢ High rate deposition of µc-Si

When further reducing d_{gap} to 8 mm we remarkably observed that both the material quality and the cell performances were only weakly sensitive to process pressure in a much wider pressure range as compared to what was observed at d_{gap} = 11 mm. Even if improved material quality is obtained at a fixed high R_d thanks to the new reactor configuration, the compactness of high R_d films cannot be improved by simple process parameter tuning. It rather depends on the interplay between the film growth dynamics and the substrate morphology and inappropriate roughness typically leads to observations of ambient (dark) degradation of the electrical device properties.

In the 2011 report, we showed that the maximum R_d achievable in our KAI-M system with d_{gap} = 11 mm was 12 Å/s, the main limitation to an efficient gas utilization being the formation of powder. In 2012 we implemented an ultra-narrow gap configuration, with d_{gap} = 8 mm, demonstrating R_d larger than 15 Å/s. In Table I we compare deposition processes at d_{gap} = 8 mm with processes developed at d_{gap} = 11 mm. On line 1 we show that working with the same pressure, *p*, and feed-in power density, P_d, we can reduce to 80% the quantity of silane gas required to deposit at R_d ~ 1 nm/s when going from 11 mm to 8 mm. On line 2 we show that ultra-narrow d_{gap} allowed increasing maximum R_d by 25% using 17% less silane gas. In this case, the process pressure was higher than for the reference process at d_{gap} = 11 mm. Thus ultra-narrow gap configuration allowed us to deposit at high pressure in powder free conditions, improving silane gas utilization efficiently.

d_{gap} (mm)	*p* (mbar)	Si	P_d	R_d (nm/s)
8/11	5.5/5.5	0.8	1	1.0/0.9
8/11	8.0/5.5	0.83	1.2	1.5/1.2

***Table I**: Comparison of high rate deposition processes in narrow (11mm) and ultra-narrow (8mm) d_{gap} configuration. The latter allows to efficiently use the silane gas and to achieve very high R_d*

We investigated the deposition parameter space with a feed-in power density of P_d,max = 0.33 W/cm2, corresponding to the maximum power deliverable from standard commercial VHF generators mounted on TEL's (formerly Oerlikon) Thin-Fabs, to find the maximum R_d achievable in this condition. In our KAI-M with d_{gap} = 8 mm, we found that using P_d,max the highest R_d is 1 nm/s independently from process pressure. In Figure 1, we show the J-V curves of single junction µc-Si devices deposited in this framework, at pressures of 5.5/8.0/10.0 mbar. Maximum conversion efficiency η = 9.6% was thus obtained at 8mbar (i.e.an improvement of 0.6% with respect to the 11 mm gap best cell). The bulk quality of the three i-layers is independent from the process pressure, with a measured FTPS absorption coefficients at 0.8 eV ($\alpha_{0.8\,eV}$) being equal to $3.7 \cdot 10^{-3}$ cm^{-1} for the three samples.

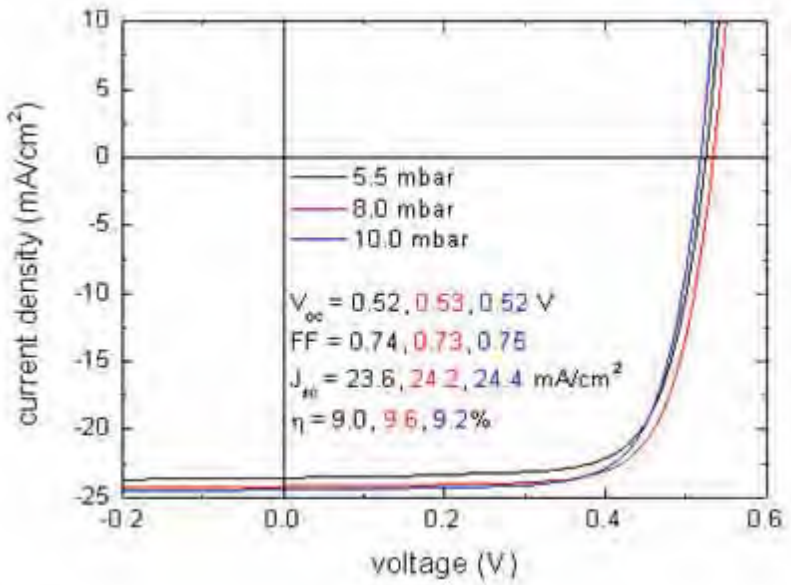


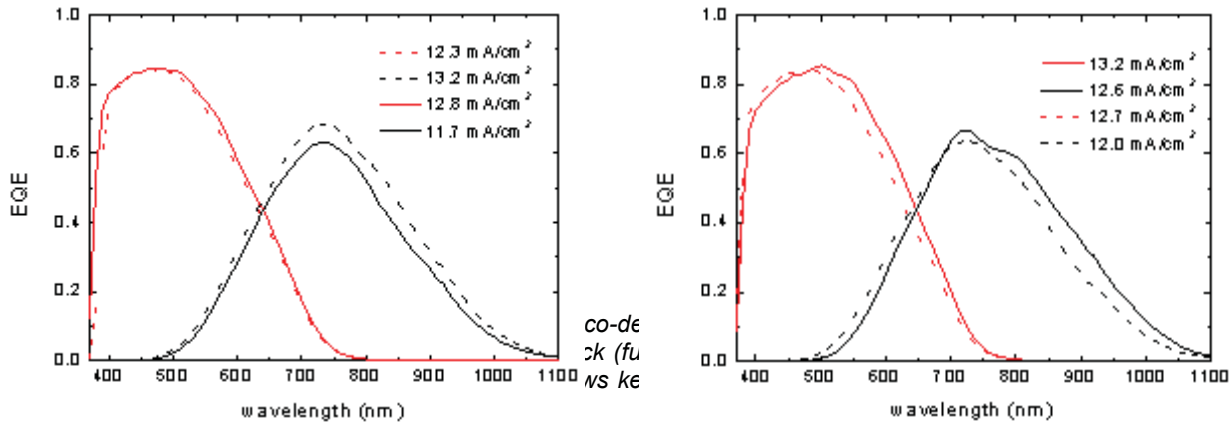
***Figure 1**: J-V curves of devices deposited at R_d = 1nm/s, with P_d. = 0.33 W·cm^{-2} and p = 5.5/8.0/10.0 mbar. A maximum efficiency of 9.6% is obtained at 8mbar even if the FTPS quality of the absorber layers is the same, independently from p (see text)*

Without this constraint on the feed-in power density we achieved conversion efficiency as high as η = 9.3% at a very high deposition rate of R_d = 15 Å/s, with V_{oc} = 525 mV, FF = 74%, J_{sc} = 24 mA·cm^{-2}. Exploring the deposition parameter space in the new ultra-narrow gap configuration (d_{gap} = 8 mm) we confirmed the trends reported last year when comparing the wide (d_{gap} = 25 mm) and narrow (d_{gap} = 11 mm) inter-electrode gap configurations: a) for all d_{gap} the product V_{oc} ·FF decreases with R_d while α0.8 eV increases, indicating that the deterioration of the bulk material quality related to high rate deposition s the main responsible for electrical performance losses. *In ultra-narrow gap configuration it is possible to keep a superior bulk quality at very high R_d*; b) at fixed R_d electrical performances are enhanced in narrow gap configuration, supposedly due to reduced ion bombardment of the growing surface thanks to high pressure processing. *In ultra-narrow gap configuration, the very low ionbombardment at low R_d could be responsible of reduced performances compared to what is obtained in narrow gap configuration*; c) with ultra-narrow gap R_d = 15 Å/s is achieved, due to the reduction of powder formation and the enhancement of the silane gas utilization efficiency.

Regarding developments of micromorph devices, we focused on a s imple and industrial-compatible device design. The major requirements are using ~2 µm thick front and back ZnO LPCVD electrodes, ~1 µm thick µc-Si i-layer and no or "simple" intermediate reflect layer (IRL). In order to minimize LID of the final device and to satisfy current matching conditions, we used 200 nm to 250 nm thick a-Si top cells with an n-SiOx layer as n-layer, which thickness was varied from standard (~25 nm) to 80 nm to also serve, in this second case, as IRL. When using a 2.5 µm thick front TCO (B52) which is EPFL standard for high efficiency micromorph cells [1], low electrical performances were obtained with bottom cell deposited at high rate. Losses of ~50 mV in V_{oc} and 3 to 5% in FF compared to devices with the bottom cell deposited at 3 Å/s were observed for devices in the same current matching conditions. This is likely related to the interplay between the film growth dynamic and the substrate morphology: we assume that when depositing at high rate, the film precursors are buried and incorporated in the film before having time to diffuse to an energetically favorable site, resulting in low bulk quality films while, at the same time, substrate features can act as a physical barrier to the diffusion of precursors leading to the development of 3-dimensional cracks.

In Figure 3.a, we show the external quantum efficiency (EQE) of two micromorph devices fully codeposited on a 2.5 µm (B52, dashed lines) and a 1.5 µm (Z1, full lines) thick front TCOs. The top cell is 200 nm thick and has a standard n-SiOx layer, the bottom cell is 1.3µm thick and the back TCO is a B52. The initial cell parameters are V_{oc} = 1.364 mV, FF = 70%, J_{sc} = 12.3 mA·cm^{-2} (top limited), η = 11.7% for the cell on B52 and V_{oc} = 1.373 mV, FF = 77%, J_{sc} = 11.7 mA·cm^{-2} (bottom limited), η = 12.4% for the cell on Z1. This device comparison shows that *i)* the lowly-doped B52 substrate permits to have high current in the bottom cell while keeping thin µc Si i-layers, which results in improved electrical performances, but an IRL is required to increase the current in the top cell; *ii)* the more strongly doped Z1 substrate, with smaller pyramids, scatters light efficiently in the top cell but also requires thicker µc-Si i-layers to satisfy the current matching condition. Still its morphology permits to keep higher electrical performances even with thicker devices.

At present, we develop in parallel micromorph devices on these two substrates according to guidelines *i)* and *ii)* in order to meet the deliverables of the project. The Z1 substrate has the potential to permit us to achieve this goal with high R_d cells, even if it is not considered as an optimal substrate for the development of micromorph devices with the bottom cell deposited at low R_d. In Figure 2.b we show the EQE of a thin and a thick micromorph cells deposited on Z1, with 200-250 nm thick top cell (dashed-full line) with 80nm n-SiOx layer acting as IRL, 1.3-1.8 µm thick bottom cell (dashed-full line) at R_d = 1.2 nm/s and B52 back TCO. Both devices are bottom limited and the cell parameters are V_{oc} = 1.371 mV, FF = 76%, J_{sc} = 12 mA·cm^{-2}, η = 12.45% for the thin one and V_{oc} = 1.370 mV, FF = 74%, J_{sc} = 12.6 mA·cm^{-2}, η = 12.73% for the thick one. The thickness of the high rate bottom cell can thus be increased on Z1 substrate without dramatic electrical losses.



In Ref [2] we have shown that the electrical performances of µc-Si devices deposited at high rate on sharp substrate are very sensitive to water vapor absorption from the surrounding atmosphere, while this is not the case for devices co-deposited on smooth substrates. Degradation is hence assumed to be linked to porous material zones in the material, with high deposition rate µc-Si being more prone to defective zone creation. We further studied this issue while working in ultra-narrow gap configuration and the obtained results confirm this picture; in particular, the electrical performances of devices deposited on sharp substrates decrease linearly with R_d. On Z1 substrates and with R_d = 1.5 nm/s we measured a reduction of the V_{oc} and FF to up to 93% and 60% of the initial values respectively, while electrical performances of devices deposited on smooth substrates is stable upon damp-heat independently from R_d.

Furthermore, when non-encapsulated devices deposited at high rate undergo standard light induced degradation (LID) experiments, a contribution to the total degradation of the micromorph device could come from the dark degradation of the non-compact µc-Si material. Indeed, on co-deposited top cells we deposited two bottom devices at 10 and 15 Å/s and they degraded upon LID by 15% and 24% respectively, while a similar relative degradation value was expected. Thus, we are now interested in understanding to which extent ambient air degradation participate to LID degradation for high deposition rate µc-Si material.

➢ TCO developments

In the first year of the PEPPER project, the transparency/conductivity trade off has been addressed which allowed to improve the transparency for a given sheet resistance by using a bilayer stack with a heavily doped nucleation layer. During the second year the possibility to decrease the crack density in the µc-Si:H cell based on improved ZnO growth process is investigated. In order to fulfill M2.1 (Layers with nano-morphology allowing reduced crack density by a factor 2 as compared to the current process at OS), two separate routes have been envisaged: First the use of ZnO deposited with ethanol precursor as cap layer on the surface of standard (deposited with H_2O) a ZnO film is investigated. In fact it has been found that the addition of ethanol to the traditional gas mixture strongly affects the structure and surface morphology of the ZnO films. This is shown in Figure 3 where an ethanol based cap layer was deposited on a standard ZnO film (the total thickness was kept constant at 2 µm). Figure 3 further shows that, as the thickness of the cap layer deposited with ethanol precursor increases, the surface morphology evolves from the traditional pyramids towards rounded features. However as the thickness is further increased (~200 nm), cracks appear in the film which are detrimental for the electrical properties of the electrode. Regarding the sheet resistance of uncracked film, it was measured to be similar to the one of standard 2 µm thick ZnO.

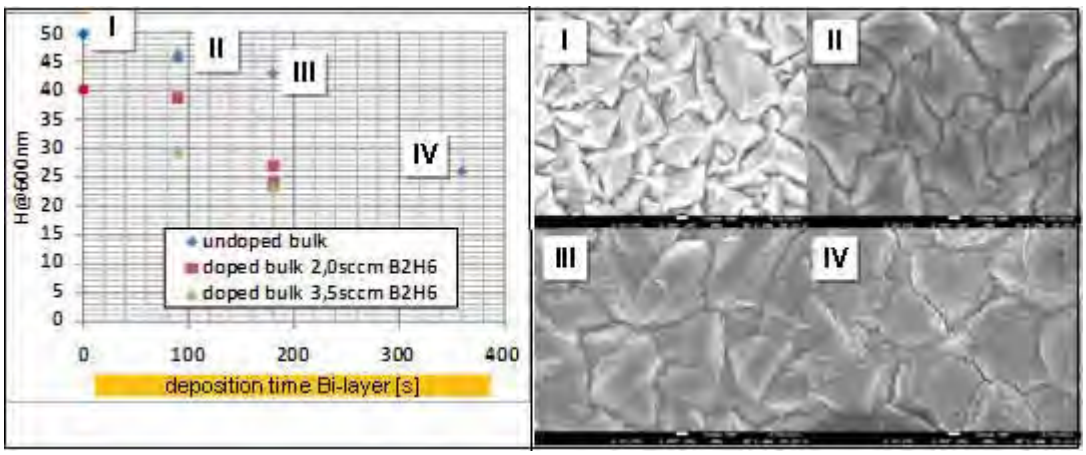


***Figure 3**: Haze variation as a function of the cap layer thickness (left). Modification of the surface morphology (right)*

The positive effect of ZnO surface morphology modification on µc-Si:H defective zones density is demonstrated in Figure 4. Scanning Electron Microscopy (SEM) images of film cross sections clearly show that the defect density (dark regions) is reduced from 0.8 cracks per micron for standard ZnO to 0.3 cracks/micron for the ZnO film capped with an ethanol based layer below 200 nm thick.

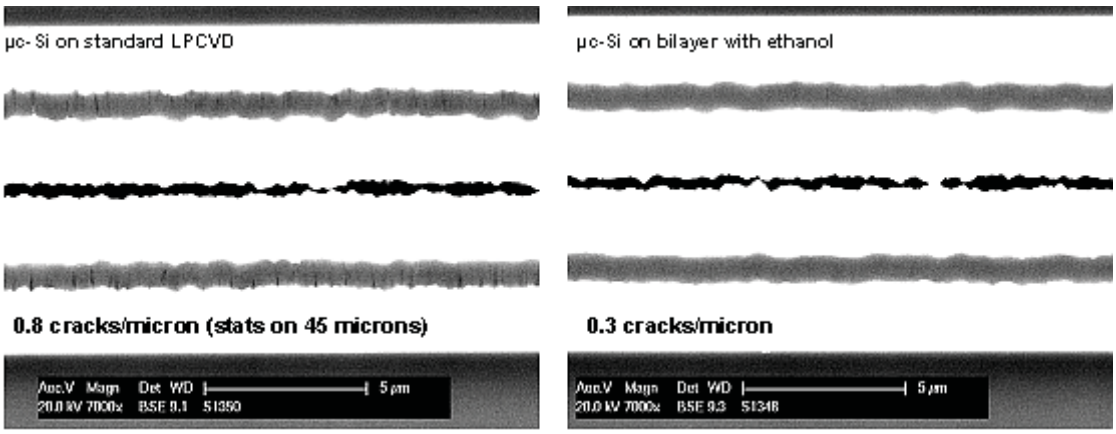


***Figure 4**: µc-Si defect density decrease when using a bilayer with an ethanol based cap compared to a standard deposited ZnO (similar to Oerlikon Solar TCO)*

Therefore the use of an ethanol based cap on top of standard ZnO is an efficient way to decrease the crack density by a larger factor than the one set in M2.1.

However, it was observed that cell deposited on the ethanol based bilayers exhibited a large open circuit resistance which led to a dramatic decrease of their Fill Factor and thus to a decrease of solar cell efficiency. The reason of such an effect is not clarified yet as the ethanol based TCO films before cell deposition exhibited a sheet resistance similar to the standard ZnO electrodes.

Two reasons could explain such a discrepancy:

1°) the sheet resistance of the bare TCO film measured with the four point probe setup does not probe the resistance of the cap layer deposited with the ethanol precursor which could be more resistive than the bulk film beneath it. Indeed the pins of the setup are applied with a given strength on the surface of the film which could lead to a penetration of the pins through the cap layer, preventing to assess the effect of the very surface layer with this technique.

2°) it is well known that the H_2 plasma used in the deposition of thin film silicon solar cell can reduce the TCO surface altering the electrical contact between the electrode and the active part of the device. This is notably the case for SnO2 which is then traditionally covered with a thin ZnO film to prevent this effect. Even though ZnO is more resilient to this plasma effect, it could still be that the use of an ethanol based cap layer leads to a ZnO surface being more sensitive to plasma attack leading to reduced interface quality.

Nevertheless, based on the good results regarding defect density reduction obtained with this technique, it has been decided to continue working on this approach by varying the thickness and ethanol concentration used in the cap layer in order to achieve sufficiently low cell open circuit resistance.

Another mean to decrease µc-Si:H porous zones density is to alter the surface of the ZnO film by varying the growth process parameters such as the growth temperature or precursor flows [3]. Indeed, it has already been shown that decreasing the growth temperature led to smooth ZnO surface morphology. However, decreasing the process temperature also leads to a steep increase of the film resistance (typically, using 160°C instead of 170 °C leads to surface roughness below 20 nm but to a sheet resistance above 100 Ω/□). Another solution is to change the diethyl zinc (DEZ), water (H_2O) ratios. It has been found that by increasing the DEZ content while keeping the water flow and temperature constant, the density of pyramidal features could be decreased to a point of achieving very smooth surface (with RMS below 15 nm) while keeping a sheet resistance below 15 Ω/□. This is shown in Figure 5:

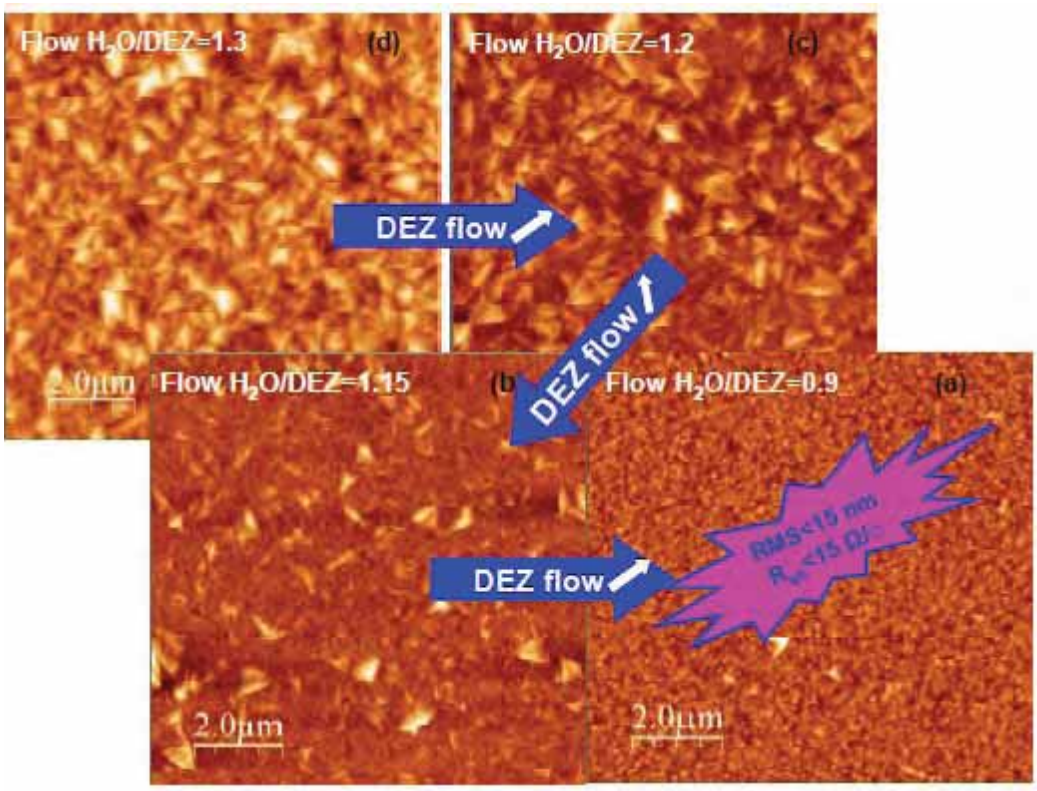


***Figure** 5: AFM images showing surface morphology changes as a function of increasing water/DEZ ratio*

As can be expected, the variation of surface morphology is associated with a variation in the haze factor. **Therefore an optimization in terms of light trapping and high cell V_{oc} and FF has to be found by using smoother ZnO films. Such optimization is currently undertaken and will also be the subject of future project development**.

National and international cooperation

In the frame of this project, PVLAB is directly collaborating with TEL Solar for TCO developments and the University of Patras for plasma modeling.

Evaluation 2012 and Outlook 2013

➢ High rate deposition of µc-Si

The project deliverable for 2012 was successfully achieved on schedule, with the exploration of the parameter space for the PECVD of µc-Si at high rate in the EPFL medium area KAI-M system, in ultranarrow gap configuration. Reducing d_{gap} to 8 mm we demonstrated that deposition rates over 15 Å/s, can be achieved in nearly powder free process conditions at high pressure. We achieved state-of-theart single junction µc-Si solar cell efficiencies up to 9.6% and 9.3% with 1µm thick i-layers deposited at 10 Å/s and 15 Å/s respectively, and initial micromorph efficiency over 12.7% with 1.8 µm thick bottom i-layer deposited at 12 Å/s. However, micromorph devices comprising bottom cells deposited at very high rate severely degraded upon LID, preventing the achievement of the milestone due, i.e. 11% stable efficiency at 1.2 nm/s. We are now investigating to which extent the ambient air (dark) degradation of non-encapsulated devices probably contribute to the larger light induced degradation observed with high rate µc-Si (especially for 15 Å/s). With further insights into the exact mechanisms we hope to reach the milestone soon.

➢ TCO developments

After demonstrating the possibility to improve the transparency/conductivity trade-off in the first year (fulfilling M2.2) leading to decreased TCO film thickness at constant device efficiency, the following work showed that two promising routes can be envisaged in order to reduce the porous zones (cracks) density appearing in µc-Si:H on rough front electrode. One of them is to use ethanol as an additional precursor while growing the last hundred nanometers of the ZnO film. This leads to a smoother morphology allowing a reduction in the crack density by a factor 3. The second route is to change the precursor ratio which can lead to smoother ZnO surface while keeping good electrical properties. In the following months, process optimization will take place to show that these approaches can indeed lead to higher cell efficiency. In addition, these different approaches will also be tested by TEL Solar in order to assess their up-scalability to large module size.

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FLEXIBLE PRODUCTION TECHNOLOGIES AND EQUIPMENT BASED ON ATMOSPHERIC PRESSURE PLASMA PROCESSING FOR 3D NANO STRUCTURED SURFACES (N2P)

Annual Report 2012

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Project- / Contract Number	N2P / 214134-2
Duration of the Project (from – to)	01.06.2008 – 30.11.2012
Date	12/2012

ABSTRACT

Although important progresses have been made in the development of novel structures for 3D nanosurfaces applications, their use at large scale is still partly limited by lack of high throughput suitable manufacturing technologies.The overall objective of this project "N2P" (Nano to Production) is to develop and substantially enhance the position of Europe in the science, application and production technologies of surface 3D nano-structuring. In this project, the consortium develops innovative in-line high throughput manufacturing technologies based on atmospheric pressure vapour phase surface and plasma processing technologies. Both approaches have significant potential for 3D nano-structuring, but their effective simultaneous combination is particularly promising. It is proposed to merge the unique potential of atmospheric pressure based plasma-chemical etching with vapour phase based nucleation and growth.

The role of the PV-lab is to guide the development of SnO2 TCO layers for thin film silicon photovoltaic activities by working in close collaboration with the University of Salford (USAL) and CVD Technologies Limited, both specialists in atmospheric CVD. Regarding photovoltaic applications, the goal is to optimize the TCO film in order to achieve energy conversion efficiencies higher (>7% relative) than the ones obtained with in-line produced industrially available TCO.

After 54 months the milestones have been achieved as the TCO produced by USAL and CVDTech led to a relative gain efficiency of 13% compared to the industry standard, well above what was expected in the beginning of the project and to a gain of 5% compared to the offline product.

Project Goal

The overall objective of this project “N2P” (Nano to Production) is to develop and substantially enhance the position of Europe in the science, application and production technologies of surface 3D nano-structuring.

Regarding the thin film silicon development, the main goal of the project is to develop the atmospheric CVD (ACVD) process for in-line TCO (SnO_2:F) on glass production in order to achieve a relative increase of 7% solar cell efficiency compared to industrially available in-line products on both single junction and micromorph devices.

Since the beginning of the project it has been shown that a relative efficiency increase of 18 % could be achieved by using the TCO developed by University of Salford (USAL) compared to the standard in-line industrial available TCO. Based on these promising results it was decided to further develop the TCO in order to achieve higher efficiency compared to cells deposited on off-line high quality/high price product thanks to the improvement of the USAL in-line process. In addition the atmospheric plasma etching surface process also has to be further developed in order to avoid particle re-deposition that was observed in the previous years. Eventually, we also started depositing tandem a-Si/µc-Si cells on the new TCOs in order to evaluate their suitability as front contacts for cells including µc-Si:H material which is well known to be sensitive to too rough TCO surface morphologies.

Description of the project

The project takes place in the framework of the FP7 theme 4: Nanosciences, Nanotechnologies, Materials and new Production Technologies. Compatible with the call, the research focus is on the application of basic research results for the development of new manufacturing processes and equipment for new science based products in order to create potentially disruptive products and production systems. The project relies on strong collaborations between teams in charge of depositing the TCO films (Universit of Salford (USAL), UK), equipment development (CVD Tech (UK), Manchester University (UK)), evaluation (EPFL) and demonstration (Nuon Helianthos (NL)).

Work and results after 54 months

In the last part of the project, different water to tin precursor ratio were investigated as it is known that it is an efficient precursor that can be used to finely tune the film surface while keeping good electrical and optical properties.

Sample 240 is the standard USAL sample while specimen 237 is grown with a high water/Sn ratio, then samples 238 and 239 were deposited in order to investigate the effect of sending the precursors sequentially on the growing surface ate different ratios. Eventually, samples 241 and 242 were used to assess the effect of a TiO2 layer as an index matching layer between the glass and the TCO and between the TCO and the Si device (note that contrary to the description, 241 has TiO2 at the bottom of the film and vice versa for 242).

The optical characterization of the different films is shown in Figure 1.

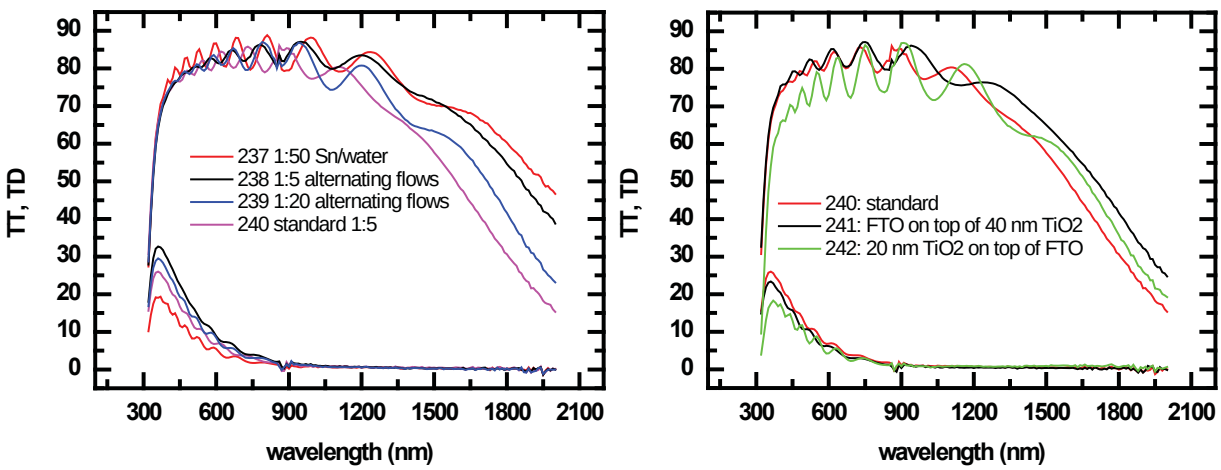

***Figure 1**: Total and diffuse transmittances of the different films*

From figure 1, it can be seen that, as expected using higher water/Sn ratio leads to a modification of the surface morphology (a smoothening in this case)leading to a decrease in the diffuse transmittance of samples 237 and 239 compared to 240 and 238, respectively. The total transmittance follows the trend of the measured free carrier concentration with the highest absorbing film being samples 240 which also shows the highest free carrier concentration. It is indeed well known that one of the main intrinsic TCO source of doping is the Oxygen atom vacancies which can be controlled by the water/Sn ratio. Regarding the use of a TiO2 layer, it is seen that putting a TiO2 film on top of FTO leads to a decrease of the haze, probably due to a smoothening of the surface. The results on the cells are shown below in figure 2 under the form of box plots which allows for a better statistical comparison between the 16 cells present on each wafer.

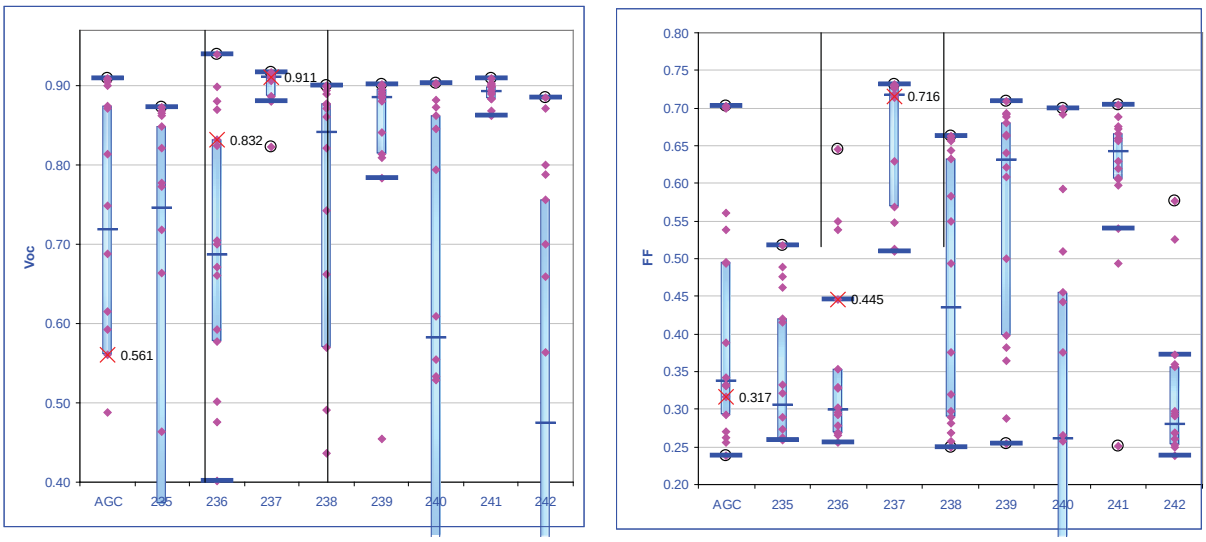

***Figure 2**: Box plots of solar cells deposited with different precursor ratio and with TiO2 interlayers*

From these graphs, it is seen that the best electrical properties are achieved with samples 237 (high water content) especially when considering the spread of the data, an indication of the homogeneity of the film (TCO+Si). This is a further indication of the beneficial surface smoothening when using higher water/Sn ratio. Sample 241 with a TiO2 nucleation layer also shows good electrical properties (below the ones of 237), however this is not well explained for the moment. **In any cases, these results show that sample 237 is better than the off-line industrial TCO AGC U and better than the USAL TCO used so fareas state-of-the-art for the project.**

Below is a summary table of the best cells measured on each substrate measured while using the photocurrent provided by the EQE.

sample	JEQE	Eff EQE	surf cm²	Isc mA/cm²	Voc (V)	FF	Rsc Ohm.cm²	Roc Ohm.cm²	Imax mA/cm²	Vmax (V)	Eff (%)	0.4 mA/c	0.4 (V)	FF 0.4	Rsc 0.4 Ohm.cm²
237	15.1	**0.101**	0.25	17.311	**0.915**	**0.731**	2491.361	5.480	15.524	0.742	11.513	0.045	0.340	0.000	13912.064
235	14.4	0.0651188	0.25	15.49	0.873	0.518	372.273	14.311	11.463	0.609	6.981	0.070	0.045	0.000	616.774
236	15.12	0.0876741	0.25	17.963	0.899	0.645	958.699	5.716	14.749	0.706	10.420	0.044	0.060	0.000	1326.306
238	15.87	0.094125	0.25	18.105	0.900	0.659	661.455	5.856	15.111	0.711	10.744	0.044	0.042	0.000	932.405
239	15.76	0.1006763	0.25	18.321	0.901	0.709	1943.738	4.613	16.039	0.729	11.692	0.046	0.230	0.000	6696.234
240	15.03	0.0951098	0.25	14.242	0.904	0.700	3979.410	8.222	12.627	0.711	8.978	0.067	0.632	0.458	32693.170
241	15.43	0.0988508	0.25	17.359	0.910	0.704	1817.118	5.800	15.271	0.728	11.117	0.044	0.229	0.000	7158.951
242	13.37	0.0682732	0.25	14.397	0.885	0.577	548.855	6.597	10.717	0.690	7.392	0.037	0.031	0.000	758.150
AGC	14.8	**0.0945**	0.25	18.475	**0.908**	**0.703**	921.458	4.388	15.832	0.746	11.814	0.049	0.074	0.000	1526.687

***Table 1**: Best cell results on the different substrates*

It is seen that as expected from the higher Voc and FF achieved on sample 237, and despite a low current due to a smoother surface, **the best efficiency is recorded on the sample with the highest water content. Indeed, it leads to an increase of 0.5% absolute efficiency (5% relative increase) when compared to the best results achieved on the AGC U substrate.** Similar results is achieved for the process using sequential usage of precursor with a high flow content, sample 239, which also combine good Voc and FF but with a higher current than in 237. Regarding the use of TiO2, its introduction as a nucleation layer results both in good current and high cell Voc and FF parameters (still below 237) which combined together provide a 0.4% absolute increase compared to the best result on AGC U.

As a conclusion from these investigations, it is clearly established that the use of a water rich process is beneficial for the TCO as it allows achieving higher Voc and FF for the cells while still keeping sufficiently high photo-generated current.

End of project deliverable, demonstrator

D4.1: **"***Thin film solar cell with efficiency increase of at least 10% compared to standard nano-textured AFG (SnO_2 coated) reference glass. Relative increase in haze of TCO in VIS+NIR region ≥50% and relative decrease in absorption in wavelength range 400-1000 nm ≥25%, on 10 cm x 10 cm area."*

Based on the results achieved in WP3 and at the beginning of WP4, it has been decided to use 10 cmx10cm TCO films deposited at USAL with high water/Sn content (270: 5/1 and 271: 20/1) and to weight them against industrial online product TEC (AFG) TCO and industrial high end offline standard AGC U TCO. In this case, the 10x10 cm^2 cell deposition was laser scribbed in 20 smaller 1x1 cm^2 independent cells as shown below:

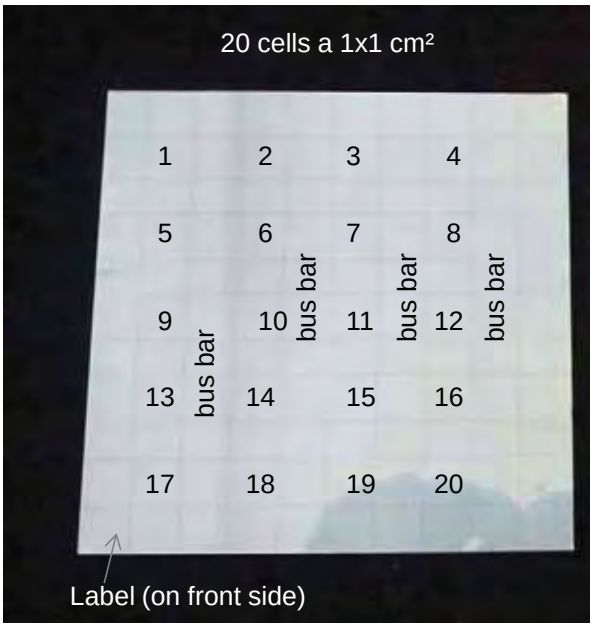

***Figure 3**: representation of the two processes: left: 20 individual cells; right: fully interconnected minimodule*

The electrical properties of tandem cells are shown below:

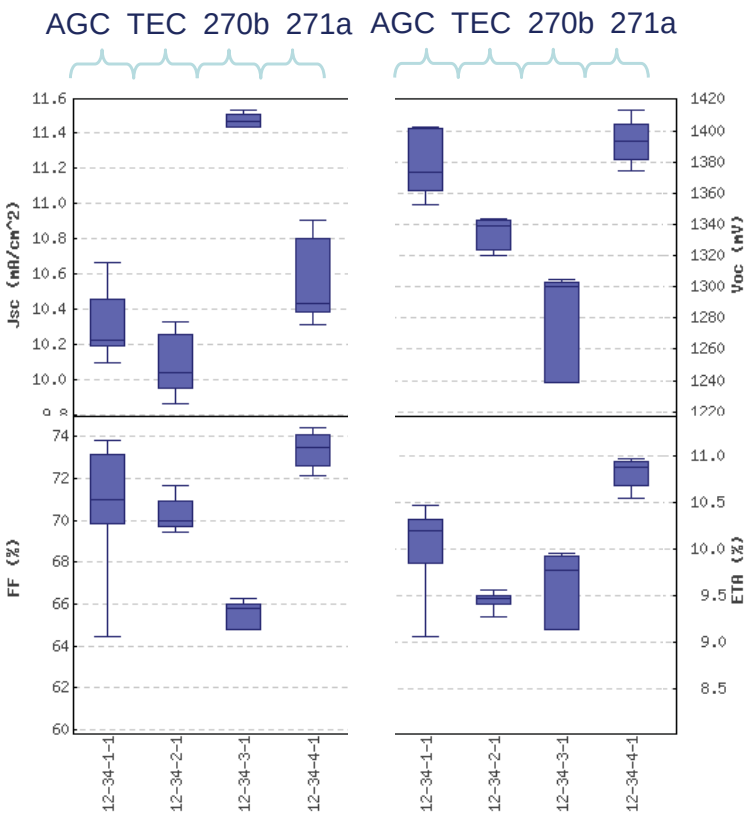

***Figure 4**: Box plots of 20 solar cells on the different 10x10 cm2 substrates*

It is seen that similarly to the results achieved on lab scale substrates, the sample with the highest water content provides the best Voc and FF characteristics while it also generates a lower current compared to sample 270. **Despite this, and as expected from previous results, sample 271 provides the best efficiency (mean on 20 cells) around 10.75% with a lower spread indicating the good homogeneity of the substrate surface.** The industrial online standard, TEC, (to which the USAL TCO should be compared) shows efficiency close to 9.5, while the high end offline industrial sample AGC U has a mean efficiency around 10.2%.

These correspond to a relative gain of 13% compared to the industry standard, well above what was expected in the beginning of the project and to a gain of 5% compared to the offline product.

International Collaboration

As stated above, the N2P project relies on strong cross cutting activities between equipment development, process optimization, device evaluation and final transfer towards a demonstrator. General assembly meetings bringing together all the partners involved in the project are organized every 6 months. In addition, for the thin film PV cells, a strong collaboration between EPFL and USAL/CVD Tech (UK) is ongoing in the form of regular intermediate technical meetings to ensure an optimum follow up of the progress. Eventually, the PV-lab also works in close collaboration with the Fraunhofer IWS in Dresden, coordinator of the project, for the development of plasma etching technique on LPCVD ZnO.

Final Evaluation

The N2P project allowed demonstrating that the APCVD TCO produced by CVDtech/USAL can compete with the high quality industrial standard of Asahi Glass Company. Based on these results an industrial exploitation plan has been setup by the main industrial partners of the project. Eventually, given the good results achieved by the consortium a new European project, PLIANT, gathering the major partners of N2P, including EPFL and CSEM, has been submitted and accepted by the EC. This new project is now in the final negotiation phase and is expected to start in the beginning of 2013.

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SILICON-LIGHT

IMPROVED MATERIAL QUALITY AND LIGHT TRAPPING IN THIN FILM SILICON SOLAR CELLS

Annual Report 2012

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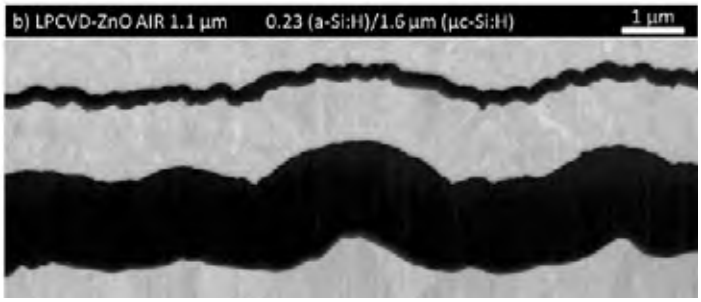
Project- / Contract Number	SILICON-Light / 241277
Duration of the Project (from – to)	01.01.2010 – 31.12.2012
Date	17.12.2012

ABSTRACT

The project SILICON-Light is devoted to the investigation of n-i-p solar cells on flexible substrates with focus on material quality, interface properties, and light management. During the third and final year, EPFL concentrated on high efficiency tandem solar cells incorporating a ZnO back electrode and a microcrystalline bottom cell, a ZnO intermediate reflector, and a thin top cell followed by a ZnO front electrode. Using this device configuration, stable efficiencies of 11.6% have been achieved, using silicon films with a total thickness below 2 µm.



The project finishes successfully in December 2012; it brought together the competences of solar cell modelling, large area imprinting, the fabrication of novel sputtering targets and device processing.

EU FP7 Project Silicon-Light

The EU project SILICON-Light started in January 2010. Its main aspects are flexible thin film silicon solar cells in n-i-p configuration. The consortium consists of:

- ECN (National Energy Research Laboratory of Holland, large area silicon deposition, coordination
- EPFL PV-Lab (high efficiency devices)
- University of Ljubljana (optical modelling)
- Technical University of Denmark (TEM analysis)
- Polytechnic University of Valencia (Mastering of nano-structures)
- Shanghai Jiatong University (Mastering of nano-structures)
- Umicore AG (Liechtenstein, manufacturer of sputtering targets)
- nanotpics GmbH (Germany, roll-to-roll processing of textured plastic substrates)
- VHF technologies S.A. - Flexcell (integration into modules)

Work performed in the reporting period 2012

Development of back reflectors for absorption enhancement in the near infrared

In n-i-p solar cells, the rear reflector has to fulfil several roles; it must transport the current, it must efficiently scatter near IR light for enhancement of the photocurrent in the bottom cell, and its texture should be compatible with the growth of microcrystalline material of high quality. Figure 1 shows the different types of back reflectors used in this study. Type 1 consists of silver deposited at elevated temperature, resulting in a relatively flat texture that is appropriate for microcrystalline material with high quality, but in the near IR its absorption enhancement is only moderate. The other reflector types incorporate a 5 µm thick ZnO film grown by LP-CVD whose pyramidal texture is adequate for scattering of IR light. Since the sharp angles of this surface texture can compromise the material quality of microcrystalline cells, the ZnO film is subjected to a plasma treatment of 45 minutes and thus referred to as Z5-45.

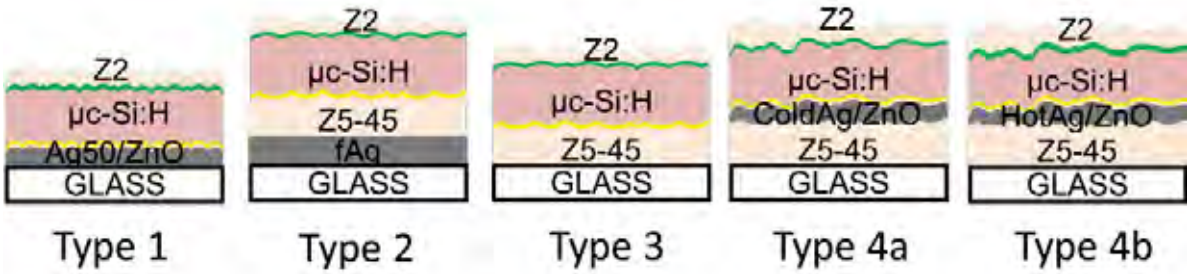


***Figure 1**: Microcrystalline cell designs used for screening of back reflectors*

The open circuit voltage (Voc) of is a first and simple way to assess the amount of recombination taking place in a solar cell. The lower right panel of figure 2 shows this quantity for microcrystalline cells grown on the various reflectors. A more sensitive method which is useful to project also their performance as bottom cell in tandem devices is to resolve the Voc versus the illumination intensity which yields the diode quality factor. Of all the reflectors with the textured ZnO, figure 2 demonstrates that the type 4b yields the highest Voc and the lowest diode quality factors which mean that it performs closest to the cell on the type 1 reflector which, however, is almost flat and therefore not very adequate for absorption enhancement.

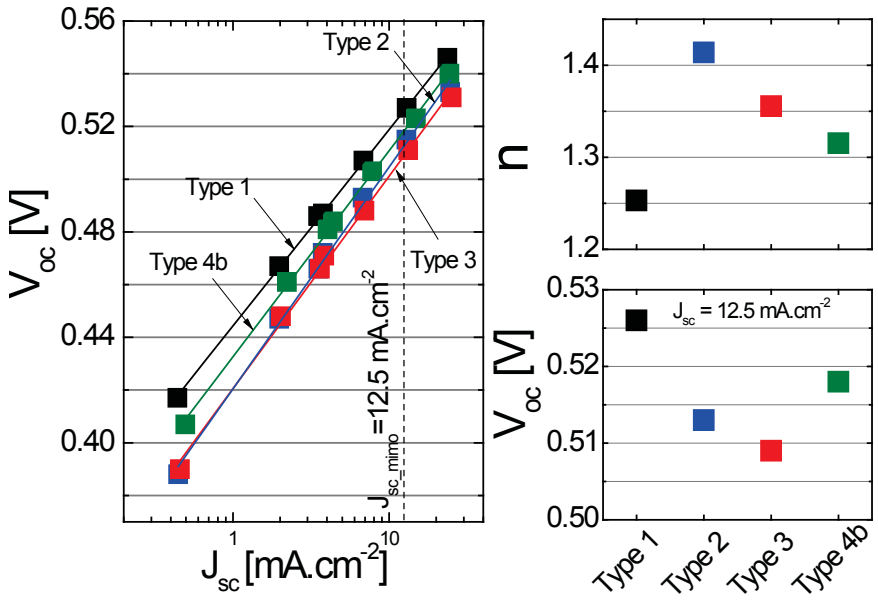


***Figure 2**: Illumination dependence of the open circuit voltage on illumination intensity (left). The right panels give the diode quality factor and the open circuit voltage under one sun.*

Intermediate reflectors

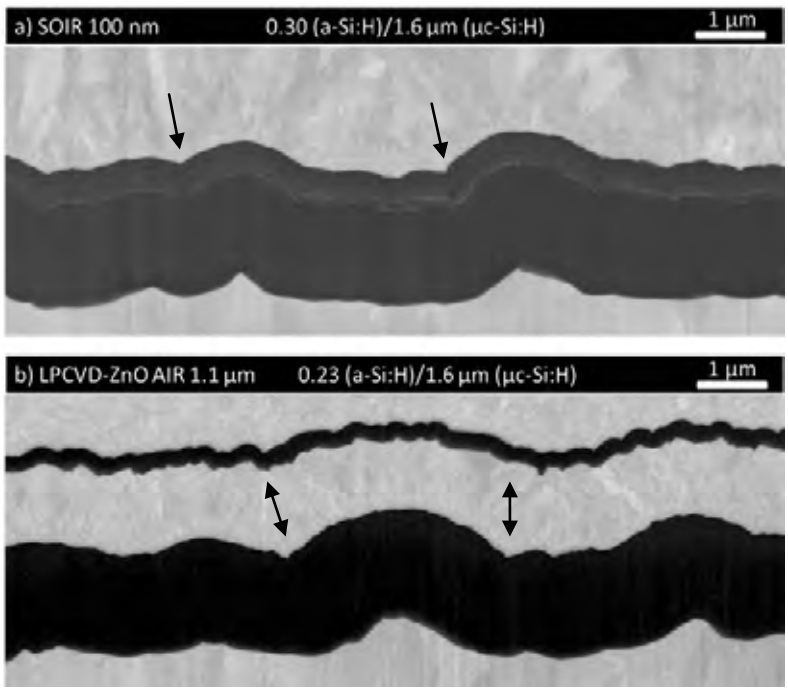


***Figure 3**: Cross sections through two tandem cells with intermediate reflectors consisiting of silicon oxide (upper panel) and of textured ZnO (lower panel).*

The material for the intermediate reflector should be transparent and conductive. In n-i-p solar tandem cells, it should provide the additional functionality of providing light scattering for the top cell. Figure 3 shows two different intermediate reflectors and their influence on the achievable top cell morphology. The arrows indicate that the thin SiOx film transports the pinched area of the bottom cell into the top cell while the thick ZnO reflector smooths out the pinch.

Tandem solar cells

Putting together the back reflector that yields bottom cells with good IR response and good electrical parameters, an intermediate reflector that yields an adequate morphology for the top cell, and a top cell with good current matching, devices with initial efficiencies up to 13.2% have been achieved. After illumination for 1000 h, the best stable device shows a Voc of 1.42 V, a FF of 68.4% and an efficiency of 11.6%. The EQE of this cell is shown in figure 4.

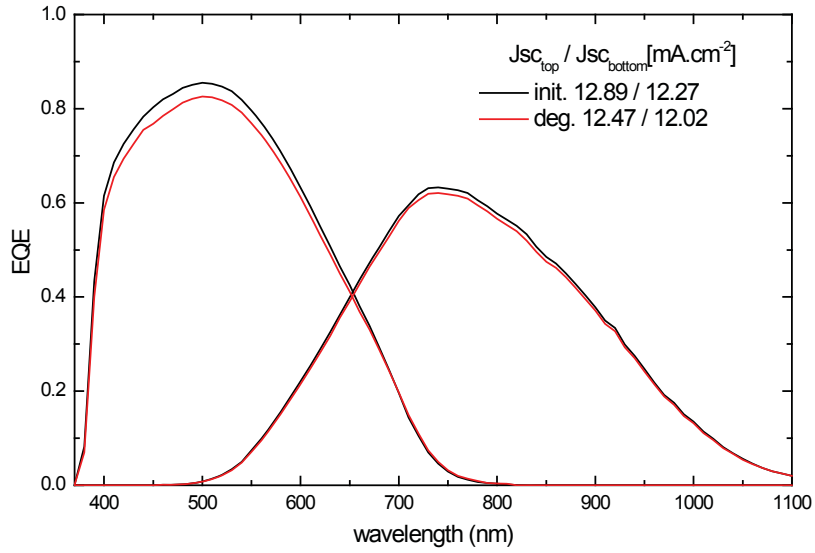


***Figure 4**: External quantum efficiency of a micromorph tandem cell with stable efficiency of 11.6%.*

Collaboration

The progress achieved in this project was also beneficial for other activities running at the PV-Lab. For example, the know-how of top cell fabrication and integration into tandem cells is equally applicable to triple junction cells. For more information, see ref. [3].

Publications in Journals

[1] R. Biron et al. “Optimization of the asymmetric intermediate reflector morphology for high stabilized-efficiency thin n-i-p micromorph solar cells”, IEEE Journal of Photovoltaics, available on-line

[2] R. Biron et al. “Origin of the Voc enhancement with a p-doped nc-SiOx:H window layer in n-i-p solar cells”, Journal of Non-Crystalline Solids (2012)

[3] K. Söderström et al. “Thin-film silicon triple-junction solar cell with 12.5% stable efficiency on innovative flat light-scattering substrate”, Journal of Applied Physics 112, p114503 (2012)

Presentations at Conferences

[i] R. Biron et al. “Optimization of the asymmetric intermediate reflector morphology for high stabilized-efficiency thin n-i-p micromorph solar cells”, 38th IEEE PVSC 2012, Austin

[ii] F.-J. Haug et al. “Optics and device performance – a trade-off”, SOLAR topical meeting of the Optical Society, Eindhoven

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FASTTRACK

ACCELERATED DEVELOPMENT AND PROTOTYPING OF NANO-TECHNOLOGY BASED HIGH EFFICIENCY THIN FILM SILICON SOLAR MODULES

Annual Report 2012

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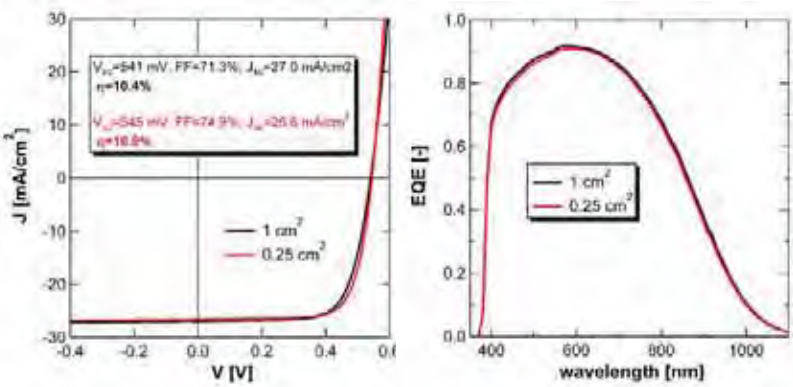
Project- / Contract Number	FastTrack / 283501
Duration of the Project (from – to)	01.03.2012 – 28.02.2015
Date	19.12. 2012

ABSTRACT

Enhanced absorption in microcrystalline cells relies on light scattering at surface textures. The development of novel textures is thus one of the central aspects of this project. At the same time, surface textures disturb the growth of material with high electronic quality. A second work package is therefore devoted to the development of absorber materials and doped layers that are less amenable to this issue. Putting these aspects together, single junction microcrystalline cells with efficiencies on world record level beyond 10% have been demonstrated in the framework of this project.



The project includes several industrial partners whose close integration ensures that the results are also transferrable into the production chain.

Project goals

The project FastTrack is within the theme “Energy” of the 7th Framework programme of the European Union. The main project goals are the development of innovative photovoltaic cell processes and their up-scaling to the level of pilot lines. These goals should be reached in terms of stable device efficiency higher than 14% and a prototype module with stable efficiency higher than 12%.

International collaboration

The project consortium consists of 19 partners; among these are 6 universities, 4 research institutes and 7 companies. The work is organized in 9 work packages devoted to novel material, solar cell processing, processes for high deposition rates, and characterization. The remaining work packages address industrial aspects like up-scaling, module integration, cost analysis, and dissemination.

Work in reporting period

EPFL leads three out of nine work packages which are devoted to novel nano-textured substrates, advanced engineering materials for better absorber films, and high efficiency devices.

Work package 1: novel substrate textures

Light trapping in advanced tandem cells must combine a fine grained texture for scattering of wavelengths around 700 nm for the amorphous top cell and scattering of large wavelengths around 1200 nm for the bottom cell[1]. Figure 1 shows schematically how multi-scale textures are can be constructed. However, this proof of concept relied on an impractically thick ZnO film. In the course of this project, nano-imprinting will be used to replace this film by a transparent lacquer. Since lacquers are generally not conducting, this approach requires high conductivity in the thin film that yields the fine grained texture. Alternatively, a thin conformal ITO film with high conductivity must be inserted in between. Both approaches are investigated.

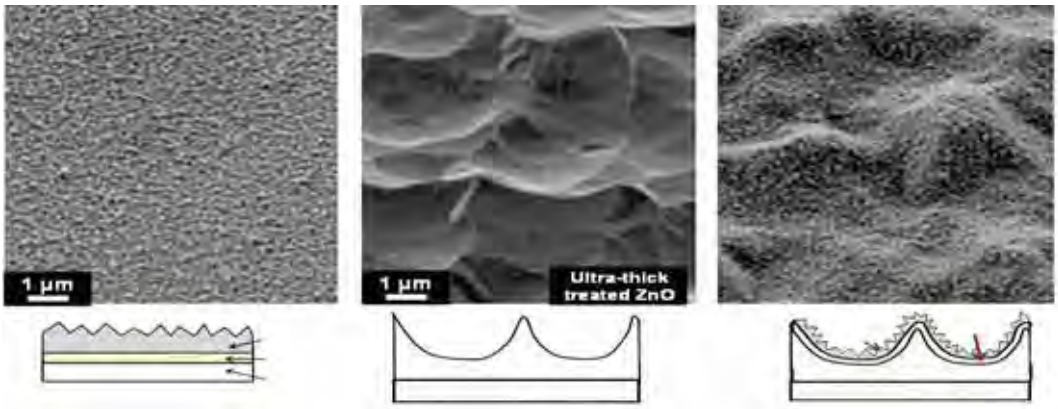


***Figure 1**: Combining fine- and large grained textures (left and middle), a multi-scale texture (right) is formed.*

Work package 2: novel materials

Light scattering at surface textures like the ones shown in figure 1 are needed for enhanced absorption in microcrystalline cells relies on. However, the growth dynamics of PE-CVD can accumulate material of bad quality above V-shaped regions of the substrate. This adverse effect is mitigated to some extent by a plasma treatment that transforms V-shaped valleys into more rounded structures of U-chape (c.f. middle panel of figure 1).

However, the process cannot be driven too far since U-shaped substrates exhibit also reduced light scattering. A way to maintain the favourable light scattering of V-shapes or slightly treated samples is to accept the growth of defective material as given and to incorporate functional layers that limit their impact on the solar cell performance. It was reported that n-doped layers of silicon oxide provide this functionality[2]. Following this approach, single junction microcrystalline cells with open circuit voltage

[1] *M. Boccard et al. Nano Letters 12, p1344 (2012)*

[2] *M. Despeisse et al. Applied Physics Letters 96, p073507 (2010)*

beyond 540 mV and current density above 26 mA/cm^2. Fill factors above 70% underline the excellent electric performance, resulting in efficiencies above 10% as shown in figure 2.

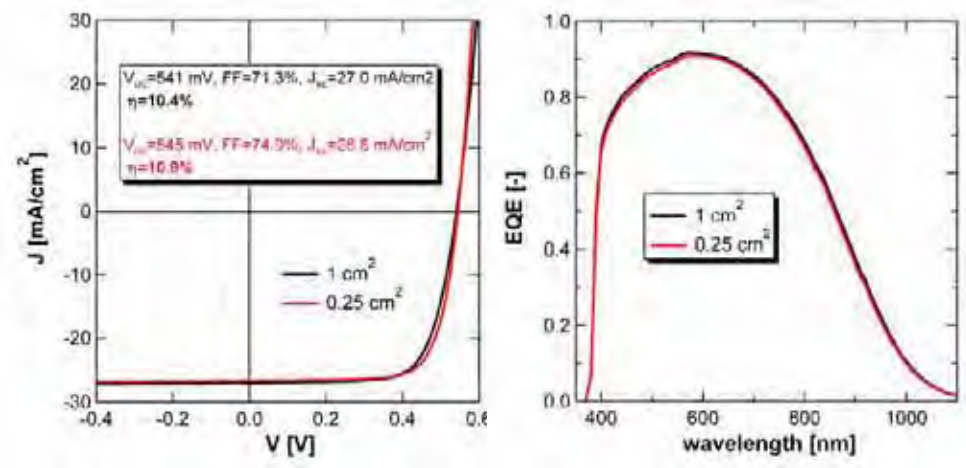


***Figure 2**: Current voltage characteristic (left) and external quantum efficiency of microcrystalline solar cells with efficiency beyond 10%.*

Work package 3: high efficiency devices

In high efficiency tandem cells it is mandatory to achieve high current density in the top cell while the effect of light induced degradation dictates to keep it as thin as possible. This can be achieved by using an intermediate reflector between top and bottom cell. Figure 3 shows how the current between top and bottom cell in a tandem device change with the thickness of the intermediate reflector layer. In addition to plain tandem cells, the figure 3 includes the behaviour of the same device with an additional anti-reflection layer. The latter is not based on interference effects of a planar anti-reflection coating but exploits the gradual change of the refractive index on a textured surface. Figure 3 shows that the main benefit of this method is for the top cell.

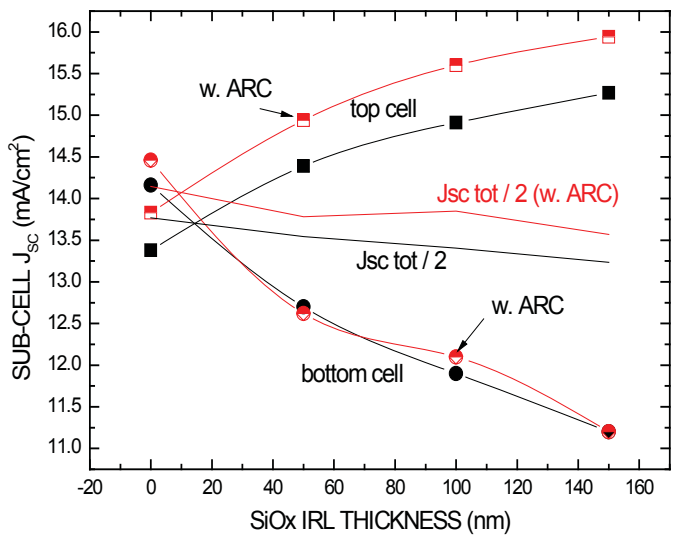


***Figure 3**: Top- and bottom cell currents in dependence on the thickness of the silicon oxide intermediate reflector layer.*

Publications in Journals

[1] S. Hänni et al. “On the Interplay Between Microstructure and Interfaces in High-Efficiency Microcrystalline Silicon Solar Cells”, IEEE Journal of Photovoltaics.

[2] M. Boccard et al. “Light trapping in solar cells: Analytical modelling”, Applied Physics Letters 101, p 151105 (2012).

Presentations at Conferences

[i] S. Hänni et al. “On the Interplay Between Microstructure and Interfaces in High-Efficiency Microcrystalline Silicon Solar Cells”, 38th IEEE PVSEC Austin (2012).

[ii] M. Despeisse et al. “Light harvesting schemes for high efficiency thin film silicon solar cells” , 38th IEEE PVSEC Austin (2012).

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INTERFACE TEXTURING FOR LIGHT TRAPPING IN SOLAR CELLS

Annual Report 2012

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Project- / Contract Number	200021/125177-01 / 200020/137700-01
Duration of the Project (from – to)	01.10.2009 – 30.09.2013
Date	09.12.2012

ABSTRACT

This project combines experimental and theoretical work on novel surface textures for light trapping.

We were able to demonstrate a novel type of substrate where the light scattering texture is buried below a flattened interface. Thus, the absorption of long wavelengths is enhanced while the flat morphology ensures high open circuit voltage. Using this configuration, a triple junction solar cell with stabilized efficiency of 12.5% could be demonstrated.

Theoretical work concentrated on studying the upper limits of absorption enhancement. Usually, contributions on this topic refer to the bulk limit of $4n^2$ given by Yablonovitch, n being the refractive index. However, it appears that a treatment as bulk is not appropriate for thin films. Applying coupled mode theory to the case of thin films, the upper limit of absorption enhancement assumes a lower value and acquires a dependence on the angle of incidence.

SNF project “Interface texturing”

The project funded by the Swiss National Science Foundation is collaboration between the PV-Lab and the group of Advanced Optics. The project aims at the development of optical simulation tools and experimental analysis of interface textures.

Work performed in the reporting period 2012

Experimental work

In the reporting period, the experimental work was focussed on light trapping in flattened reflectors. The concept is based on the observation that the growth of microcrystalline silicon is very sensitive towards substrate textures. Nevertheless, they are required for enhancement of the photocurrent. The n-i-p configuration offers the possibility to satisfy both needs; we designed a reflector with a buried interface between ZnO and silicon that is rough, but electrically inactive. Subsequently, the silicon layer is polished to just expose some tips of the underlying ZnO pyramids to establish the electric contact. Finally, a microcrystalline cell with excellent performance can be grown on this substrate. The cell design is schematically shown in figure 1.

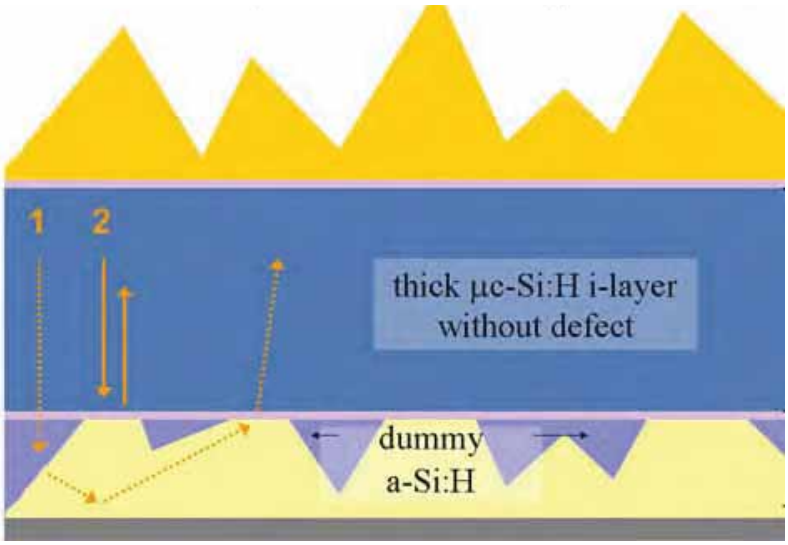

***Figure 1**:Cross section through a microcrystalline cell. The flattened reflector in the lower part consists of zinc oxide whose pyramidal texture is filled with amorphous silicon and subsequently polished.*

Unfortunately, parasitic absorption in the amorphous dummy layer of the flat back contact cannot be suppressed completely, it is thus necessary to apply this concept directly to tandem solar cells where the relevant part of light is already absorbed in the top cell before reaching the back reflector. Finally, aspects of current matching make it more recommendable to actually use a triple junction with two microcrystalline cells. The external quantum efficiency (EQE) of the resulting device is shown in figure 2.

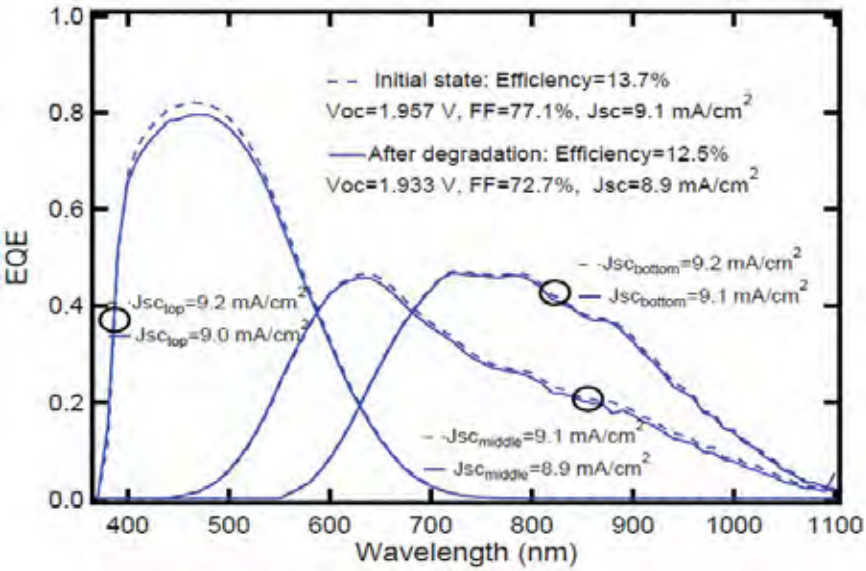

***Figure 2**: External quantum efficiency (eqe) of a triple junction solar cell on the flattened substrate. Dashed and full lines denote the initial and the stabilized state, respectively.*

Figure 2 includes the electric parameters of the device. Owing to its high open circuit voltage and its excellent fill factor (FF) after light induced degradation, this cell exhibits a s tabilized efficiency of 12.5% which equals the highest certified efficiency of this device configuration (reported by United Solar Inc.). More details can be found in refs [1,2].

Theoretical work

Based on a model that describes the solar cell as waveguide (c.f. previous report), we are now able to take into account also the confinement of the guided modes. This is necessary since the electromagnetic field of a guided mode can extend out of the actual guiding medium into adjacent layers like the front or back contact where absorption does not contribute to the photocurrent. Figure 3 illustrates the theoretically achievable absorption enhancement, here for the case of a texture that is periodic in one dimension. Different from two dimensional textures, the average enhancement is not equal to $4n^2$, the result of Yablonovitch, but to πn. For silicon, this is approximately 12 and the uppermost zigzag line eventually approaches averages out to that limit. Our considerations apply to the specific case of a 200 nm thick silicon film where the fact that a part of the field leaks out of the absorber, yields a lower limit. The limit would likewise average below the value of $4n^2$ that applies to thick bulk material if a two-dimensional texture were used.

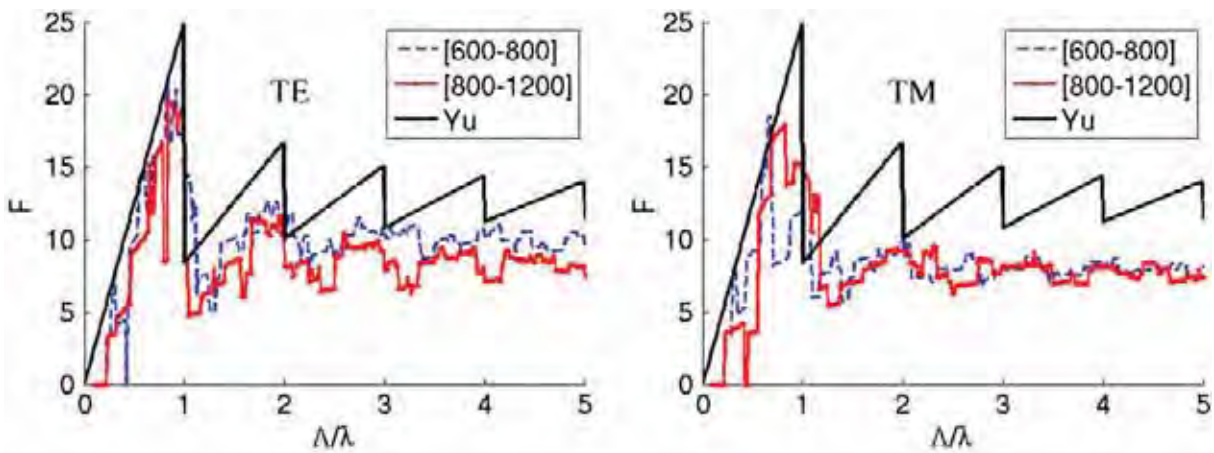

***Figure 3**: Absorption enhancement in 200 nm thick silicon film with a one-dimensional periodic interface texture.*

The absorption enhancement is sensitive to the angle of incidence. Figure 4 presents colour maps for the angular range from 0° (perpendicular incidence) to 90°. It is observed that the zigzag behaviour averages out beyond 40°. More details can be found in ref. [3].

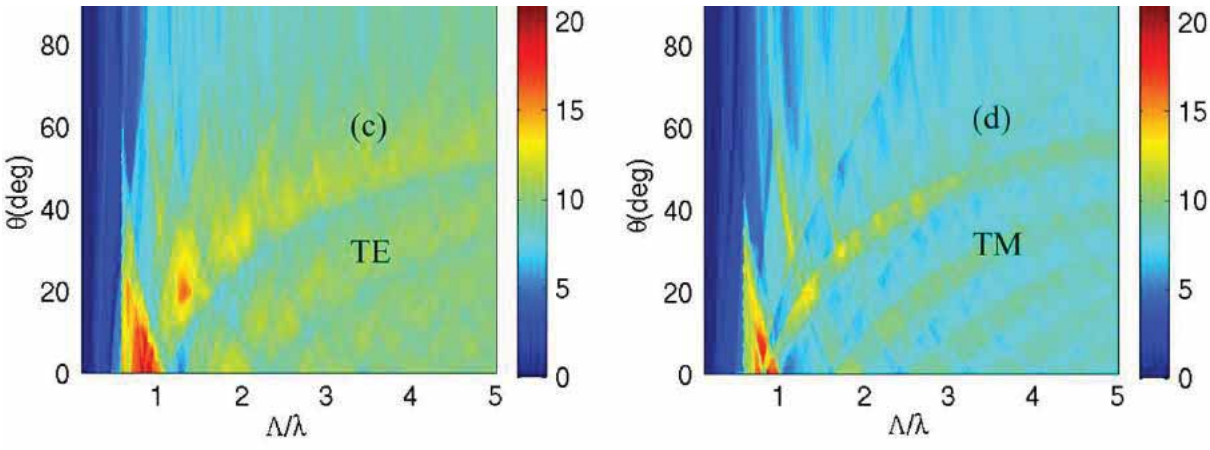

***Figure 4**: Absorption enhancement with respect to the incident angle. The plots of Figure 3 represent 0 degrees, i.e. the abscissa.*

Publications in Journals

[1] K. Söderström et al. ”Experimental study of flat light-scattering substrates in thin-film silicon solar cells” Solar Energy Materials and Solar Cells 101, p193 (2012)

[2] K. Söderström et al. “Thin-film silicon triple-junction solar cell with 12.5% stable efficiency on innovative flat light-scattering substrate”, Journal of Applied Physics 112, p114503 (2012)

[3] A. Naqavi et al. “Light trapping in solar cells at the extreme coupling limit”, Journal of the Optical Society of America B 30(1), p13 (2013)

[4] A. Naqavi et al. “Angular behavior of the absorption limit in thin film solar cells”, accepted for publication in Progress in Photovoltaics

Presentations at International Conferences

[i] K. Söderström et al. “Electrically flat/optically rough substrates for efficiency above 10% in n-i-p thin film silicon solar cells”, MRS Spring Meeting, San Francisco

[ii] A. Naqavi et al. ”Light trapping limit revisited: how guided modes enhance light absorption in solar cells?” SOLAR topical meeting of the Optical Society, Eindhoven (2012)

[iii] A. Naqavi et al. “Geometrical impact on guided mode excitation in solar cells” SOLAR topical meeting of the Optical Society, Eindhoven (2012)

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A NEW LOW ION ENERGY BOMBARDMENT PECVD REACTOR FOR THE DEPOSITION OF THIN FILM SILICON FOR SOLAR CELL APPLICATIONS

Annual Report 2012

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Project- / Contract Number	KTI 13271.1 (KTI 9675-02)
Duration of the Project (from – to)	01.01.2012 – 31.12.2012
Date	12.12.2012

ABSTRACT

A novel electrode configuration is proposed for improved plasma-enhanced chemical vapour deposition of films such as amorphous silicon and micro-crystalline silicon. The new electrodes are designed to de-couple the film deposition from the plasma generation zone. The deposited films are thus protected from damage by plasma ion bombardment, which is crucial for the manufacture of high-performance photovoltaic material. The new plasma reactor concept is being optimised in laboratory experiments and has been developed into a R&D industrial pilot reactor. Tests of film and device quality tests are currently underway.

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ZWEIDIMENSIONALE NANOSTRUKTUREN FÜR SILIZIUM-SOLARZELLEN

Annual Report 2012

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Project- / Contract Number	SI/500141 / SI/500141-01
Duration of the Project (from – to)	01.10.2008 – 15.12.2012
Date	16.12.2012

ABSTRACT

The main goal of the project is the development of **efficient numerical methods** to solve the Maxwell equations in order to calculate the optical properties of crossed gratings rigorously.

The structures shall be optimized for **broad-band absorption of both polarizations in thin films**. This optimization should take into account the various experimental limitations. Prototypes should be fabricated with e-beam lithography by the LMN of PSI, and experimental characterisation of the structures, as well as a prototype solar cell fabrication is to be done by the IMT in Neuchâtel.

Einleitung / Projektziele

In diesem Projekt sollen zweidimensional-periodische Nanostrukturen durch numerische Berechnungen untersucht werden. Diese sind von besonderem Interesse für die Photovoltaik, da sie es ermöglichen, die Lichtabsorption in dünnen Schichten stark zu verbessern. Dabei sollen solche Strukturen für eine möglichst **breitbandige Absorption beider Polarisationen** optimiert werden.

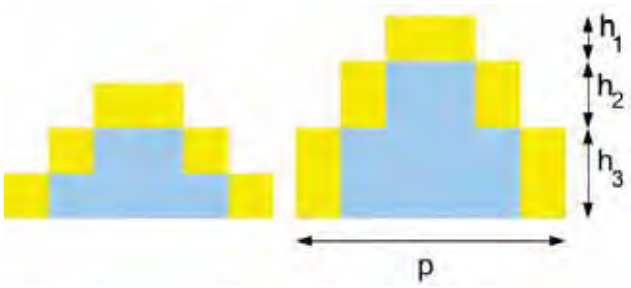
Die Motivation für das Projekt ergibt sich aus Resultaten sowohl für die TM Polarisation der Absorption bei eindimensionalen Gittern (z.B. [1],[2]), wie auch aus Resultaten für schmalbandige totale Absorption bei zweidimensionalen Gittern (z.B. in [3]). Deshalb wird eine spürbare Effizienzsteigerung von Dünnschichtsolarzellen bei relativ geringen Zusatzkosten erwartet.

Zunächst wurde ein Computerprogramm geschrieben, das die Analyse **zweidimensionaler Strukturen** erlaubt. Dabei wird der Schwerpunkt auf die Untersuchung von idealisierten Strukturen gelegt, um genaue numerische Referenzresultate für reale Strukturen zu erhalten. Dies vor allem deshalb, weil solche zuverlässige numerische Referenzen für Systeme mit kleinen Absorptionskonstanten in der Literatur kaum zu finden sind (siehe den Übersichtsartikel [4]). Parallel zur Arbeit von A. Naqavi am IMT Neuchâtel werden verschiedene Strukturen untersucht, vor allem solche, die sich später für kostengünstige Massenfabrikation eignen könnten. Die gezielte Suche nach optimalen Strukturen wird voraussichtlich am IMT durchgeführt, um diese konkret an die realen Verhältnisse anzupassen. Unter anderem sollen die Halbleitereigenschaften der Materialien nicht beeinträchtigt werden. Dabei sollen in Zusammenarbeit mit dem IMT und dem Labor für Mikro- und Nanotechnik Strukturen mit Hilfe von Elektronenstrahl-Lithographie konkret realisiert werden, und experimentell untersucht werden.

Kurzbeschrieb des Projekts

Im Allgemeinen existieren zwei Ansätze für die Berechnung stationärer elektromagnetischer Felder. Einerseits sind dies Methoden, bei denen der Raum diskretisiert wird mit Auflösung *h* bei fixer Approximationsordnung *k*, zum Beispiel bei der Methode der finiten Differenzen, oder bei einer finiten Elementmethode mit variabel gewähltem Gitter. Die Konvergenz ergibt sich bei diesen Methoden indem die Auflösung h kleiner und kleiner gewählt wird. Andererseits kann die Approximationsordnung *k* bis zur Ordnung 1/h erhöht werden, dies entspricht einer Spektral- oder Galerkinmethode. Wird das elektromagnetische Feld nach Eigenmoden der Helmholtzgleichung entwickelt, so spricht man von einer modalen Methode. Die Genauigkeit der Approximation wird durch die Anzahl *d* der berücksichtigten Eigenmoden bestimmt.

Für das vorliegende Problem wird eine Methode gewählt, die das Beugungsgitter in Schichten aufteilt, und die Beugungsgitter durch Treppenstufen approximiert. Dies bringt zwar gewisse Herausforderungen für glatte Strukturen mit sich, bietet aber viele Vorteile, wenn ganze Klassen von Strukturen mit unterschiedlicher Tiefe effizient gerechnet werden sollen (siehe Figur 1), wobei die Erhöhung für die einzelnen Schichten unabhängig gewählt werden kann. Innerhalb solcher Schichten basiert unser Code auf einer modalen Methode, indem das elektromagnetische Feld nach Eigenfunktionen der Helmholtz-Gleichung entwickelt wird. Wie man eine modale Methode auf ein beliebiges, eindimensionales Beugungsgitter anwendet, findet sich zum Beispiel in [5,6]. Hierbei ist festzustellen, dass es einen numerischen Unterschied gab bei der Polarisation des Lichts, wenn die Eigenfunktionen nach Fourier-Moden entwickelt wurden. Es konvergierten transversal elektrische (TE) und transversal magnetische (TM) Polarisation nicht gleich schnell. Für eine derartige Entwicklung sinkt der Fehler für die TE Polarisation wie $1/n^3$, für die TM Polarisation wie $1/n^2$, und für konische Diffraktionsprobleme sind die beiden Polarisationen gekoppelt und daher wird die Konvergenz durch die langsamer konvergierende Polarisation begrenzt.



***Figur 1**: Diese Strukturen lassen sich mit relativ wenig zusätzlichem Aufwand für viele verschiedene Werte der Höhenparameter hi berechnen.*

Die Verallgemeinerung auf zweidimensionale Strukturen wurde in [7] behandelt, für die die Rechnungen noch langsamer konvergieren weil E- und H-feld immer gekoppelt auftreten, und damit die langsamere Konvergenz des H-Falls immer limitierend wirkt. Konkret konvergieren die Eigenwerte auf Grund der quadratisch wachsenden Moden- und Basisfunktionszahlen sogar nur wie $1/n$. In den Ref. [8],[9] wurde eine Methode gefunden, um die Konvergenz von quadratisch auf kubisch zu verbessern. Eine Analyse der Methode findet sich in [10]. Diese Verbesserung ist entscheidend, denn nun sinkt der Fehler wie $1/n^{3/2}$ in zwei Dimensionen. In [11] wurde diese Methode mit zusätzlichem Formalismus für zwei Dimensionen und nicht-rechtwinklige Elementarzellen verallgemeinert. Unter Berücksichtigung von Symmetrien kann der Rechenaufwand reduziert werden, wie in [12] dargelegt wird, in [13] für hexagonale Symmetrien, und in [14] für quadratische Symmetrien, wobei die Konvergenz im Prinzip nicht verändert wird.

Die Diskussion der Konvergenz ist wesentlich im Rahmen des verbesserten Lichteinfangs, weil die zu untersuchenden Solarzellen zum einen aus stark reflektierenden Metallen an den Kontakten, und zum anderen aus sehr dünnen, schwach absorbierenden Halbleiterschichten bestehen. Die Herausforderung besteht darin, dass die Absorptionskonstanten in dem Wellenlängenbereich sehr gering sind, wo der Lichteinfang besonders benötigt wird. Die geforderte hohe Absorption in schwach absorbierende Materialien bedingt die Nutzung von Resonanzeffekten, um die Intensität der elektromagnetischen Felder zu optimieren. Dabei soll möglichst nur die Absorption in der optoelektrisch aktiven Schicht erhöht werden. In diesem Bereich hoher Resonanz ist es anspruchsvoll, die Maxwell'schen Gleichungen numerisch exakt zu lösen, da die Anzahl der Moden d zunimmt, die berücksichtigt werden müssen. Daher haben traditionelle Verfahren in diesem Bereich Mühe, numerisch exakte Resultate zu erhalten.

Bei der Entwicklung der Eigenfunktionen nach einer Basis kommen weitere Schwierigkeiten hinzu. Einerseits sind nur ungefähr n/3 Eigenfunktionen akzeptabel genau in der Basis dargestellt, und andererseits gibt es auch $O(1)$ Moden, die zwar das algebraische Eigenwertproblem lösen, aber keine Lösungen der Differentialgleichung sind. Diese Artefakte wurden eingeführt, als der Differentialoperator ersetzt wurde durch einen Operator, der auf einen n-dimensionalen Raum wirkt.

In [15] wurde eine Methode vorgestellt, die aufgrund ihrer exponentiellen Konvergenz den Anforderungen an numerische Exaktheit genügt. Die Methode [15] wird deshalb in dieser Arbeit auf zwei Dimensionen verallgemeinert. Hierbei wird das elektromagnetische Feld in Eigenfunktionen der Helmholtzgleichung dargestellt. Diese Eigenfunktionen werden dann in Regionen mit jeweils konstanter Permittivität nach Legendre-Polynomen entwickelt. An den Grenzflächen müssen die *E*- bzw. *H*-Felder die exakten Randbedingungen erfüllen, das heisst, dass sowohl die Felder stetig sein müssen, als auch $\mathrm{d}E/\mathrm{dn}$ und $(1/\varepsilon)\mathrm{d}H/\mathrm{dn}$, wobei n die Normale auf die Grenzschicht bezeichnet. Dank dieser Trennung in Regionen mit konstanter Permittivität gelingt es, die exponentielle Konvergenz bezüglich der Ordnung n der Entwicklung zu garantieren, wie es eben nach der Approximationstheorie möglich sein muss für Systeme, in denen das Feld überall unendlich oft differenzierbar ist mit Ausnahme der Grenzflächen des Gebiets der Entwicklung.

Eine weitere Schwierigkeit ergibt sich aus der Forderung der Optimierung der Absorption. Aus diesem Grund wollen wir die Absorption lokal berechnen. Einerseits wollen wir die Absorption im optoelektrisch aktiven Teil kennen und maximieren, das heisst im undotierten Silizium, und andererseits wollen wir die parasitäre Absorption in den anderen Bereichen, wie den Kontakt- und Antireflexschichten kennen und minimieren. Dafür ist wesentlich, dass die Berechnung der Absorption lokal erfolgt, und nicht nur schichtweise, da innerhalb einer Schicht mehrere Materialien vorkommen können. Diese Berechnung ist kaum möglich, wenn traditionelle Methoden verwendet werden, welche die diskreten Brechungsindexsprünge mit einer abgeschnittenen Fouriertransformation verbreitern.

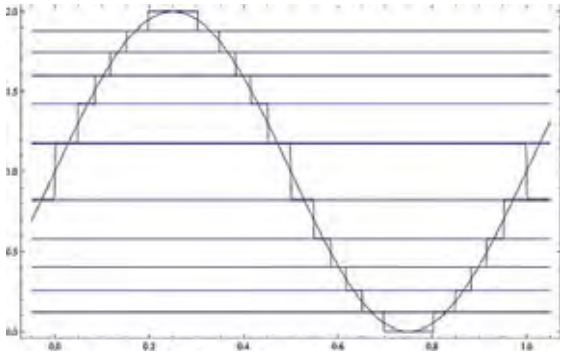
Durchgeführte Arbeiten und erreichte Ergebnisse

Wie im letzten Bericht angekündigt, wurde dieses Jahr ein Schwerpunkt auf das Lösen des zweidimensionalen Problems gelegt. Aus programmiertechnischen und anderen der Numerik geschuldeten Gründen wurde hierzu eine vollkommen neue, auch für eindimensionale Strukturen anwendbare Methode entwickelt, das Eigenwertproblem zu lösen, die wir im Folgenden Trapezmethode nennen. Die Trapezmethode ist nicht nur einfacher zu implementieren als die Polynommethode, sondern sie lässt sich auch einfacher auf allgemeine Geometrien übertragen, und sie zeigt kaum Eigenwerte, die der Differentialgleichung nicht gehorchen, wie letztes Jahr beschrieben. Ähnlich der Polynommethode beschreibt sie die Randbedingungen bei Materialübergängen exakt. Was sie besonders auszeichnet, ist der Umstand, dass der Poynting-Vektor in nicht-absorbierenden Materialien lokal exakt erhalten ist,

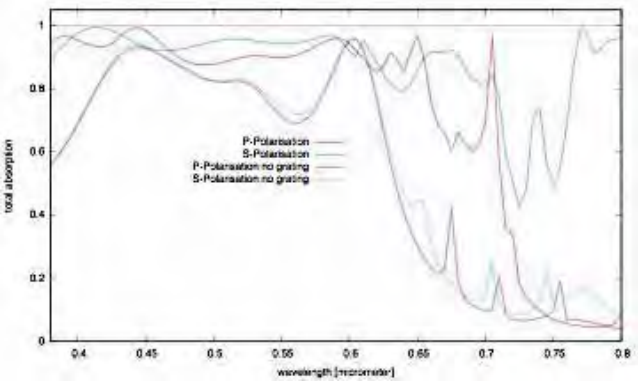
und zwar unabhängig von der gewählten Diskretisation h. Diese Eigenschaft macht sie zur Methode der Wahl, wenn genaue Absorptionsberechnungen gefordert sind.

Bei der Trapezmethode handelt es sich um eine Ortsraum-Methode, in der an den Stützstellen im Ortsraum nicht nur die Werte des elektromagnetischen Feldes sondern auch dessen Ableitungen bis zur Ordnung k benutzt werden. In unseren eindimensionalen Rechnungen haben wir die Trapezmethode bis zur Ordnung k=5 untersucht und die Konvergenz $h^{(2k+1)}$ der Eigenwerte nachgewiesen. Die wählbare Konvergenzordnung ist ein wesentliches Merkmal gegenüber Fourier-Methoden mit im besten Fall kubischer (k=1) Konvergenz. Für zweidimensionale Gitter ist die sinnvolle minimale Trapezordnung k=2 und für höhere k ist die Implementation zwar möglich, wird aber sehr umständlich. Die Eigenwerte und Eigenvektoren der Helmholtzgleichung sind hier ebenfalls durch ein algebraisches lineares Eigenwertproblem bestimmt. Doch ist dieses durch ein System von linearen Nebenbedingungen eingeschränkt und erfordert ein sorgfältiges Vorgehen, damit die Rechnung numerisch stabil ist. Unsere Untersuchungen haben gezeigt, dass es eine numerisch optimale Method gibt, die maximale Stabilität zufolge hat. Sie basiert auf einer QR-Zerlegung der Matrix der linearen Nebenbedigungen, notwendigerweise mit Spaltenpivotierung, die für die Stabilität essentiell ist.

Die spezielle geometrische Struktur der Trapezmethode, in der jeweils das elektromagnetische Feld und seine Ableitungen jeweils an 2 Nachbarpunkten im Ortsraum verbunden werden, erlaubt die Anwendung bei praktisch beliebiger Geometrie der Beugungsstrukturen, wobei man beachten muss, dass die Grenzflächen zwischen Materialien mit verschiedener Permittivität auf Stützpunkte zu liegen kommen. Dies erlaubt es, die Randbedingungen an den Grenzflächen numerisch exakt zu erfüllen.



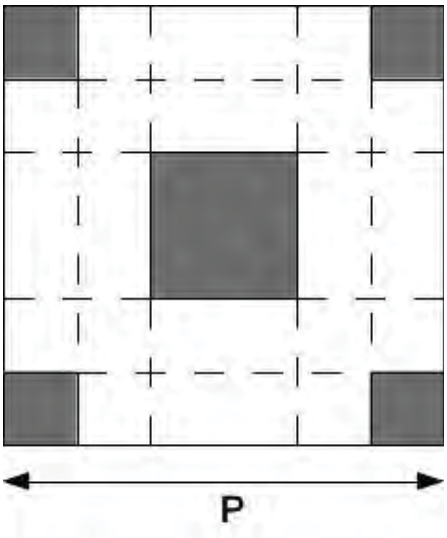
***Figur 2**: Ein sinusförmiges Gitter mit optimaler 11-stufiger Treppenapproximation.*



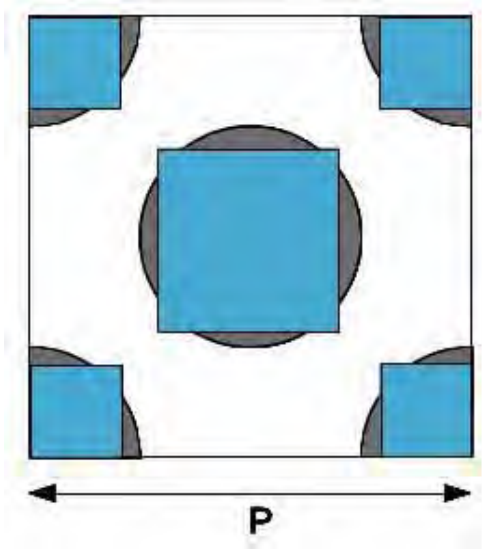
***Figur 3**: Absorptionsspektrum einer amorphen Silizium Solarzelle mit Sinusgitter verglichen mit einer unstrukturierten Solarzelle.*

Im Rahmen der Treppensapproximation war ein weiteres Arbeitsfeld die Entwicklung einer optimierten Approximation des Sinus, welche die Schichtdicken und Materialübergänge entsprechend dem Prinzip von gleichen Fehlerflächen festlegt, wie in Figur 2 zu sehen ist. Dabei werden die Höhen und Positionen der Grenzflächen so gewählt, dass die "Fehlerflächen" alle gleich gross werden. Die so gefundene Treppenapproximation ist eindeutig für jede gewählte Anzahl der Stufen. In den Modellrechnungen, siehe Figur 3, zeigt es sich, dass die für optimale Absorption notwendige Periode und Strukturhöhe nur sehr schwach von der Anzahl Treppenstufen der Approximation abhängt. Der Fortschritt liegt hier in der Reduktion der benötigten Schichten für eine gut konvergierende Rechnung. Dies ist auch für die lokale Berechnung der Absorption von Bedeutung, an der auch gearbeitet wurde. Es geht hierbei darum, mit genauen Werten des Poynting-Vektors an allen Grenzflächen eine hinreichend genaue Berechnung der Absorption in den jeweiligen Materialien durchführen zu können.

Bewertung 2012 und Ausblick 2013



***Figur 4**: Die Projektion einer zweidimensionalen Struktur mit Löchern, bzw. Höckern, wie sie demnächst gerechnet werden soll.*



***Figur 5**: Vergleich der zu rechnenden "Schachbrett" Struktur mit einer "Tropfenstruktur". Bei Querschnitten ist ein 2-dimensionaler Sinus näher an einer Schachbrett Struktur als an einer Tropfenstruktur.*

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20 PERCENT EFFICIENCY ON LESS THAN 100 µM THICK INDUSTRIALLY FEASIBLE C-SI SOLAR CELLS (20PLµS)

Annual Report 2012

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ABSTRACT

20plµs (20 percent efficiency on less than 100 µm thick industrially feasible c-Si solar cells) is a project sponsored by the European Commission. This project links together world-class EU companies and institutes with experience in the field of crystalline silicon solar cells. The guiding principle of this project is to develop new and innovative process steps for wafer, solar cell, and module fabrication on wafers less than 100 µm thick, taking into consideration transfer of the processes to a pilot production line. The project's goal is to demonstrate the industrial feasibility of high-efficiency solar cells on very thin wafers in Europe. For this, both high- and low-temperature processes are being studied and compared. Our laboratory is focusing on amorphous silicon (*a*-Si:H) / crystalline silicon (*c*-Si) heterojunction solar cells processed at low temperatures. Our target is to demonstrate ultra-high efficiency (up to 23%) *a*-Si:H/*c*-Si heterojunction solar cells on thin wafers.

At the Institute of Microengineering (IMT) of the Ecole Polytechnique Fédérale de Lausanne, we started activity in 2005 in the field of silicon heterojunction solar cells. Based on extensive plasma diagnostics and materials characterization, we have developed both a comprehensive physical understanding of the passivation mechanisms in silicon heterojunction solar cells and the know-how to reproducibly fabricate devices with open-circuit voltages in excess of 720 mV. We can now fabricate 22% efficient solar cells on (thick) textured wafers with industrially relevant technologies, in particular with PECVD deposition at 40 MHz. These results were achieved in projects partially co-financed by Axpo. Our efforts are shifting to understanding and improving optical and electrical losses in devices, and, in the framework of the 20plµs project, to light trapping in thin wafers.

In this report we show that the infrared response of heterojunction solar cells can be maximized with a high-mobility front transparent conductive oxide (TCO) layer and very transparent, 150-nm-thick rear TCO layer. This combination best mitigates the plasmonic absorption in the rear silver reflector that significant reduces short-circuit current. With optimized TCO layers and our best passivation, we achieved several new records in 2012, including a 20.8%-efficient solar cell on a 96-µm-thick wafer, a 21.4%-efficient cell on a thick *p*-type wafer, and a 22.1%-efficient cell on a thick *n*-type wafer.

Goals of the project

The ***overall objective*** of the 20plμs project is the development of ***20% efficient silicon solar cells*** with ***thicknesses below 100 μm***. The developed processes will be transferred to an ***industrial pilot line*** with the aim of achieving a yield comparable to that obtained in standard solar cell production and a conversion efficiency of ***19.5% on 100-μm-thick 156 x 156 mm^2 wafers***. IMT is concentrating on reaching this objective using the silicon heterojunction solar cell design. Within the project, IMT's goals for 2012 included the development of amorphous silicon (*a*-Si:H) passivation layers that are both highly transparent and enable high open-circuit voltages (V_{oc}s) on thin wafers, identification and mitigation of infrared parasitic absorption losses to enable high short-circuit current (J_{sc}), and demonstration of new front-grid metallization techniques to reduce front reflection.

Brief description of the project

The 20plμs project consists of ten work packages covering all aspects of crystalline silicon solar cell manufacturing ranging from wafering to cell fabrication on an industrial pilot line. IMT is a principal contributor to the work packages related to emitter formation, passivation, light trapping, metallization, and prototype cell fabrication. Consequently, we are developing new scientific understanding and fabrication processes for each of these topics as they relate to silicon heterojunction solar cells, focusing on achieving 20% efficient cells on wafers less than 100 μm thick.

Work performed and results achieved in 2012

At the end of 2011, IMT's record efficiency for a 2 x 2 cm^2 silicon heterojunction solar cell was 21.2%, with V_{oc} = 723 mV, J_{sc} = 37.9 mA/cm^2, and fill factor (*FF*) = 77.5%.

Within the framework of the 20plμs project, we studied infrared (IR) light management in heterojunction solar cells [1]. Excellent light trapping and very low IR parasitic absorption are crucial for high-efficiency solar cells on thin wafers because, as illustrated in Fig. 1b, IR external quantum efficiency (*EQE*)—and thus J_{sc}—decreases with wafer thickness since IR light is absorbed weakly in the wafer. IR light is absorbed parasitically in three layers in heterojunction solar cells (shown schematically in Fig. 1a): the front TCO, rear TCO, and rear silver.

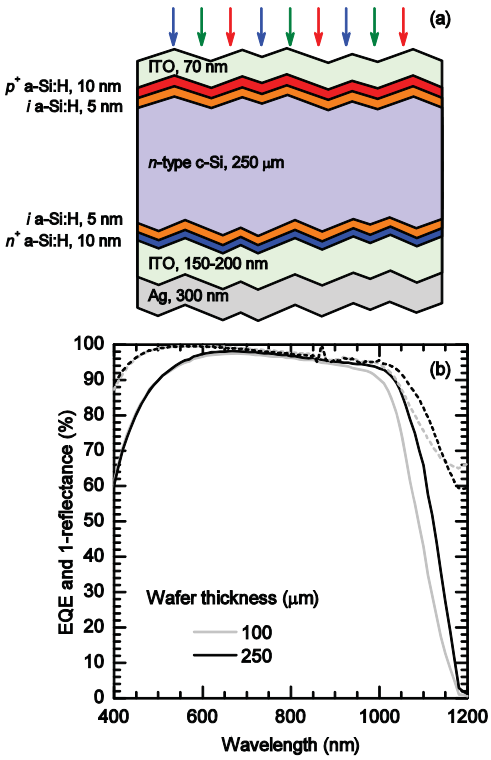

Figure 1: *(a) Schematic of silicon heterojunction solar cells, including the default layer thicknesses used unless otherwise stated. (b) External quantum efficiency (solid) and 1-reflectance (dashed) of silicon heterojunction solar cells co-deposited on wafers 100 and 250 μm thick. From [1].*

We demonstrated that ***the rear TCO should be made as transparent as possible and 150 nm thick*** [1]. This design ***minimizes plasmonic absorption of evanescent waves in the silver reflector***. This is shown in Fig. 2c, in which the measured and simulated reflectance at 1200 nm of a solar cell (a metric of how little parasitic absorption exists) increases with increasing TCO thickness (here, the TCO is replaced by a non-absorbing silicon nitride layer). The thickness of the front TCO layer, by contrast, is fixed by its role as an anti-reflection coating. The only way to minimize its contribution to IR parasitic absorption is to ***maximize the free-electron mobility, as we have demonstrated with hydrogen-doped indium oxide (mobility > 100 cm^2/Vs)*** [2]. We showed that in heterojunction solar cells with optimized TCO layers, ***the front TCO limits IR EQE***, and thus future research should be biased towards its improvement [1]. By integrating our new best TCO layers into complete solar cells, we achieved an ***active-area J_{sc} well in excess of 41 mA/cm^2***.

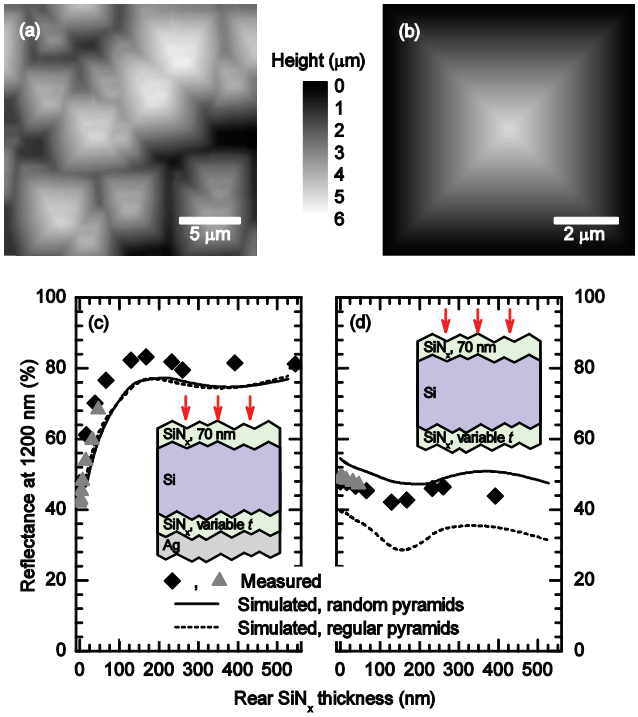

Figure 2: *(a) Random and (b) regular pyramid textures used at the front and rear surfaces of the simulated optical structures. Measured and simulated total reflectance of 1200 nm light incident on textured wafers with front and rear SiN_x layers, (c) with and (d) without a silver layer at the rear. From [1].*

In 2012, we fabricated our first silicon heterojunction solar cells on wafers less than 100 µm thick. After only a few wafers, we achieved a 2 x 2 cm^2 ***solar cell on a wafer only 96 µm thick with an efficiency of 20.8%***, V_{oc} = 735 mV, J_{sc} = 36.7 mA/cm^2, and FF = 77.3%. This solar cell had an active-area J_{sc} of 40.3 mA/cm^2, demonstrating the success of our approach to minimize current losses as wafer thickness is decreased. With this cell, ***we exceeded the goals of the 20plµs project***; we will concentrate on larger-area solar cells next.

Finally, within the framework of several ongoing projects related to silicon heterojunction solar cells, we investigated *a*-Si:H passivation of both *n*-type wafers, on which heterojunctions are typically fabricated, and *p*-type wafers, which are more widely available. Of particular interest, we demonstrated for the first time that ***excellent passivation can be achieved on p-type as well as n-type wafers with a-Si:H, with implied V_{oc}s of over 730 mV*** on both wafer types (Fig. 3) [3]. Equally important, we showed that ***heterojunction solar cells on p-type wafers will always have lower FF than their n-type counterparts*** because the effective minority carrier lifetime at the maximum power point (MPP) is lower.

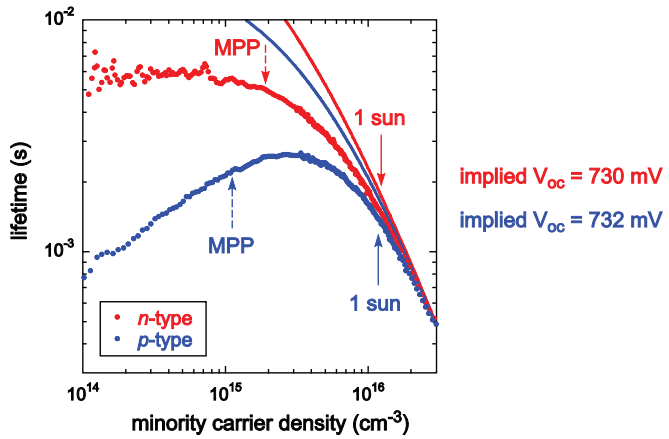

***Figure 3**: Minority carrier effective lifetimes of solar cell precursors (textured wafers passivated with co-deposited in$^+$ and ip$^+$ a-Si:H stacks) on n - and p-type FZ wafers. The injection levels corresponding to 1-sun illumination are marked by solid arrows, and the corresponding implied V_{oc} values are given. From [3].*

Nevertheless, with excellent passivation layers and TCOs optimized as described above, we achieved ***a certified new world record efficiency of 21.38% for silicon heterojunction solar cells on p-type wafers*** (Fig. 4) [3]. We also obtained ***a new personal best cell on n-type wafers***, which had a ***certified efficiency of 22.14%***, V_{oc} = 727 mV, J_{sc} = 38.9 mA/cm^2, and FF = 78.4%. These results were obtained within the 20Plus project, but also through projects sponsored by the Axpo Naturstrom Fonds.

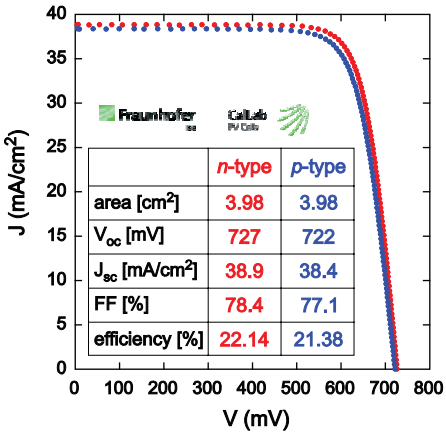

***Figure 4**: Illuminated IV curves of the best 2 cm x 2 cm cells on n- and p-type FZ wafers (certified by Fraunhofer ISE CalLab). From [3].*

National and international collaboration

Due to the nature of this European Project, IMT is in collaboration with many of the the major European institutes, universities, and companies working on crystalline silicon solar cells. These partners include University of Konstanz, Fraunhofer Institut für Solare Energiesysteme, Q-Cells (now part of Hanwha), and PSE AG from Germany; New and Renewable Energy Centre Limited (Narec) from the United Kingdom; Eni S.p.A. from Italy; and Mechatronics Systemtechnik GmbH from Austria. Moreover, in Neuchâtel, IMT also has an ambitious collaboration with Roth & Rau on the development of production technology for silicon heterojunction solar cells.

Evaluation of 2012 and perspectives for 2013

2012 was a successful year for IMT in the 20plμs project. All deliverables, milestones, and internal goals were met, and we developed new scientific understanding and technological know-how to make excellent solar cells. We fabricated our first solar cells on wafers 100 μm thick and achieved record efficiencies. In 2013, we will expand our activities on very thin and large-area heterojunction solar cells, aiming for efficiencies in excess of 21% on areas larger than 100 cm^2 and wafers 100 μm thick. As we have already developed excellent *a*-Si:H and TCO layers to maximize V_{oc} and J_{sc}, special attention will be paid to *FF*, and the interfaces between doped *a*-Si:H and TCO layers in particular.

Acknowledgements

Part of these results was obtained in projects financed by Roth and Rau Switzerland and the Axpo Naturstrom fonds, for which we gratefully thank them.

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CIGS MULTI-STAGE IN-LINE PILOT MACHINE DEMONSTRATION

Annual Report 2012

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Duration of the Project (from – to)	01.01.2012 – 01.06.2014
Date	07.12.2012

ABSTRACT

The goal of the project is to develop and demonstrate a CIGS deposition system where the innovative multi-stage co-evaporation process developed in the lab for small area substrates in static positions can be scaled up for coating on in-line moving large area substrates. Demonstration of such a pilot scale deposition system could play a pivotal role in industrialisation of CIGS deposition technology for high efficiency solar cells and modules in future.

Introduction/Aims of the project

CIGS is recognized as an important thin film PV technology for cost effective manufacturing because of high efficiency potentials shown by the solar cells developed in research laboratory. However, there is a lack of CIGS production equipment supplies with proven process for high efficiency solar cell manufacturing on industrial scale.

There is no company providing CIGS evaporation systems with a process of multi-stage evaporation known to provide the highest efficiency devices. This is severely hindering the growth of CIGS PV industries since new companies with interest in CIGS production do not have possibilities of acquiring such systems. The proposed demonstration system would prove the industrial capability of the process and help in industrialisation of the technology and strengthen the position of Switzerland internationally in the field of photovoltaics.

Goal of the proposal

The goal of the proposed pilot project is to develop and demonstrate a CIGS deposition system where the innovative processes developed in the lab can be scaled up towards industrial applications. Demonstration of such a system plays a pivotal role in industrialisation of highly efficient PV technology for large volume production.

The overall objectives of the pilot project are therefore:

- to develop an in-line vacuum deposition system for the demonstration that the multi-stage CIGS co-evaporation technology can be scaled up for large size moving substrates
- to demonstrate a pilot level deposition system proof of concept based on a proprietary design and process know-how
- to attract industries as potential end users for subsequent scale-up for production
- to demonstrate that solar cells on large area substrate as well as solar modules of high efficiency can be produced based on the multi-stage process that has not yet been implemented on industrial scale
- to demonstrate the true potential of highly efficient CIGS technology for sustainable and safe solar electricity production to the public

The objectives for the reporting period include:

- Preliminary planning of the machine which includes investigation of the deposition parameters window for the multi-stage CIGS deposition process.
- Evaluation of the competences of potential equipment manufacturers for the joint development of the planned demonstration coater.

Short description of the project

Innovative multi-stage evaporation processes for the CIGS absorber layer were developed at Empa for obtaining an optimum chemical composition grading which proved to be highly reliable and reproductible and therefore suitable for industrial scale up. The developed processes are however stationary, i.e. the substrate is not moving relative to the evaporation sources. In this P&D project Empa wants to demonstrate that the multistage co-evaporation process can be transferred to industrially relevant in-line equipment.

Key issue of the development of the demonstration machine is the design of appropriate vacuum deposition system with evaporation sources having appropriate sequences and vapor flux profiles which allow the same composition grading of the CIGS for a moving substrate. A schematic of such source sequence is shown in figure 1.

The more detailed conceptual design studies which were elaborated with different potential equipment manufacturers are subject to bilateral NDAs and cannot be presented here.

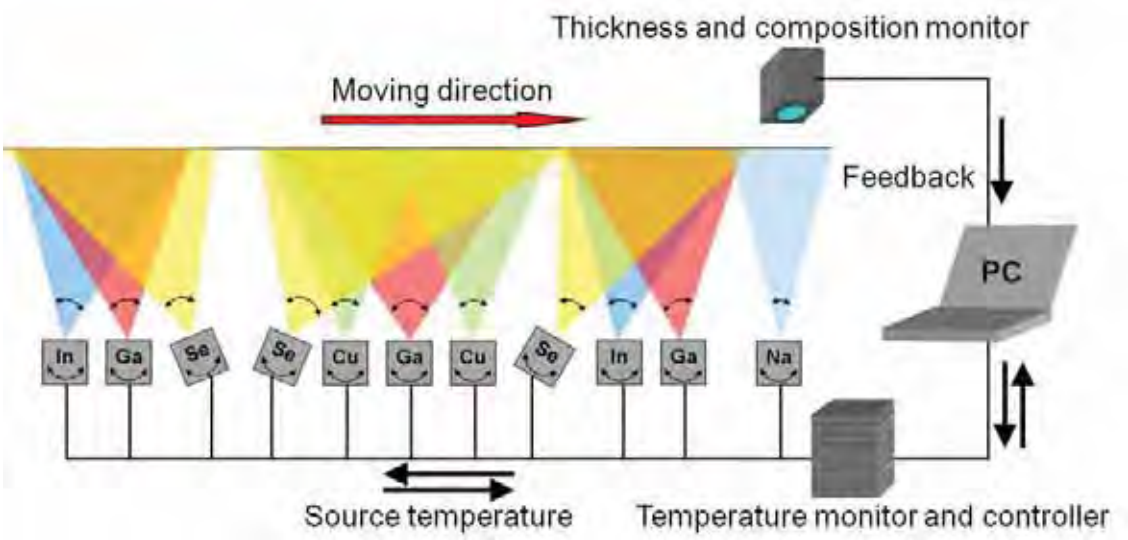


Figure 1: *Simplified schematic of the pilot system for multistage evaporation of CIGS based on the Empa process which yields world record efficiencies flexible solar cells on polymer and metal foils. The processes are applicable also for high efficiency cells on glass.*

The features of the in-line multi-stage CIGS deposition machine are the following:

- Proprietary low-temperature CIGS process allowing various substrate materials including flexible polymer and metal as well as glass substrates
- Continuous supply of moving substrates
- Multiple evaporation zones representing the different stages in the multi-stage process
- Evaporation sequences designed for reaching the same optimized composition grading in the CIGS layer as obtained from the laboratory scale process, for this optimization process the machine will be equipped with variable beam shapers and aligners for the evaporation sources
- Process control for chemical composition including feedback loop

The uniqueness of this pre-industrial pilot machine is the high level of degrees of freedom in the evaporation geometry which will allow the 1to1 transfer of the sophisticated multistage co-evaporation process.

Work carried out and results achieved

Experiments for the conceptual design of the in-line CIGS deposition system[1]:

For the design of the demonstration equipment, especially for the concept of the evaporation profiles and source sequence, it is important to identify the reproducibility and the process windows of the relevant deposition parameters. Figure 2 shows the open circuit voltage and fill factor of 23 subsequently processed CIGS solar cell samples (one sample contains 18 individual solar cells). Except of run 20 the V_{oc} of the best cell on the sample as well as the average of the best 10 cells lies between 670 and 715 mV. The fill factor only varies slightly between 76 and 78%. These values compare very well with the values of the record cell with 18.7% efficiency (V_{oc}=712 mV, FF=75.7%).

[1] *Manpower and consumables of the presented work are financed by internal projects and the FP7 R2R-CIGS project*

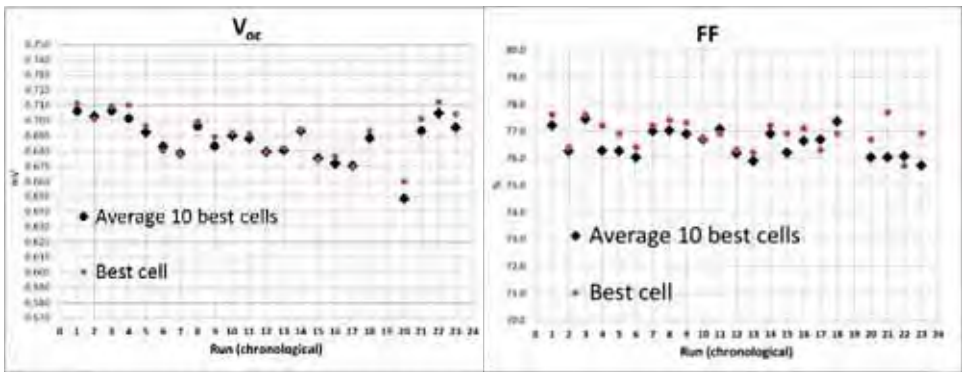


Figure 2: *Photograph of CIGS solar cell sample and reproducibility plots for Voc and FF of 23 subsequently processed CIGS samples.*

A very important property of the CIGS layer is the gallium vs. indium concentration in the compound, which depends on the evaporation flux and ramp (profiles) of the evaporation sources of the two elements. Figure 3 s hows that the developed CIGS process allows a v ariation of the average [Ga]/([Ga]+[In]) ratio between 0.34-0.395 without losses in performance of the devices. Too high values (above the presented range), however, result in major losses in Voc, while too low values result in an unfavorable energy band gap of the absorber layer.

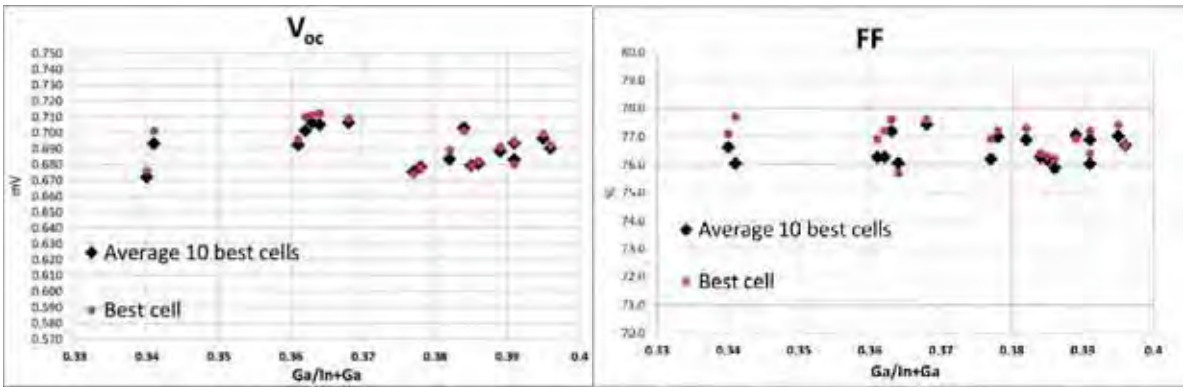


Figure 3: *Impact of average [Ga]/([Ga]+[In]) ratio variation on Voc and FF. The ratios were determined from XRF measurements.*

Figure 4 shows the fill factor of CIGS solar cells with different final copper concentration in the CIGS layer. It was possible to prove that a variation of the [Cu]/([Ga]+[In]) ratio between 0.75-0.85 has no impact on the performance of the CIGS solar cells. This is an important result for the control of the 3rd stage length and for less stringent control of Cu evaporation rate during the 2nd stage of the multistage co-evaporation process.

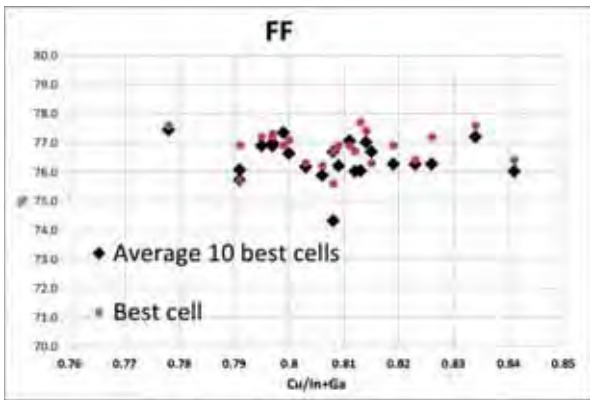
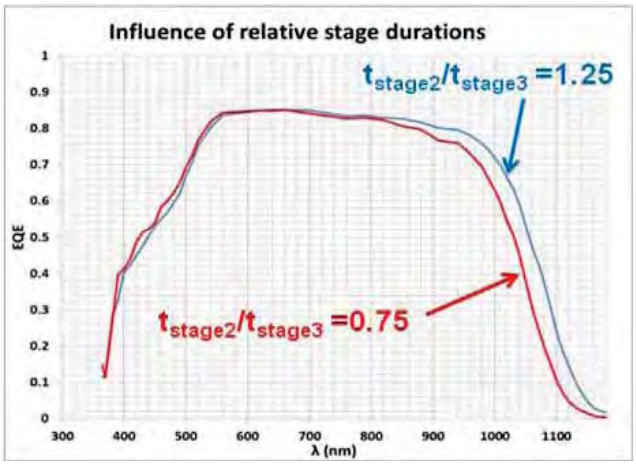


Figure 4: *Impact of average [Cu]/([Ga]+[In]) ratio on FF. The ratios were determined from XRF measurements.*

The impact of the variation of the duration of different stages of the multistage evaporation process is shown in figure 5. In a in-line equipment, this duration would be equivalent to the length of an evaporation zone and therefore very important parameter for the design of the equipment. A change of the relative stage durations has a large influence on the Ga content and also on the Ga grading across the layer thickness. This can be observed in the shifted EQE curve of the sample t_{stage2}/t_{stage3}=0.75 and the higher [Ga]/([Ga]+[In]) ratio shown in the table. The Jsc and the fill factor of the sample are lower leading to lower overall efficiency. This result shows that the last evaporation zone (here named stage3) has a very critical influence on the device performance and, therefore, proper planning of the dimensions and evaporation profile in that particular zone is essential.



Best cell parameters					
t_{stage2}/t_{stage3}	V_{oc} [V]	J_{sc} [mA/cm²]	FF [%]	Efficiency [%]	Ga/In+Ga
1.25	0.701	31.9	77.7	17.3	0.34
0.75	0.712	30.8	75.7	16.6	0.36

Figure 5: *Influence of duration of the 2nd and 3rd stage, and therefore average [Cu]/([Ga]+[In]) ratio, on quantum efficiency profiles of solar cells. The ratios were determined from XRF measurements.*

National and international cooperation

Part of the presented work is (co)-financed by a FP7 project "R2R-CIGS". The European consortium consists of 4 research institutes (TNO, Netherlands; Empa, Switzerland; ZSW, Germany; CPI, UK) and 6 companies (Manz CIGS GmbH, Germany; Flisom, Switzerland; Isovoltaic, Austria; Beneq, Finland; Solaytec, Netherlands; Mondragon Assembly; Spain).

Evaluation 2012 and Outlook 2013

We encountered challenges related to the non-availability of suitable vendors to construct the customized roll-to-roll pilot system to our specifications within the approved budget and the desired timeframe. The response of companies indicated difficulties for reliable and economical procurement of some crucial components needed for the customized development of the pilot system. Long delivery time of the equipment by some companies was another problem. Therefore, we thought it is necessary to reconsider the execution plan of the project and concluded that certain modifications in the original proposal will be beneficial.

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HIPO-CIGS: NEW CONCEPTS FOR HIGH EFFICIENCY AND LOW COST IN-LINE MANUFACTURED FLEXIBLE CIGS SOLAR CELLS

Annual Report 2012

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ABSTRACT

The EU project hipo-CIGS project aims at the development of cost efficient flexible solar cells and modules based on the compound semiconductor CIGS. Efficiency and cost limitations in state-of-the-art flexible CIGS solar cells have been identified and solutions were elaborated for each step in production and each layer of the multilayer structure in order to overcome these limitations. For accomplishing these tasks a European consortium of leading R&D institutes and industries was established. Topic of the reporting period was the investigation of sodium incorporation into the CIGS layer during different deposition stages and its impact on device performance. A post deposition treatment after the CIGS process proved to be most effective.

Using a novel multi-stage CIGS deposition process and the PDT method for sodium incorporation solar cell efficiencies towards 19% have been achieved on two different flexible and lightweight substrates. Also on other flexible substrate materials promising results have been obtained.

Another topic during the reporting period was the investigation of reduced CIGS deposition time and layer thickness. Based on the obtained results it is suggested that a deposition time of 6’ is possible with efficiency of approximately 15%, and further improvement and optimization should lead to an even shorter deposition time, for an absorber with 1 µm thickness and with efficiency above 16%.

Introduction and Project Goals

The Cu(In,Ga)Se2 (CIGS) on glass technology is already heading towards industrial maturity, but to meet the production cost target of below 0.6 Euro/Wp in mid-term and below 0.4 Euro/Wp in long-term, development of highly efficient flexible modules is an attractive option.

The ultimate advantage of thin-film technologies is the possibility of monolithically connected flexible modules produced with high speed roll-to-roll manufacturing systems. Transfer of a “static deposition” process to “in-line deposition” on moving substrates brings additional challenges for control of layer composition and interfaces. Choices of an appropriate substrate and deposition process to overcome problems related to thermal mismatch induced stress are important for high performance and monolithic cell interconnection.

The main goal of the project is to develop innovative flexible substrates and deposition processes that are suitable for the in-line and/or roll-to-roll production of highly efficient solar modules using thinner (< 1 micron) CIGS absorbers and with potential for production costs below 0.6 Euro/Wp in future. The objective will be achieved by developing novel concepts in growth of “high quality” layers and interfaces for efficiency improvement, aiming a new world record efficiency of 16% on PI and low-cost metal (mild steel and alumina) foils. Also, the implementation of in-line compatible buffer layers, improvements in interconnection technologies and application of multifunctional top layer will lead to advancement towards roll-to-roll manufacturability of integrated solar modules. This project will help research institutions to maintain a global lead in the CIGS field and will enable the European industries to implement the research excellence in industrial production of low cost flexible CIGS solar modules in future.

In order to achieve the challenging aims and objectives of this project a European consortium consisting of 8 partners from R&D and industry was established and is coordinated by ZSW (Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Germany).

The project is divided into seven work packages covering activities on flexible substrates (WP1), back contact and Na supply (WP2), CIGS deposition (WP3), buffer layers (WP4), interconnections (WP5), TCOs (WP6), and assessment of results (WP7). Empa is contributing to WP1-4 with the following goals for the reporting period:

- Incorporation strategies for Na on polyimide, Al and stainless steel substrate.
- To reduce the CIGS deposition time by applying higher growth rates.
- To reduce the CIGS absorber thickness below 1µm with less than 10% relative loss in performance in order to minimise material consumption and material waste.

Work and Results

Incorporation strategies for Na on polyimide, Al and stainless steel substrate

The addition of sodium is well-known to improve the performance of CIGS solar cells. The most common method to introduce Na into the CIGS layer is by diffusion from a Na containing substrate (e.g. soda-lime glass). However, when using Na-free substrates such as polyimide, aluminum or stainless steel foils Na has to be supplied from a different source. EMPA is following a strategy to add Na from an additional NaF evaporation source in the CIGS deposition chamber. This allows adding Na before, during or after, so-called post deposition treatment (PDT), the CIGS growth process in a very controlled manner. Because Na influences the interdiffusion of the elements during the CIGS growth the timing of Na addition has to be optimized with respect to the evaporation profile of the other sources Cu, In, Ga, and Se.

The most common way to produce a CIGS layer is a three-stage process, where in the first stage In and Ga are deposited onto the Mo coated substrate. In the second stage Cu is added until the layer becomes Cu-rich. After adding some excess Cu, the layer is again transformed back to finally Cu-poor composition by adding again In and Ga in the third stage. Selenium is present during the whole deposition process. Table 1 shows the PV performance of solar cells where identical amount of Na was added either during 1st, 2nd, 3rd stage or by post deposition treatment (PDT). For the CIGS deposition a low temperature three-stage process was used [1]. Clearly, the addition of Na either during the 3rd

stage or as PDT results in best PV performance. Note that for the device with Na supplied during PDT an additional anti-reflective coating was applied, which increases the J_{sc}. The reason for the lower performance of device in case Na was added during 1st or 2nd stage is the formation of a more pronounced [Ga]/([Ga]+[In]) gradient, which increases recombination in the CIGS layer [2,3].

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	Eff [%]
1st	605	30.5	66.2	12.2
2nd	638	30.8	68.5	13.5
3rd	683	31.8	75.4	16.4
PDT	688	34.7*	73.6	17.6

Table 1: *Influence of adding sodium during or after CIGS deposition, using a 3-stage process, on PV performance. An anti-reflective coating was applied on the device with Na PDT.*

Recently Empa developed a multi-stage process, which is a modification of the three-stage process where the evaporation rates of the individual sources is no longer constant during each stage and In/Ga is also added during the 2nd stage. This results in a smoother [Ga]/([Ga]+[In]) gradient in the CIGS layer compared to the standard 3-stage process and therefore to less recombination [3]. Again Na was added during one of the “three stages” or as a PDT using the multi-stage process. As shown in table 2 only the device with Na PDT shows high performance in case of the multi-stage CIGS deposition process. The lower performance of the device where Na was added during CIGS deposition is mainly due to loss in J_{sc} (all devices were coated with an anti-reflective layer) and V_{oc}, which is again attributed to reduced elemental interdiffusion in the presence of Na.

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	Eff [%]
1st	633	23.6*	73.8	11.0
2nd	630	24.2*	74.2	11.3
3rd	659	24.9*	73.9	12.1
PDT	692	31.8*	76.0	16.7

Table 2: *Influence of adding sodium during or after CIGS deposition, using a multi-stage process, on PV performance.*

The results shown above emphasize that sodium supplied by post deposition treatment yields highest efficiency solar cells, for low temperature processed CIGS solar cells on sodium free substrates. With this knowledge CIGS solar cells were also produced on other Na-free substrates listed in table 3. The lower PV performance of cells on Al and mild steel (low carbon steel) substrates is attributed to impurity diffusion from the substrate into the CIGS layer (c.f. [4]).

Substrate	V_{OC} [mV]	J_{SC} [mA/cm^2]	FF [%]	η [%]
Polyimide	712	34.8	75.7	18.7
Stainless Steel	705	34.4	77.2	18.7
Aluminium	679	33.5	75.1	17.1
Mild Steel	667	30.1	72.4	14.5

Table 3: *Best cells achieved with PDT on different substrate materials*

Reduction of CIGS deposition time and layer thickness

A possible strategy to reduce production cost of CIGS solar modules in a roll-to-roll or inline manufacturing system is to reduce the thickness of the absorber layer. Standard high efficiency cells usually have a thickness of 2-3 µm, even though only 1 µm is necessary to absorb all the incoming light from the sun. Decreasing the absorber thickness would not only reduce the material consumption, but also offer a decrease in deposition time, therefore leading to a higher production throughput.

Up to now, reducing the thickness while maintaining high performance has been very challenging. It remains unclear how the standard deposition process for thicker absorber should be adapted for thinner absorber layers. Modified Ga grading profile, poorer microstructure, shunt paths, scribing issues, as well as incomplete light absorption for thickness <1µm are problems that have to be understood in order to obtain highly efficient devices with reduced absorber thickness.

Empa's low-temperature multi-stage process has been adapted to deposit thin absorbers on flexible polyimide substrates, aiming at solar cell efficiency above 15% for absorber layers with thickness ≤1µm. Sodium was added by post-deposition treatment. The amount of Cu-excess has been varied, in order to actively shift the Ga-dip position and heights, as well as allowing a longer time for 3rd stage and recrystallization. Results obtained for absorbers with thickness of approximately 0.8 µm are given in table 4. It has been found that lower Cu excess leads to higher performance, as already observed for state-of-the-art high efficiency devices. A 20% decrease in efficiency is seen compared to a reference sample. Quantum efficiency measurements also show that some absorption losses occurred, and that the minimal band gap of the absorber shifted to higher values for thin absorbers. This finding is confirmed by SIMS measurements, where the Ga-profile of the absorbers shows a much less pronounced double Ga-grading as compared with thicker absorbers.

Best cell parameters					
Cu excess	**Thickness [µm]**	**V_{oc} [mV]**	**J_{sc} [mA/cm^2]**	**FF [%]**	**Efficiency [%]**
Reference	2.78	676	32.7	77.1	**17.0**
25%	0.81	627	29.5	73.9	**13.6**
50%	0.70	611	28.3	73.7	12.8
75%	0.79	578	29.6	69.0	11.8

Table 4: *Influence of Cu excess during a modified 3-stage process on PV performance.*

Based on the results discussed above, further experiments have been conducted in order to actively modify the Ga-profile and find out the influence of [Ga]/([In]+[Ga]) ratio, as well as final Cu content. A Cu-excess of 5% has been used, and In and Ga ramps added, as done standardly in our state-of-the-art multi-stage process. It was not possible to significantly modify the quantum efficiency curve, but the losses in longer wavelength region could be reduced. Table 5 shows the PV performance of 3 samples with thicknesses between 0.8 and 1.3 µm. It can be seen that V_{oc} and FF can be maintained even for sub-micrometer absorbers, with an efficiency of 15.4% achieved for a thickness of 0.88 µm. The high FF also gives information on the high quality of the junction.

Best cell parameters				
Thickness [µm]	**V_{oc} [mV]**	**J_{sc} [mA/cm^2]**	**FF [%]**	**Efficiency [%]**
2.7	676	32.7	77.1	**17.0**
1.24	681	32.0	74.8	**16.3**
1.06	683	30.4	74.4	**15.5**
0.88	664	29.9	77.3	**15.4**

Table 5: *PV performance for different thicknesses, using a modified multi-stage process developed for thinner absorber layers.*

Furthermore, it should be noted that efficiency above 16% has been obtained with a thickness of 1.24 µm only, while the original goal of the hipoCIGS project was to reach 16% for standard thickness. This reflects the significant progress that has taken place in the field of low-temperature processed CIGS solar cells on flexible substrate over the past years, not only from the processing point of view, but also in understanding the device physics. Empa has reached world record efficiencies on different flexible substrates, as for example seen in figure 1.

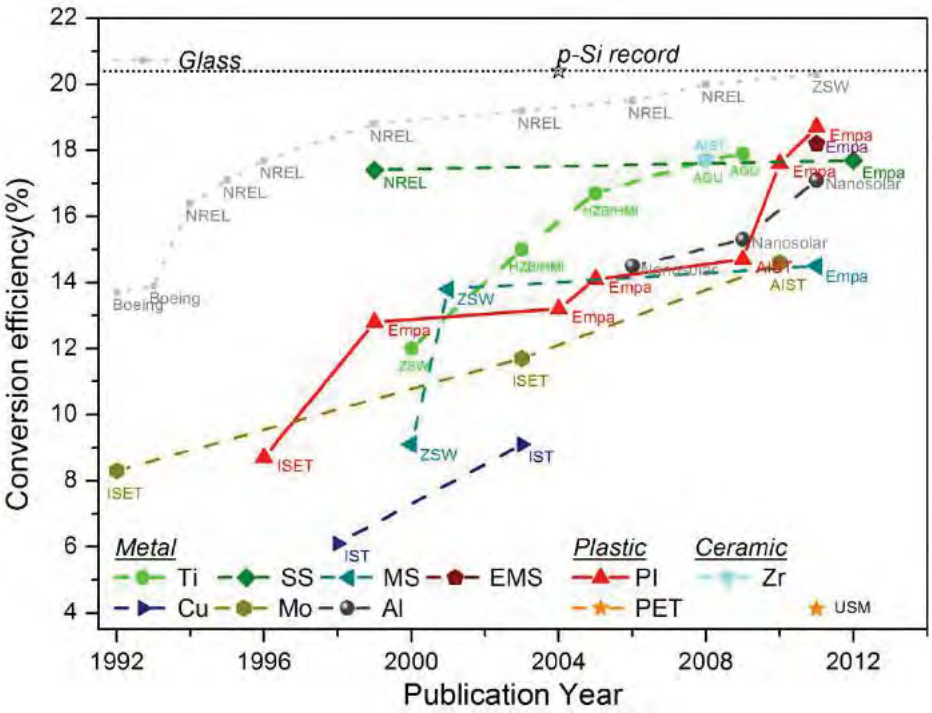

Figure 1: *Evolution of record efficiency for CIGS technology on different substrates (adapted from [5])*

In order to decrease the deposition time further, increasing the deposition rate of each stage is a very interesting strategy. It has been shown previously that deposition rate of 1st and 2nd stage can be increased without any detrimental influence on final device performance. However, higher rates in the 3rd stage were shown to be critical for our multi-stage process [6]. Combining higher rates with thinner absorbers is then a good strategy to increase the manufacturing throughput further, and leads to a deposition time under 10 minutes. Deposition rates have been increased up to 4 times for each stage (always keeping the 2 others at a standard rate) in order to investigate the influence on final device

properties. Limitations in our machine setup does not allow us to carry out such experiments for all stages simultaneously, because the sources and temperature detectors do not/cannot react fast enough to ensure a sufficient process control. Nevertheless, it has been found that increasing rates can lead to increased performances compared to the reference thin absorber, most probably by modifying the absorber compositional profile. An efficiency above 15% for an absorber thickness of 0.9 µm has been achieved for an absorber grown with a 3-fold deposition rate in the 2nd stage. No degradation of the performance has been observed, even if deposition times of 2', 1'20 and 2'30 are used for the 1st, 2nd, or 3rd stage, respectively. A deposition time of 6' is therefore possible with efficiency of approximately 15%, and further improvement and optimization should lead to an even shorter deposition time, for an absorber with 1µm thickness and with efficiency above 16%.

National / international Cooperation

The consortium of the EU-FP7 hipo-CIGS project consists of four R&D partners ZSW (Germany) TNO (Netherlands), Technical University of Warsaw (Poland), and Empa (CH) and four industrial partners Flisom (CH), Tata Steel (Netherlands), Pemco (Belgium), and Würth Solar (Germany).

Appraisal 2012

A post deposition treatment (PDT) proved to be most effective for the incorporation of sodium into the CIGS layer processed with low-temperature deposition method. Using a novel multi-stage CIGS deposition process and the PDT method for sodium incorporation solar cell efficiencies towards 19% have been achieved on two different flexible and lightweight substrates. Also on other flexible substrate materials promising results have been obtained.

An efficiency of 15.4% has been achieved with an absorber thickness of 0.9 µm. Lower Cu-excess during deposition leads to better performance. Modifying the evaporation profile of Ga and In by adding ramps in 1st and 3rd stage does not lead to a performance increase.

An efficiency of 16.3% has been achieved with an absorber thickness of 1.2 um, satisfying the objective for flexible solar cell efficiency of the hipoCIGS project even with an absorber with decreased thickness. Increasing the deposition rates of each separate stage up to 4x is found to positively impact the performance of devices with thinner absorber layers. By combining higher rates and thin absorbers, it is shown that a deposition time below 10 min is feasible without significant losses in efficiency.

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NOVA-CIGS: NON-VACUUM PROCESSES FOR DEPOSITION OF CIGS ACTIVE LAYER IN PV CELLS

Annual Report 2012

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ABSTRACT

Current production methods for thin film photovoltaics typically rely on costly, difficult to control (over large surfaces) vacuum-based deposition processes that are known for low material utilization of 30-70%. EU project NOVA-CIGS proposes alternative, non-vacuum deposition processes for thin film $Cu(In,Ga)Se_2$ (CIGS) photovoltaic cells. The low capital intensive, high throughput, high material yield processes will deliver large area uniformity and optimum composition of cells.

The overall project goal is to develop an ink based, simple and safe deposition process of the CIGS absorber layer for highly efficient low cost solar cells. Major scientific breakthroughs of the project include improved materials control in novel precursor materials by using nano-sized precursors of specific chemical and structural characteristics and innovative ink formulation, to enable coating by printing processes while avoiding the use of toxic gases or solvents in subsequent process steps.

Specifically, research work at Empa is focused on the deposition and activation of CIGS layers from formulated precursor suspensions and solutions, providing a feedback to the project partners engaged in precursor materials and ink formulation, and preparing background for large area solar cells and industrial implementation.

During the third project year, selected Cu-, In, and Ga-containing hydroxide nanoparticle dispersions were received from projects partners, and deposited on rigid Mo-coated substrates by means of knife-coating and printing, and activated in selenium atmosphere to yield the CIGS absorbers. Reactivity of individual hydroxide nanoparticle dispersions as well as reaction kinetics during the selenization step have been studied in order to access the formation of intermediate Cu-rich phases during the evolution of the main CI(G)S phase. A novel multilayer, stacked approach has been tested in order to promote the grain growth via a local formation of highly mobile Cu-Se phases. An improved sintering has been observed, although induced voids in the selenized layer as well crystalline segregations on the surface limited the conversion efficiency to 6%.

Introduction and project objectives

Concept

Photovoltaics (PV) is a key technology option to meet the rising demand for energy and counter rising energy prices whilst reducing CO_2 emissions and encouraging energy independence in Europe. However, the dominating crystalline silicon (c-Si) technology remains expensive, and it is also comparatively energy intensive to manufacture and results in rigid and heavy devices. A radically different step-change concept is required to become competitive with fossil-based energy.

With 100 times thinner absorbers than conventional c-Si wafers, the emerging inorganic Thin Film (TF) PV technology uses only small quantities of semiconductor material to achieve viable cell efficiencies, allowing light weight and flexible modules. There are three major families of inorganic TF PV: i) amorphous / micro crystalline silicon (a-Si/micro-Si), ii) Cadmium Telluride (CdTe) and iii) Copper Indium Gallium Diselenide (CIGS) and Copper Indium Sulfide (CIS).

The current deposition process for TF PV relies on well-known vacuum-based sputtering or co-evaporation technologies. Whilst allowing controlled deposition of high purity thin layers, these techniques experience limitations such as high investment and operating costs, low throughput, low materials yield and high energy consumption, amongst others. This leads to TF PV module costs of about 1-1.5 $/Wp.

However, TF PV has significant cost reduction potential. Thin layers can be applied by non-vacuum deposition processes such as printing, which are low capital intensive, exhibit high throughput, high material yield and are suitable for roll-to-roll processes that deliver large area uniformity and optimum composition. The EU PV Technology Platform suggests that development of such technology should lead to medium term (2013-2020) TF module cost of around 0.8 $/Wp.

The feasibility of this method was shown by companies ISET and Nanosolar that reported CIGS solar cells with 13.6% and 17.1% efficiency, respectively [1,2] by printing pastes containing oxide nanoparticles. Kaelin et al. reported 6.7% efficient cells in 2005 [3] by selenization of metal salt solution pastes, which has been recently improved to 7.7% by Uhl et al. [4]. Todorov et al. utilized hydrazine as a solvent reaching an efficiency of 15.2% [5], but the industrial implementation might be hindered due to the toxic and explosive nature of hydrazine.

Global project objectives

The goal of NOVA-CI(G)S is to develop an ink based non-vacuum, simple, and safe deposition process of the CIGS absorber layer for highly efficient low cost solar cells. The CIGS absorber is the core of the solar cells, and also the most scientifically challenging and most cost intensive layer to produce. The project aims to demonstrate the following:

1. Non-vacuum deposition of the CIGS layer is possible whilst maintaining high efficiency.
2. Non-vacuum deposition of CIGS layers can be realized at high speed on rigid and flexible substrates whilst maintaining acceptably high efficiency on assembled cells.

The overall aim being to make a significant impact on reducing the cost of the CIGS layer and pave the way to future development addressing the device's adjoining layers with a similar fully integrated low cost deposition process ultimately achieving a CI(G)S TF module cost of below 0.8 €/Wp.

Specific research objectives at Empa

Research work at Empa is focused on the deposition and activation of CIGS layers from formulated precursor suspensions and solutions, providing a feedback to the project partners engaged in precursor materials and ink formulation, and preparing background for large area solar cells and industrial implementation. Three specific work packages at Empa are:

1. layer deposition
2. layer activation
3. solar cell processing and characterization

The layer deposition is optimized individually for each precursor material for a good adhesion of the precursor layers and homogeneous film formation. This work is important for large-area deposition and the development of solar modules. The starting point is the raw precursor material which has to be converted effectively into an efficient photoactive layer upon thermal annealing, with or without

addition of chalcogen. The deposition process is a means to transfer the precursor to the substrate to achieve a thin precursor layer. By nature, printing processes are likely to introduce potential contaminants, which need to be accounted for. Therefore, an intensive iterative process takes place throughout the project for the materials synthesis, ink formulation layer conversion and deposition process to ensure that the layer is correctly applied, that there is minimal interference by ink formulation chemistry, the layer has adequate adherence, optimal chemistry and crystallography / phase structure.

The layer activation via thermal treatment is required in order to transform printed precursor layers into crystalline CIGS absorbers with correct composition, homogeneity and morphology. Usually a two-step method is applied to first sinter the precursor at 200-300°C in order to remove solvent and binder material and to densify the precursor. In most cases an additional selenization/sulfurization step at higher temperatures (500-600°C) in a closed reactor furnace with Se/S atmosphere will be necessary. The selenization conditions (partial pressure of Se, temperature ramps, annealing time, etc.) must be optimized to obtain single phase CIGS layers of optimum structural and opto-electronic properties. Depending on the precursor material, especially depending on its selenium content (pure metals without selenium or binary selenide compounds), the selenization or conversion process has to be adapted. Rapid thermal processing (RTP), which offers fast heating rates, will be tested in order to avoid detrimental reaction pathways during layer activation and increase processing speed.

Methodology

The non-vacuum deposition of CIGS absorbers can be divided into four steps (see Figure 1). A suitable precursor paste is formulated from nanoparticle dispersions. The paste is then transferred on a molybdenum coated substrate by means of a non-vacuum technique. Dispersions were applied on molybdenum coated soda-lime glass (SLG) by knife blading technique or ink-jet printing. Various coating defects were observed for dried precursor films, and respective measures were taken in order to obtain homogeneous, pin-hole free layers. Consecutive drying on a hotplate or drying lamp in ambient or inert atmosphere facilitates the evaporation of solvents and chemical additives. In a last step CIGS phase is obtained via a heat treatment at 500-600°C in selenium atmosphere. Standard selenization was carried out in a two temperature zone tubular furnace. The precursors are thereby exposed to reactive Se vapors that are carried onto the substrate by a N_2 gas flow. While all steps are important for a successful absorber deposition this work will mainly focus on the paste formulation and optimization of the CIGS conversion.

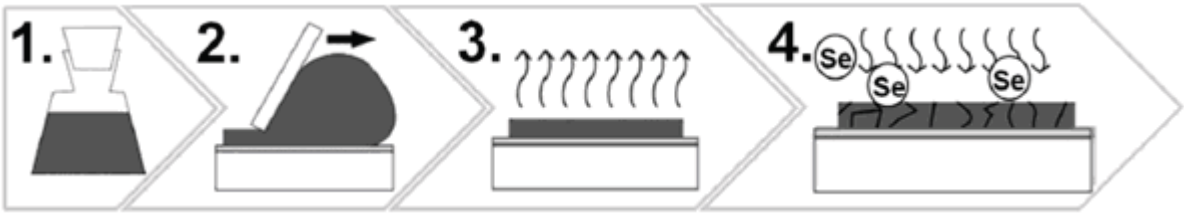

***Figure 1**: CIGS formation steps: 1) precursor formulation, 2) non-vacuum deposition, 3) drying in ambient atmosphere to remove solvents, 4) selenization step to convert precursor into absorber layer.*

The morphology, phase and elemental composition of both precursor and selenized layers were evaluated using in-situ and ex-situ X-ray diffraction (XRD), scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDX), as well as X-ray fluorescence (XRF).

Performed work and results

Nanoparticle dispersions

Three individual nanoparticle inks based on Cu-, In-, and Ga-hydroxides were employed, allowing the stoichiometric adjustment of the final precursor layer by means of adequate mixing ratio or sequential processing. The inks were provided from project partners undergoing constant improvement in respect to ink chemistry, solid load, and amount of stabilizing agents.

Layer activation

Depending on the chemical coordination and type of metal used, a different reactivity towards selenium can be observed. Figure 2 shows the reactivity of individual Cu-, In-, and Ga-precursors during the exposure to the reactive Se atmosphere. As temperature increases in the furnace the compositional ratio of Se/Me increases as measured by XRF, indicating an incorporation of selenium and hence, conversion into respective selenide phases. It can be seen that Cu-particles exhibited highest reactivity followed by In and Ga.

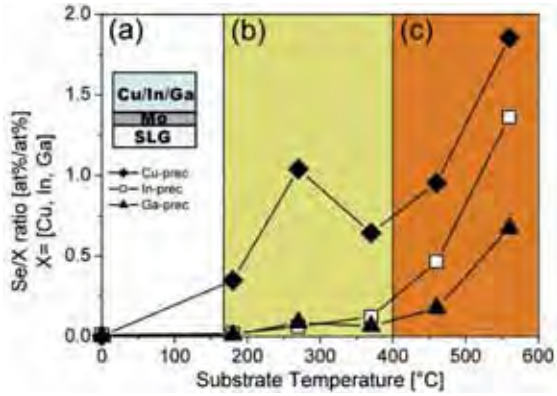

***Figure 2**: XRF determined chalcogen to metal ratios for individually selenized precursors. The highest reactivity with selenium is observed for the Cu-precursor, followed by In and Ga [6].*

Investigation of reaction kinetics

It is critical to observe and understand the involved crystalline modification of the involved metals to optimize the conversion process towards phase pure, large grained, and morphologically smooth material. Ex-situ and in-situ XRD characterization are valuable tools to investigate the formation of crystalline phases in respect to temperature and selenium atmosphere. During the selenization of Cu for instance, a multitude of different crystalline and stoichiometric phases can be promoted. Figure 3 shows the temperature evolution of various Cu-phases by ex-situ XRD and their corresponding SEM micrographs.

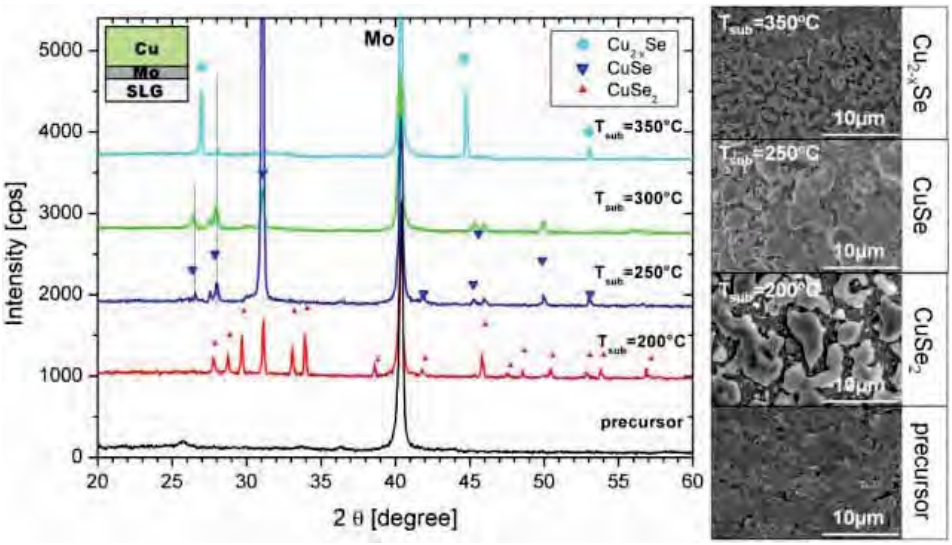

***Figure 3**: Ex-situ XRD shows changing Cu-Se phases from $CuSe_2$ to CuSe to $Cu_{2-x}Se$ with increasing temperature in agreement to the phase diagram. The microstructure is revealed by SEM. Large grains are apparent for $CuSe_2$ and CuSe [6].*

To further elucidate the origin of morphological changes, in-situ XRD measurements have been conducted. Figure 4 shows the temperature evolution of the respective diffractograms. Neglecting the carbon reflections from the graphite peak around 26.3° and 42.6°, the low temperature regime from 100 to 220°C is dominated by the crystallization of the Se top layer. Above that temperature, selenium is molten and available for metal conversion. The formation of $Cu_{2-x}Se$ is visible at around 270°C and

this phase remains until 440°C. The first CIS reflections appear around 300°C and are accompanied by $MoSe_2$ at around 440°C. The resulting films appear phase pure, containing CIS as the primary phase with $MoSe_2$.

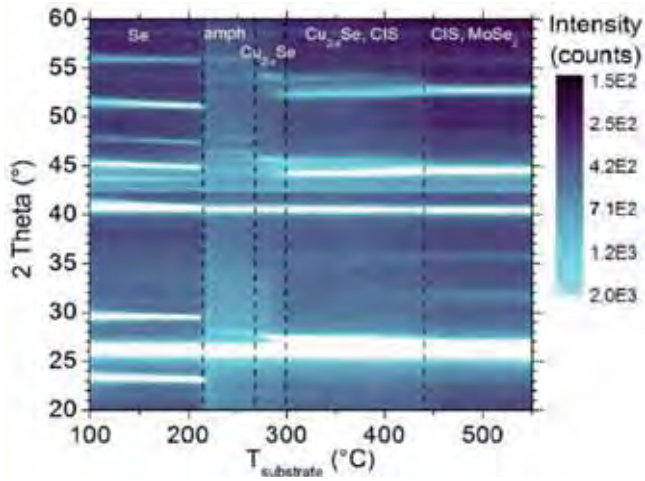

***Figure 4**: In-situ XRD measurements during selenization of precursor layer. These model experiments visualize the formation of binary selenides during the reaction to CIS. $Cu_{2-x}Se$ is formed between 270 - 440°C while $MoSe_2$ appears from 450°C onwards [7].*

Multilayer (stack) approach

Since it is well known that copper-rich selenide phases can improve grain growth, multilayer approach was tested. In this case, a locally Cu-rich layer in form of a Cu-precursor film was surrounded by a top and bottom layer of mixed Ga and In precursors. In comparison to results from mixed particle precursors, it is apparent in Figure 5 that the morphology significantly changed. Cross-section SEM images reveal a porous intermediate layer at the position of former Cu-precursor. While top-view SEM pictures indicate improved sintering of the top layer, large grained segregations of $CuInSe_2$ and $Cu_{2-x}Se$ – as confirmed by EDX – appear on the surface. Since Cu-Se appears to be more mobile than other phases, it is responsible for the void after selenization at the position of the Cu-layer as well as segregations on the surface.

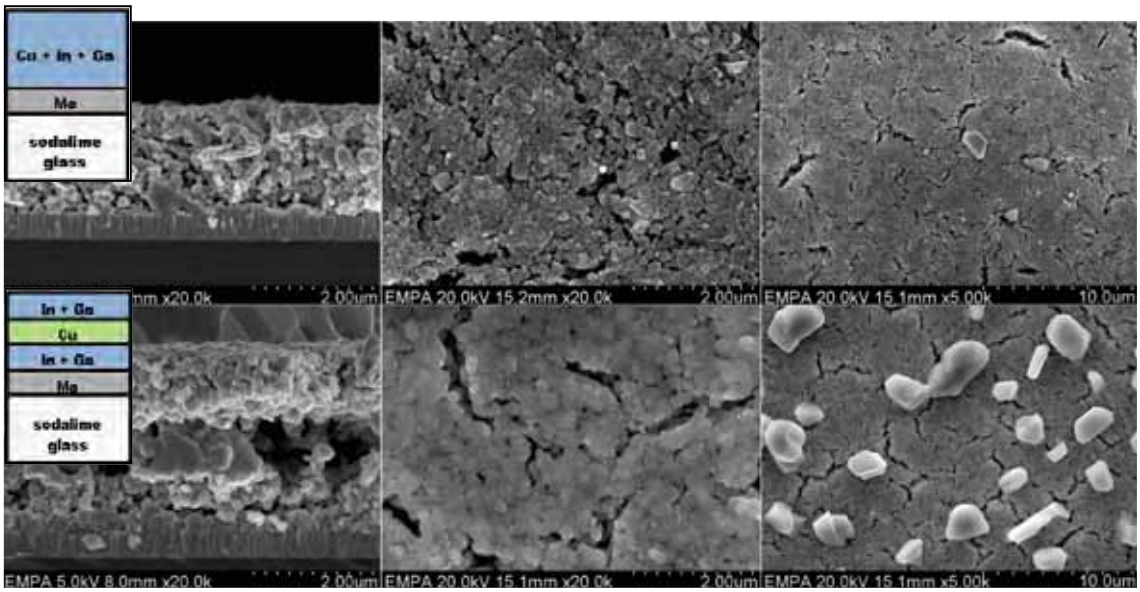

***Figure 5**: Comparison of mixed (top) and stacked (bottom) approaches as visible on in cross section (left) and top view (middle & right) SEM images of selenized CIGS absorbers. The presence of Cu-rich layer in the stack approach leads to the formation of highly mobile Cu-Se phases that leave the void behind and give rise to large-grain CIS and $Cu_{2-x}Se$ crystallites on the surface [7].*

Rapid thermal annealing (RTP)

In order to reduce the activation duration, as well as avoid the formation of undesired binary phases on the way towards the CIGS phase, a custom-designed rapid-thermal processing (RTP) system AS-One-150 was installed. Preliminary experiments indicated that the CIGS phase can be obtained very fast, only within 30-60 seconds after starting an RTP process. However, numerous parameters, such as temperature profiles, selenium supply, and operation pressure should be optimized to obtain the fastest and full conversion into CIGS layer, Figure 6.

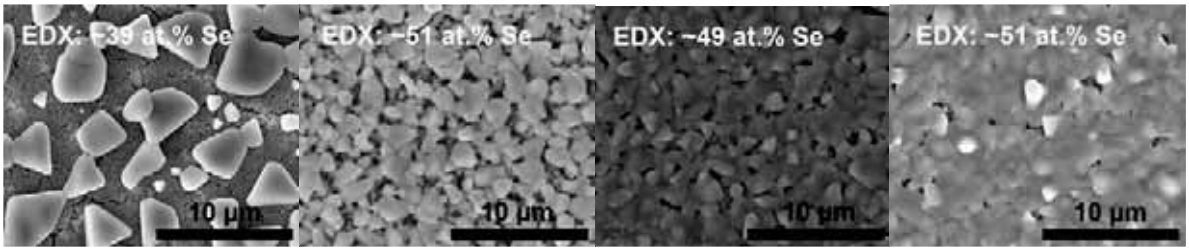

***Figure 6**: Top view micrographs of precursor layers selenized by various RTP processes. Various topological morphologies can be produced. An optimized process (most right) exhibits a dense, sintered layer with only a few pin-holes and an adequate Se content of >50 at%.*

Solar cell fabrication

Selected CIGS absorbers were coated with a CdS buffer layer by chemical bath deposition and an i-ZnO/ZnO:Al window bi-layer transparent contact by RF magnetron sputtering. After mechanical scribing to define individual cells, current-voltage (I-V) and quantum efficiency (QE) measurements were performed under simulated AM1.5 global illumination. Figure 7 shows one of the first solar cells, based on the CIGS absorber processed from nanoparticle precursor, yielding 4.8% and 5.8% conversion efficiency for mixed and stacked approaches, respectively.

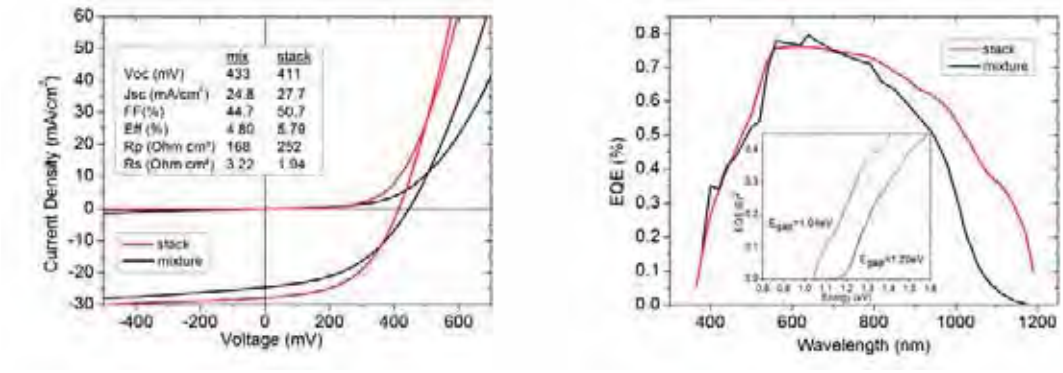

***Figure 7**: I-V characteristics (left) and QE response (right) of a CIGS solar cell processed from nanoparticle precursors. As seen by the long wavelength behaviour, the absorption edge can be tailored by varying the precursor from mixed to stacked (see Figure 5). Solar cell efficiencies up to 6% could be achieved [7].*

National and international collaboration

The project Consortium includes four academic-research partners and four industrial partners:

* Umicore S. A., Brussels, Belgium (coordination)
* Eidgenössische Materialprüfungs- und Forschungsanstalt (Empa), Switzerland
* FLISOM AG, Switzerland
* Zentrum für Sonnenenergie und Wasserstoffforschung (ZSW), Stuttgart, Germany
* Würth Elektronik Research GmbH, Stuttgart, Germany
* VTT Technical Research Center of Finland
* Technische Universität Chemnitz, Germany
* Xennia Technology Ltd., Letchworth, UK

Empa is collaborating intensively with ZSW to elaborate different routes for post deposition annealing and selenization, as well as concepts of defining optimum structural, compositional and electronic properties of absorber layers.

Conclusions 2012 and Outlook 2013

- Reactivity of individual hydroxide nanoparticle dispersions as well as reaction kinetics during the selenization step have been studied in order to access the formation of intermediate Cu-rich phases during the evolution of the main CI(G)S phase.
- A novel multilayer, stacked approach has been tested in order to promote the grain growth via a local formation of highly mobile Cu-Se phases. An improved sintering has been observed, however induced voids in the selenized layer as well crystalline segregations on the surface should be avoided.
- Solar cells with conversion efficiency of up to 6% have been fabricated using the stacked approach.

In the remaining 6 months of 2013 main efforts will be directed for achieving solar cells with efficiency exceeding 10% using optimized nanoparticle dispersions and rapid thermal annealing procedure.

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ROLL-TO-ROLL MANUFACTURING OF HIGH EFFICIENCY AND LOW COST FLEXIBLE CIGS SOLAR MODULES (R2R-CIGS)

Annual Report 2012

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Date	17.12.2012

ABSTRACT

Thin film solar cells with Cu(In,Ga)Se2 (CIGS) compound semiconductor as absorber material show excellent efficiency and with proper encapsulation long term performance stability. CIGS solar module technology on rigid glass substrate is already mature and industrial companies are producing hundreds of MWp each year. Bringing flexible CIGS solar modules to industrial maturity will yield the next breakthrough for further cost reduction by taking into account the inherent advantages of thin film technology, e.g. high throughput and large scale coating with less energy and material consumption. Record efficiencies of 18.7% have been achieved for lab-scale flexible CIGS solar cells on polymer substrate with front and back interface properties of the CIGS controlled on nanoscopic range. The project R2R-CIGS will contribute to industrial large scale production of flexible high efficiency CIGS solar cell devices based on processes for roll-to-roll manufacturing. The aim is to develop efficient solar modules by implementing innovative cost-effective processes such that production costs below 0.5 €/Wp can be achieved in large volume factories with annual capacity of 500MWp in future.

Introduction and Project Goals

The project R2R-CIGS will contribute to industrial large scale production of flexible high efficiency CIGS solar cell devices based on processes for roll-to-roll manufacturing. The aim is to develop efficient solar modules by implementing innovative cost-effective processes such that production costs below 0.5 €/Wp can be achieved in large volume factories with annual capacity of 500MWp in future. This ambiguous target will be achievable when the efficiencies of flexible solar cells are comparable to those based on glass substrates and high throughput process with less energy and material consumption are implemented.

An important objective for meeting this target is to achieve 20% cell efficiency and to develop 16% module efficiency on flexible substrate in order to demonstrate the technical potential and to reach comparable performance to CIGS technology on glass. On large area solar module level the roll-to-roll (R2R) manufacturability of monolithically interconnected cells has to be demonstrated for achieving high efficiency modules with long term performance stability.

For cost-effective manufacturing some of the bottleneck problems have to be solved including but not limited to: Chemical bath deposition (CBD) of CdS should be substituted by a deposition method for Cd-free buffer layer which is more compatible to R2R production. Moisture barrier coatings for efficient and low-cost encapsulation should be developed to overcome the problems of efficiency degradation due to corrosion of electrical contacts. Improvements in the current state-of-the-art will be achieved by implementing the concepts of nanotechnology in terms of modification in the structural, chemical, and electrical characteristics on nano-scale range for improving the CIGS absorber, buffer layer, TCO and encapsulation. Control of properties of surfaces and interfaces on nano-scale will be the most important aspect for achieving high efficiencies and stable performance of solar cells. These concepts, especially of buffer-, barrier-, and TCO- layers have already shown encouraging results for technologies based on rigid glass, however, some of them need further development for roll-to-roll manufacturing.

A key advantage of thin film solar cells is the monolithical interconnection, successfully implemented on glass but still a challenging task for flexible substrates. Although preliminary results are shown, further development is needed for improving the patterning technique and reducing the losses due to laser-material interactions.

The knowledge gained in this project, based on some innovative concepts that have shown promising results, will be transferred to pilot line scale and for industrial production.

The main objectives of Empa in this project are:

- Flexible solar cells on polymer film with 20% efficiency and mini-module with 16% efficiency by control of composition gradient, surface, and interface properties on nano-scale
- Transfer of innovative buffer layer process for roll-to-roll manufacturing and replacing problematic CBD-CdS by higher yield processes such as ultrasonic spray
- Scale-up of static multi-stage CIGS deposition process from laboratory scale towards inline R2R compatible processes
- Implementation of the up-scaled multi-stage CIGS deposition process into pilot lines yielding flexible CIGS modules with 14% efficiency from R2R manufacturing

The consortium of this project includes 4 European research institutes and 6 European industries and SMEs:

1. TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek), Netherlands
2. Empa (Swiss Federal Institute for Materials Science and Technology), Switzerland
3. Manz CIGS GmbH, Germany
4. Flisom AG, Switzerland
5. ZSW (Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg), Germany
6. CPI (Centre for Process Innovation), UK
7. Isovoltaic GmbH, Austria
8. Beneq Oy, Finland
9. SoLayTec, Netherlands
10. Mondragon Assembly Coop., Spain

Work and Results

Nanostructures and surface modification by USP

Ultrasonic Spray Pyrolysis (USP) is a suitable method for nano-structured buffer layer deposition in chalcopyrite based solar cells. With this method, a layer is formed on a heated substrate through a chemical reaction of thermally decomposed precursors. The reactants, delivered to the heated substrate surface, are dissolved in a solution which is nebulized to small droplet of micron-size range. The droplets are either generated by a pneumatic nozzle (high droplet velocity and broad distribution in droplet size) or by an ultrasonic actuator (low velocity and narrow distribution of droplet size)

The deposition of homogeneous and compact In2S3 and ZnS nano-structures with continuous substrate coverage has been proven at EMPA with deposition temperature around 200°C. Impurities of extrinsic elements such as chlorine and oxygen can be minimized by increasing the temperature and amount of sulphur excess in the solution. However, the experiments showed that the elevated temperature which is necessary for the USP deposition amplifies oxygenation of the CIGS surface, i.e. selenium vacancies are filled with oxygen and with this, positive surface charges of the CIGS are reduced. This effect can be minimized by oxygen control during the deposition. Minimum copper excess, copper-poor finish and gallium reduction in the 3rd stage proved to be a CIGS absorber deposition procedure yielding reproducible results with USP-In2S3 buffer layer. With this process highest total area efficiency of 13.1% was achieved corresponding to 13.7% of the CBD-CdS reference device. With the application of a MgF2 anti-reflection coating, the total area efficiency of this CIGS solar cells is increased to 14.2% and the active area efficiency is 15.0%.

In the reporting period Empa modified the existing USP setup for better control of the abient before and during deposition and implemented the possibility of moving substrates.

Flexible CIGS solar cell with nano-scaled compositional grading

Within this task very high efficient flexible CIGS solar cells (~20%) will be developed. In order to achieve this goal the innovative process for nano-scaled composition grading from hipoCIGS will be optimized and fine-tuned in a first phase. In a second phase recombination at interfaces will be further reduced with nano-structured buffer layer at the front end and MoSe2 at the back end. Additionally, the devices will be optimized for optical losses with input from WP1-3. The progress with those two phases will lead to flexible CIGS solar cells with efficiency above 20%.

The purpose of this task is not only to increase the solar cell efficiency but more importantly to improve the robustness of the process. In hipoCIGS the focus is on reducing the absorber layer thickness as well as to increase the deposition rates (see annual report hipoCIGS). The output of those tasks will be very valuable for the process development in the R2R-CIGS project. In the R2R-CIGS project the focus is on the process parameters and determining the process window of the multistage deposition process in order to improve its robustness.

Expected results from this activity are the mentioned efficiency improvements towards 20% but more importantly the process know-how needed for designing the R2R multi-stage CIGS co-evaporation coater.

Nano-scaled composition grading of CIGS deposited on polyimide has been further investigated. A representative set of samples (more than 20) have given some more insight on the process window and process stability. Fluctuations in Ga content (therefore bandgap), final Cu content, thickness and relative stage durations have been observed. Cell efficiencies above 18% can be obtained for Ga/In+Ga contents between 0.33 to 0.39, for Cu contents of 0.78 to 0.84, and for thickness ranging from 2 to 3 um.

Some more understanding has also been gained about the influence of the different stage durations on the final nano-scaled compositional grading and final device performance. Good control of the different sources evaporation rates is nevertheless necessary to obtain a highly robust process. Further work is being pursued in order to increase device efficiency, improving not only the compositional nano-structuring of the absorber, but also the other layers of the device.

Development of R2R inline multi-stage CIGS deposition process[1]

Negotiations with possible suppliers for the R2R equipment for CIGS deposition are ongoing.

Appraisal 2012 and Outlook 2013

The FP7 R2R-CIGS has been launched in the first half of 2012. Most of the tasks in this project are related to the development of equipment and process for pilot production of CIGS thin film solar cells. Therefore the main activities in the reporting period were related to evaluation and design of new equipment. It is expected that the USP machine is available for experiments in the first half of 2013 and the R2R CIGS deposition equipment starts operation in the second half of 2013.

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[1] *Development co-financed by BFE P&D Project "CIGS MULTISTAGE IN-LINE PILOT MACHINE DEMONSTRATION" and Empa internal projects.*

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SCALENANO

DEVELOPMENT AND SCALE-UP OF NANO-STRUCTURED BASED MATERIALS AND PROCESSES FOR LOW COST HIGH EFFICIENCY CHALCOGENIDE BASED PHOTOVOLTAICS

Annual Report 2012

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Project- / Contract Number	SCALENANO / 284486
Duration of the Project (from – to)	01.02.2012 – 31.07.2015
Date	20.12.2012

ABSTRACT

SCALENANO aims at contributing to a further reduction of manufacturing costs of PV solar modules, in line with the 20/20/20 target established by the European Commission and the European Strategic Energy Technology Plan (SET-Plan). Cu(In, Ga)(S, Se)2 PV technologies, have already entered the stage of mass production. However, current production methods typically rely on costly, difficult to control over large surfaces, vacuum-based deposition processes which are known for lower material utilization of 30-50%. This compromises the potential reduction of material costs inherent to thin film technologies. At the forefront of this, SCALENANO will develop alternative environmental friendly and vacuum free processes based on the electro-deposition of nanostructured precursors. The project also includes the exploration and development of alternative processes with a very high potential throughput and process rate, as well as their extension to next-generation kesterite based absorbers that will allow the proposition of an industrial roadmap for the future generation of chalcogenide based cells and modules.

The status of the project is briefly reviewed.

Project partners

SCALENANO, **funded by the 7th Framework Program (Energy) of the European Union** with a budget of over EUR 10 million (CHF 12 mio.), is one of the largest R&D projects on PV ever funded by the EU. For its accomplishment an interdisciplinary consortium of 13 R&D groups was appointed. This comprises five research institutes, four universities and four companies from different industrial sectors. SCALENANO runs from February 1, 2012 to July 31, 2015.

- IREC (Research Centre, Spain, Coordinator)
- SUPSI (University, Switzerland)
- EMPA (Research Centre, Switzerland)
- IIT (Research Centre, Italy)
- Uni-Luxemburg (University, Luxemburg)
- Uni-Nottingham (University, UK)
- FUB Uni-Berlin (University, Germany)
- HZB (Research Centre, Germany)
- CEA (Research Centre, France)
- NEXCIS (SME, France)
- IMPT (SME, UK)
- MERCK (Industry, Germany)
- SEMILAB (SME, Hungary)

Involvement of SUPSI in the project

Within the project the **Institute for Applied Sustainability to the Built Environment Institute (ISAAC)** of SUPSI will actively help the industrial partners to scale-up the technology **from the solar cell to the module level**. SUPSI is in fact mainly involved and leads work-package WP5 (Scale-up processes: from cell to module) which started in m7 (August 2012).

Thin film solar modules: electrical layout

So far R&D activities have so far mainly regarded the optimization of the electrical layout of the module based on Nexcis' design (the so-called *hybrid interconnection* of cells).

This patterning approach, *hybrid interconnection* (HI) *of cells,* lies somewhere in between the traditional monolithical interconnection (MI) used for thin films and the tabbing of cells in c-Si modules.

When compared to the conventional MI, the *hybrid interconnection* provides the following advantage: as the laser or mechanical ablation comes only at the end of the deposition processes, there is no need to interrupt the deposition of the semiconducting layers for the P2 and P 3 cuts. This method would provide particularly valuable for vacuum-based processes. An additional advantage of this method is to be more flexible in terms of cell number and dimensions, and consequently in terms of output voltage and current.

SUPSI and NEXCIS are running in parallel simulations, which will then be cross-checked, for optimizing the module's output in terms of efficiency. Input parameters (material, solar cell's PV and diode parameters) were provided from Nexcis to Supsi.

Encapsulation of modules

Preliminary activity is on-going at Nexcis. Supsi has now purchased a laminator, which will be dedicated to this task. The laminator should be installed and operational in April 2013. Nexcis will provide SUPSI with un-encapsulated devices which will then test different encapsulant materials (EVA, PVB, ionomer, etc.). These devices will provide testing material for the ageing/stress tests, which in turn will provide a feedback to the encapsulation process.

Testing of PV modules

Moreover, the testing laboratory for PV modules (SPVMTC) at ISAAC will help assessing the performance (power, Wp), durability and energy-yield (kWh/kWp) of the devices manufactured within the project. Preliminary activities have already started.

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DURSOL

EXPLORING AND IMPROVING DURABILITY OF THIN FILM SOLAR CELLS

Annual Report 2012

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Duration of the Project (from – to)	01.01.2010 – 31.12.2013
Date	27.12.2012

ABSTRACT

Several Swiss research institutes work on the most promising thin film photovoltaic technologies such as silicon, cadmium-telluride, dye sensitized and organic solar cells. DURSOL's objectives are focussed towards the understanding of fundamental degradation phenomena in thin film solar cells. We use the competences of the partners to i) understand fundamental processes and microscopic origins of degradation phenomena; ii) modify materials properties of absorbers, electrical contacts, interfaces and device architecture such that degradation is suppressed; iii) exclude harmful external contaminants (oxygen, water) from reaching the active layers by using appropriate encapsulants and barrier coatings; iv) achieve long term stability and high performance of thin film solar cells, potentially at low production costs.

During the second year of this project, a highlight was the international workshop and conference on the durability of thin film solar cells held at Empa. A dye sensitized solar cell demonstrator was shown at the energy exhibition at the Swiss museum of transport. Important work was carried out on interface layers and aging studies, new test equipment was setup and progress in the electro-optical modeling of transient thin film solar cell experiments was made. The work has also led to a number of publications and awarded conference contributions.

Introduction

The direct conversion of sunlight into electricity using solar cells is a key technology for the sustainable energy supply of the future. Thin film solar cells are the fastest growing branch of the booming photovoltaic market. They can be fabricated using inorganic (a-Si, mc-Si, CdTe, CIGS) or organic (OPV, DSC) materials and they can be deposited on rigid or flexible substrates using large-scale compatible coating and printing processes. The main advantages of thin film solar cells over today's typical silicon wafer-based photovoltaic modules are flexibility and lower cost of production.

Thin film solar cell research is a quickly developing field and rapid progress is being achieved in all areas covering device design, upscaling and solar cell power conversion efficiency. The DURSOL project objectives are focused towards the understanding of fundamental degradation phenomena in thin film solar cells and enhancement of lifetime. Degradation is due to complex mechanisms related to inherent material stability, interdiffusion across junctions and due to external influences such as ambient atmosphere and solar light, and depends on the type of semiconductors being used in the devices and how the solar cells are encapsulated. The way degradation processes are identified relies on the observation of the temporal evolution of device performance and its relationship to microscopic changes in device materials and morphology. The goal of this project is to use the competences of the partners in micromorph silicon, compound semiconductors, dye sensitized and organic thin film solar cells, solar cell testing and modeling to scrutinize durability of thin film photovoltaic devices.

DURSOL is a project consortium consisting of the following Swiss research groups: Empa (FP and TFPV Laboratories, Dübendorf), EPFL (IMT and LPI Laboratories, Neuchâtel and Lausanne), ZHAW (ICP Laboratory, Winterthur), CSEM (Polymer Optoelectronics, Basel), SUPSI (Photovoltaic Test Center, Canobbio). Severval industrial partners are involved as well: BASF, AMCOR, Solaronix AG, Oerlikon Solar AG, Pramac, Flisom, Fluxim.

Results

Chemical alteration of the PV device components by external influence

Performance measurements of state of the art CdTe solar cells before, during and after light irradiation and thermal stressing were performed. A new way to introduce Cu into the solar cells was proposed. Generally the lower the copper content the less pronounced was the relative degradation of the fill factor and the power conversion efficiency.

A post-deposition treatment for single-junction and multi-junction Si solar cells was introduced, following promising results obtained with such treatment directly on (bare) Low Pressure Chemical Vapor Deposition Zinc Oxide (LPCVD ZnO). This post-deposition treatment consisted of a hydrogen plasma at 200°C, which lead to a massive increase of both the mobility and free carriers density in lowly doped ZnO. This treatment was applied on complete, non-encapsulated solar cells. H_2 plasma permitted to achieve a record efficiency of 10.4% for a 1.06 cm^2 cell.

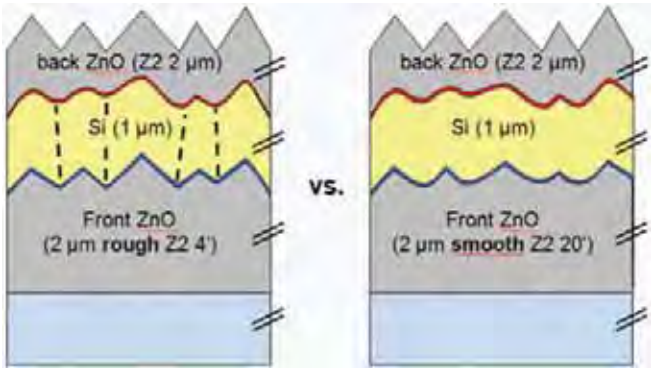

Figure 1: *Schematic view of cells used to demonstrate the impact of superstrate roughness upon post-deposition treatment (H2 or annealing in vacuum). Porous zones (also referred to as "cracks"), typically appearing when Si material is grown on rough, inappropriate superstrate morphology, are represented as dotted lines in the Si material.*

The effect of hygroscopic conductive polymer buffer layers (PEDOT) on degradation of polymer solar cells exposed to water vapor was revealed. Replacing this layer with inorganic oxide layers such as MoO_x provided clear improvement in device lifetime under exposure to ambient atmosphere. The performance and stability of cyanine dye-C_{60} heterojunction solar cells were investigated both in the regular and the inverted deposition sequence of device layers.

The stability of dye sensitized solar cells (DSC) measured under one sun conditions at 60°C and at 80°C in dark was monitored. The variation in the photovoltaic parameters was investigated by transient photovoltage decay and electrochemical impedance spectroscopy. These analyses allowed determining the electron lifetime variations in the TiO_2 film and the movement of the TiO_2 conduction band edge during the aging process to explain changes observed in the devices' V_{oc}.

The MPPT 3000, developed at SUPSI, was adapted for the measurements of mini modules. First measurements were done outdoor with DSC mini modules. A setup for indoor IV curve measurements was also installed. A solar simulator with uniformity of class A (5 x 5 cm^2) and spectral match of class B is available at the moment.

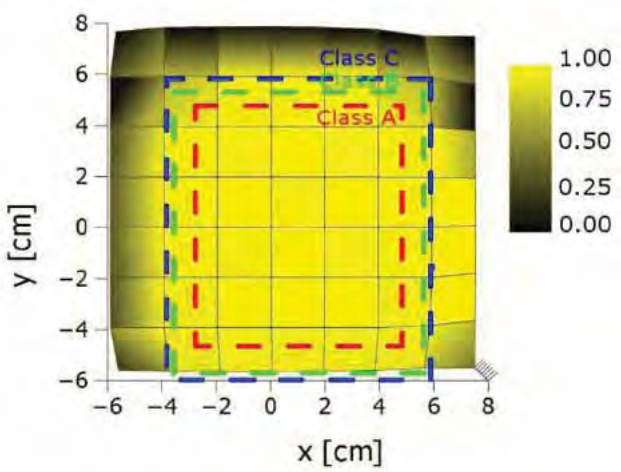

Figure 2: *Solar simulator - uniformity of irradiance.*

Improving morphological stability of the PV device layers

MoO_x layers were found to be the best back contact buffer layer for normal substrate geometry CdTe solar cells. The evolution of this layer during solar cell processing was studied in detail. It was found that the as deposited $MoO_{2.94}$ transformed entirely to MoO_2 upon solar cell processing. With the MoO_x back contact and a new approach to introduce Cu into the cell CdTe, cells in substrate configuration with an independently certified efficiency of 12.04% were produced, corresponding to the highest efficiency for such solar cells reported so far.

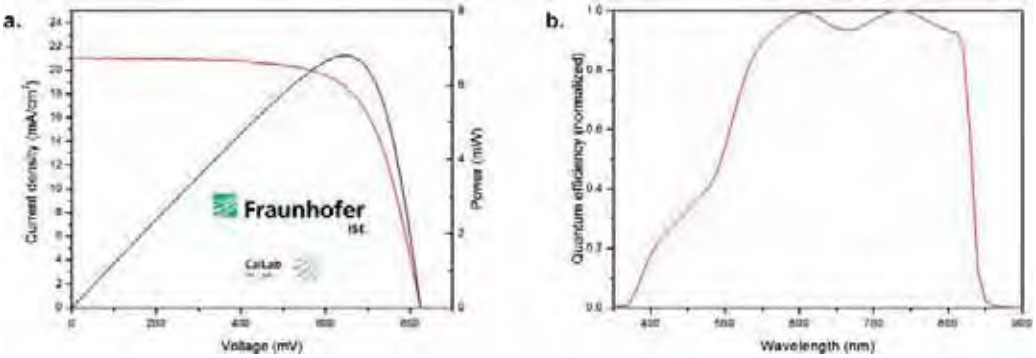

Figure 3: *Certified I-V (a.) and quantum efficiency measurements (b.) of the 12.04% CdTe record cell in substrate configuration.*

The stability of amorphous Si bulk material during plasma deposition under different pressure, temperature and hydrogen dilution regimes has been investigated. The relative light induced degradation was minimal for the high pressure plasma deposition process.

The stability of organic dye semiconductor solar cells was improved by inserting MoO_x buffer layers and by changing the multilayer sequence in the device architecture (inverse architecture). Optimized devices showed unchanged performance for several months of storage in inert atmosphere. First tests under light exposure at room temperature showed unchanged behavior for several days.

Optical simulations on thin film silicon solar cells and modules are carried out to calculate the scattering distribution for reflection and transmission at textured surfaces. This will allow for the quantitative assessment of transparent electrode surface textures in the framework of a complete optical cell model.

Defects in solar modules such as shunts and inhomogeneous layer properties have detrimental effects on the electrical module performance. Electro-thermal transport in the transparent electrodes and encapsulating layers leads to a spreading out of this negative impact. A quantitative analysis of these defects, therefore, calls for a spatially resolved model of the electrical and thermal transport in the plane of the current-collecting layers. With IV measurements under partial illumination and lock-in thermography measurements of amorphous silicon mini-modules a FEM model is validated to account for these processes.

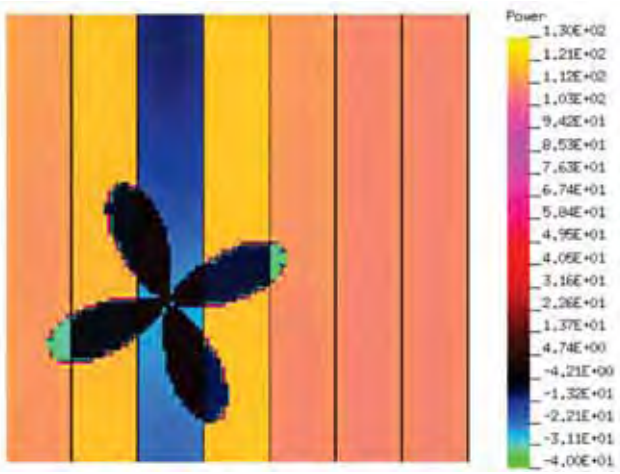

Figure 4: *Leaf shaped shadow on a thin-film solar module. Depicted is the calculated local power production/ dissipation.*

Mechanical effects of stress on device lifetime

A compressive shear test method was designed to characterize adhesion of standard PV encapsulants to a glass substrate, before and after degradation in damp-heat conditions. A data acquisition system of a mechanical module stress test was accomplished.

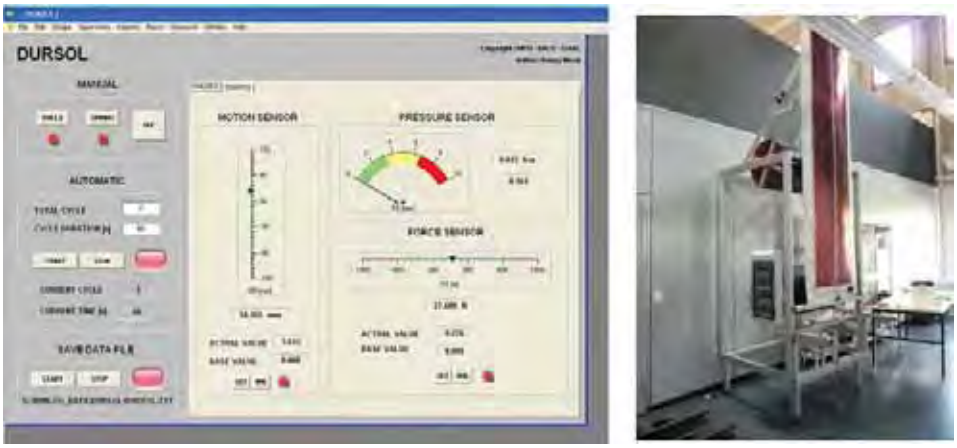

Figure 5: *Screen shot of the software to control the mechanical stress test system .*

Barrier properties of encapsulation materials

A review and comparison of the available methods for the spatial assessment of moisture diffusion along PV modules was carried out. The methods include FTIR, capacitance sensors, TCO's resistance sensors and Ca sensors.

National and international cooperation

We organized an international workshop and conference on the "Durability of Thin Film Solar Cells, Status and Assessment", on April 4th, 2012 at Empa in Dübendorf. A panel of international speakers from academy and industry attracted more than 80 participants.

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NIR: SENSITIZERS FOR DYE SENSITIZED SOLAR CELLS - HEPTAMETHINE DYES WITH A GREAT SPECTRAL DIVERSITY ABOVE 700 NM

Annual Report 2012

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Project- / Contract Number	NIR / KTI 10584.1
Duration of the Project (from – to)	01.11.2009 – 31.10.2012
Date	14.12.2012

ABSTRACT

The company Solaronix and Empa focus on the development of new unsymmetrical heptamethine dyes for application in dye sensitized solar cells. Because of their out-standing physical properties (e.g. high extinction coefficient and absorption maximum above 700 nm), these dyes are very promising NIR sensitizers. By skilful combination of different heterocycles and dianil derivatives, it is possible to synthesize and characterize various functionalized unsymmetrical heptamethine dyes. Furthermore, the efficiency of industrial dye sensitized solar cells prepared with such sensitizers is up to 1.3%. Remarkably, dye sensitized solar cells with heptamethine dyes, which solely absorb light in the NIR, appear in light yellow, the colour of the electrolyte

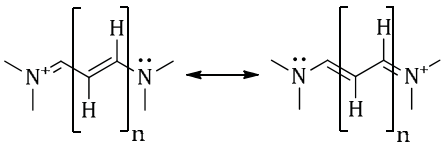
Introduction

Although, the efficiency of dye sensitized solar cells (DSCs) clear the benchmark of 10 % a great challenge is still to optimize all cell components - semiconductor, redox system, electrodes and, of course, the sensitizers - with the sophisticated objective to reach the maximal possible efficiency of DSCs. In order to realize this target, investigations and improvements on the sensitizers have the greatest potential. Up to now, one deficiency of the well-established metal based Ruthenium complexes, such as the known derivatives N3, N719, Z907 and Black Dye, is that the sunlight is absorbed in the UV-Vis domain with an insufficient, low molar extinction coefficient. Furthermore, popular arguments against ruthenium dyes are the high commodity price of the rare metal ruthenium as well the limited spectral diversity of these dyes in the near infrared (NIR) domain. But one should keep in mind that DSCs with ruthenium based sensitizers are today's yardsticks regarding the efficiency.

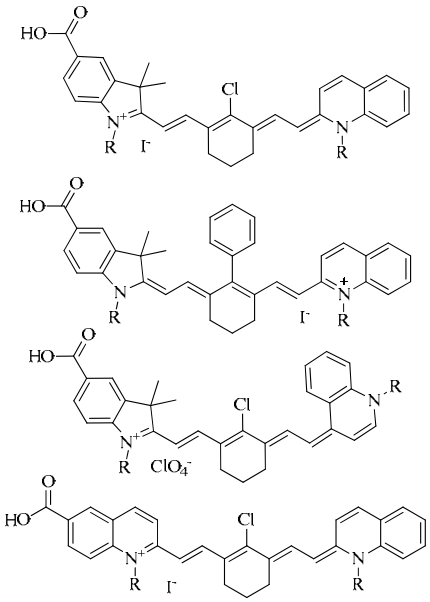
Nevertheless, a more efficient use of the sunlight with high molar extinction coefficients together with an enlargement of the spectral diversity of the dyes towards the NIR domain as well as new metal free molecular structures as alternatives or useful supplements for ruthenium dyes are a starting point for the investigation on novel NIR heptamethine sensitizers.

Heptamethine Dyes

The well-known class of cyanine dyes consists of very promising sensitizers for DSCs because of their outstanding photopyhsical properties. These sensitizing dyes are characterized by intense absorption in the visible as well as in the infrared regime of the solar spectrum with very high molar extinction coefficients reaching up to 400000 $Lmol^{-1}cm^{-1}$. The type of chromophore for these molecules is the amidinium-ion system with extreme resonance structures where the formal charges are located at the ends of the synthon. The important characteristic that influences the absorption wavelength for these dyes is the length of the conjugated polyene chain and the nature of the terminal groups. In general, cyanine dyes mainly contain an odd number of methin (CH=) moieties and two heterocyclic synthons:



Symmetric NIR absorbing heptamethine cyanine dyes (short: heptamethine dyes) are the product of a condensation reaction between an unsaturated bisaldehyde and a heterocyclic base with enlarged π-electron system containing an activated methyl group. If the condensation reaction is carefully controlled and one of the heterocyclic base contains a carboxylic anchor group unsymmetrical heptamethine dyes for application in DSCs are achievable. With a further molecular design of the heptamethine dye structure, the aggregation of the dye in solution or on surfaces can be controlled by bulky moieties substituted to the cyclohexene synthon or the heterocyclic bases. Additionally, the counter ion of the heptamethine dye plays an important role and is crucial for dye solubility and aggregation. Considering all above mentioned conditions, series of unsymmetrical heptamethine dyes for application in DSCs were synthesized (see right chemical structures on the right).



Dye sensitized solar cells

UV-vis investigations impressively demonstrate the great spectral diversity above 700 nm of the unsymmetrical heptamethine dyes. The UV-vis spectra of one typical unsymmetrical dye in solution and the spectrum of the sun's solar radiation (AM1.5) are shown in Figure 1. In general, all dyes intensively absorb in the range of 700 up to 900 nm and exhibit a very high extinction coefficient >100000 Lmol-1cm^{-1}. Furthermore, the redox potentials and higher excited levels of the heptamethine dyes are well positioned to provide the necessary driving force for charge injection into the TiO_2 conduction band. Additionally, charge delocalization over the molecule couples the dye to the semiconductor surface.

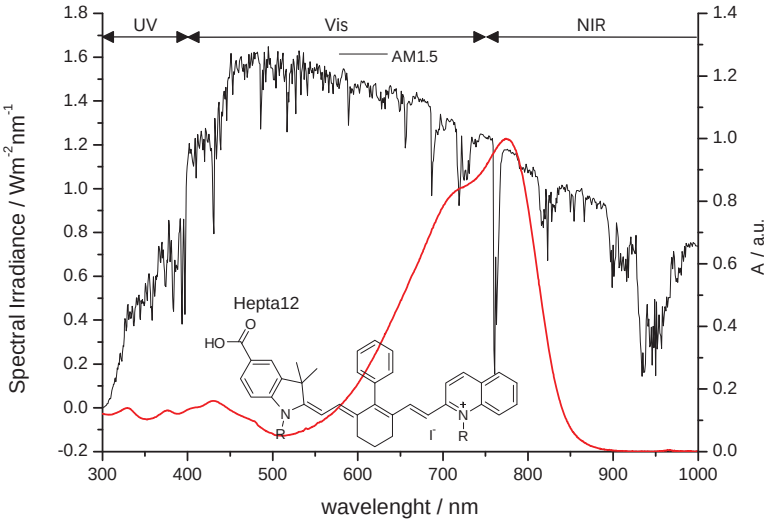


Figure 1: *UV-vis spectra of a heptamethine dye in chloroform and the spectrum of the Sun's solar radiation (AM1.5).*

Finally, the unsymmetrical heptamethine dyes were tested in laboratory dye sensitized spot cells (glas/FTO/TiO_2/dye/iodid-triiodid(acetonitril)/Pt/FTO/ glas) with an active area of 0.72 cm^2 as well as in large area solar cells. The dyes were immobilized on the semiconductor surface from methanol or chloroform solution under the influence of a co-adsorbent (chenodeoxycholic acid) in order to prevent aggregation of the dye. Optimized dye sensitized solar cells using Hepta12 showed a short circuit current density (J_{SC}) of 3.47 mAcm^{-2}, an open circuit voltage (V_{OC}) of 495 mV and a fill factor (ff) of 0.76 leading to an overall conversion efficiency η of 1.31% obtained under 1000 Wm^{-2} illumination intensity. Remarkably, dye sensitized solar cells with heptamethine dyes, which absorb light in the NIR, almost appear in light yellow, the color of the electrolyte.

Summary

In summary, first metal-free unsymmetrical heptamethine dyes were successfully prepared. Unsymmetrical heptamethine dyes satisfy important requirements to function as a sensitizer in a DSC namely: a localized excited state charge density, well positioned redox levels and higher excited levels to fit those of the TiO_2 conducting band and electrolyte redox potential, the ability to harvest NIR photons for energy conversion and finally a huge extinction coefficient which allow the use of even thinner TiO_2 nanoparticle layers. This work provides a way for designing new NIR absorbers for transparent colorless organic photovoltaic devices.

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ORION

ORDERED INORGANIC-ORGANIC HYBRIDS USING IONIC LIQUIDS FOR EMERGING APPLICATIONS

Annual Report 2012

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Duration of the Project (from – to)	01.10.2009 – 30.09.2013
Date	02.02.2013

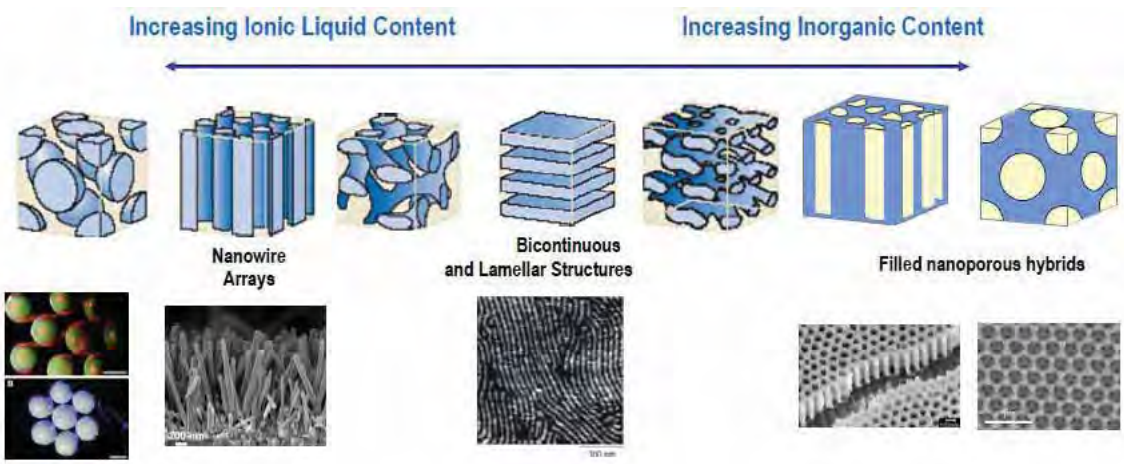
ABSTRACT

ORION puts together a multidisciplinary consortium of leading European universities, research institutes and industries with the overall goal of developing new knowledge on the fabrication of inorganic-organic hybrid materials using ionic liquids. Maximum research efforts within ORION will be addressed to achieve inorganic-organic hybrids with an ordered nanostructure and to understand and characterize the next generation of inorganic-organic hybrids for energy conversion and storage. The final goal is to optimize the best possible materials and processing methods for increasing the performance of batteries and innovative solar cells.

Aims of the project

The main concept of the project is the development of a new family of functional inorganic- organic hybrids materials characterized by an ordered morphology. The hybrids will be composed of an inorganic material such as (TiO2, SiO2, ZnO, Si, Sn, LiCoO2) and a new functional ionic liquid as the organic component. At high inorganic oxide contents the preferred structures will be ordered nanoporous inorganics filled with ionic liquids hybrids.

At low inorganic oxide contents, nanoparticle, nanotube and nanowire arrays embedded in ionic matrixes will be searched. At intermediate compositions bi-continuous and lamellar structures will be presumably obtained. The phase diagram of the ordered inorganic-organic hybrids is shown below. The ordered geometry of the final hybrid will allow a synergic combination of the properties of each individual component, ensuring good electrochemical and photonic performance.



Two different complementary generations of hybrids will be developed. First, Generation 1 inorganic-organic hybrids will be synthesized for applications in lithium batteries. Although the complete phase diagram will be investigated, the expected morphologies of choice will be nanoporous structures because of their higher charge capacity and enhanced charge/discharge rate possibilities. On the other hand, Generation 2 inorganic-organic hybrids will be developed for application in innovative solar cells. In this case, a third component named light sensitizer (dye, semiconducting polymer or quantum dot) will be added to the inorganic component/ionic liquid system. Generation 2 will prefer nanoparticle and nanowire arrays morphologies. This will facilitate electronic and ionic transport and will allow the introduction into the hybrid of a third component (light sensitizer) which will be added to bring optical activity to the hybrid.

Generation 1	Generation 2

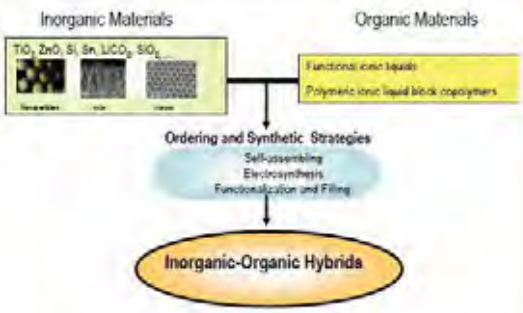
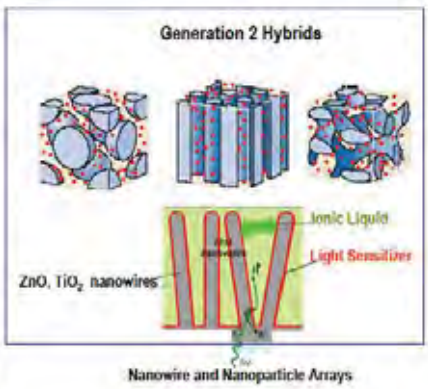

	

Illustration of the synthetic approaches to Generation 1 Ordered Inorganic-Organic Hybrids.	Graphical presentation of generation 2 hybrid architectures (inorganic nanoparticle or nanowires surface functionalized with a light sensitizer and embedded into ionic liquid media).

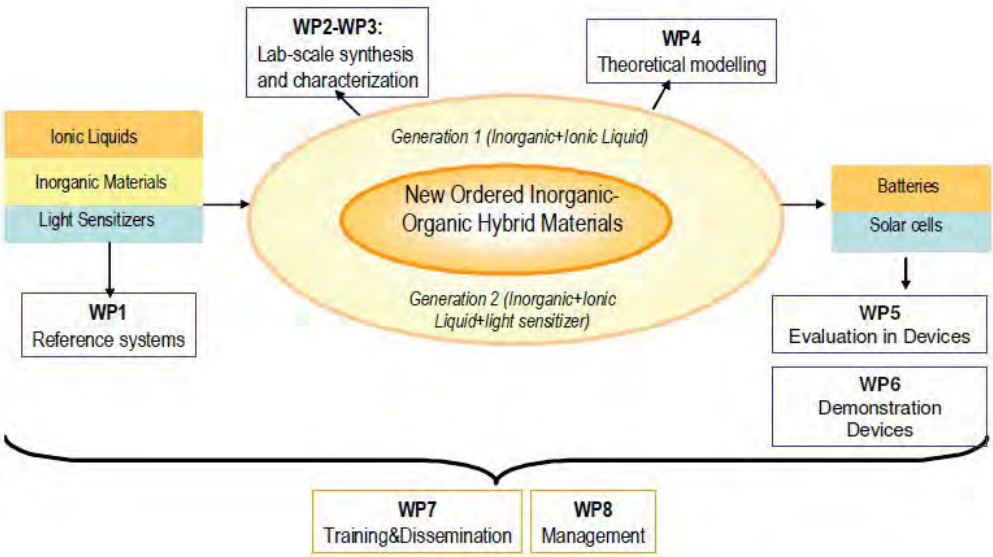
Scientific and technical objectives:

ORION captures the main goal into the next particular scientific and technical objectives to be achieved in the project:

- Design and processing of ordered inorganic-organic hybrid materials for energy applications.
- Understanding of self-assembling methods for the synthesis of ordered inorganic-organic hybrids using ionic liquids.
- Development of new methods for ordering inorganic-organic hybrids using functional and polymeric ionic liquid block copolymers as structure directing agents.
- New functional Ionic Liquids and polymeric ionic liquid block copolymers including chemical functional groups such as triethoxysilane, carboxylic, phosphoric and thiol functionalities enabling the ionic liquids to act as functional templates in the synthesis of ordered inorganic-organic hybrids.
- Development of ordered hybrid materials composed of an inorganic component and ionic liquid for battery applications. (Generation 1)
- Synthesis of light sensitizers (organic dyes, quantum dots and semiconducting polymers) with adequate functionality to be added to the inorganic-organic hybrids.
- Development of complex ordered hybrid materials composed of an inorganic component, ionic liquid component and a third component named light sensitizer (organic dye, semiconducting polymer or quantum dot) for innovative solar cells.(Generation 2)
- Complete characterization of innovative hybrid materials: morphological characterization, electrochemical and transport studies including ionic, electrical and hole conductivities, and functional performance (half-cell devices).
- Theoretical modeling of new inorganic-organic materials and prediction of their properties and performance in devices.
- Processing of inorganic-organic hybrids by different methods including ink-jet printing and screen printing.
- Development and optimization of innovative inorganic-organic electrode materials for lithium batteries. To propose a high storage capacity battery with a long lifetime (respectively>200 Wh/kg, 30% improvement).
- Development and optimization of innovative inorganic-organic hybrids for solid solar cells with high efficiencies (>10%) and high cyclability (10'000 h) (30% improvement).
- Evaluation of organic/inorganic hybrids in other applications (supercapacitors, sensors and light-emitting devices).

Project partners & role of Solaronix

ORION is a Large Scale Collaborative Project involving 17 partners with duration of 48 months. The work program is divided into 7 logical Work packages (WPs), covering RTD, Management, Demonstration and Training activities



Work carried out and results achieved

In WP2 the titania nanoparticle size optimization was continued to tune for the best performance with ionic liquid electrolytes.

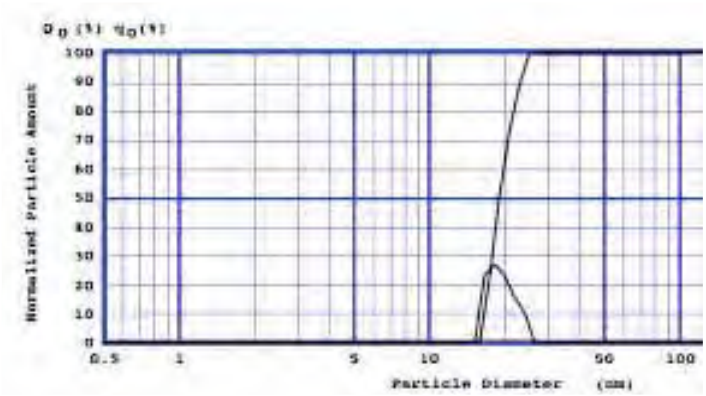
The most frequently used randomly packed TiO_2 nanoparticle network is usually constituted of 18 nm particles that demonstrated the highest efficiency in dye sensitized solar cells (DSSC). But, trying to get monodisperse TiO_2 nanoparticles resulted in a decrease in efficiency especially when using viscous ionic liquids electrolytes.

Titania screen printable paste made using narrow titania particle size distribution presented:

- Bad adhesion properties that could be attributed to the formation of a compact film on the glass substrate.
- High viscosity after few days. This high viscosity leads to a bad printability of the paste and a low quality of the film formed.

The poor adhesion properties leaded to the impossibility to perform a post $TiCl_4$ treatment. The latter is essential for the cell performance.

Particle size (nm)	25% D	50% D	75% D	Std Dev.
Narrow distribution	17.35	18.99	21.45	0.062



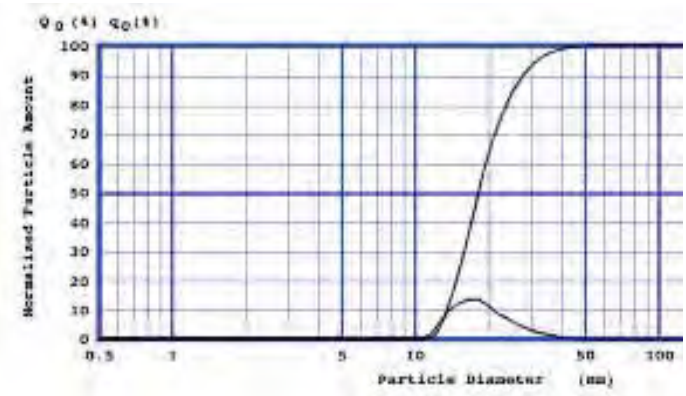
Narrow particle size distribution between 15 and 25 nm diameter.

Typical ionic liquid based cell performance using narrow distribution (average on 5 cells).

	J	Voc	FF	Eff.
Solaronix	7.69	0.595	0.65	2.97 %

To solve these issues, the particle size distribution has been tuned by introducing a small amount of larger particles while keeping the distribution centered around 18 nm (optimum size for DSSC).

Particle size (nm)	25% D	50% D	75% D	Std Dev.
Broad distribution	16.26	18.62	22.27	0.096



Broad particle size distribution

Introducing these bigger titania particles allowed to control the film porosity. $TiCl_4$ treatment was performed on the formed film without delamination issues. The treatment leaded to a dramatic increase in the cell performance especially with ionic liquid electrolyte.

	J	Voc	FF	Eff.
Solaronix	10.01	0.690	0.71	4.91%

Typical ionic liquid based cell performance using broad distribution after $TiCl_4$ treatment (average on 5 cells).

Titania nanorods:

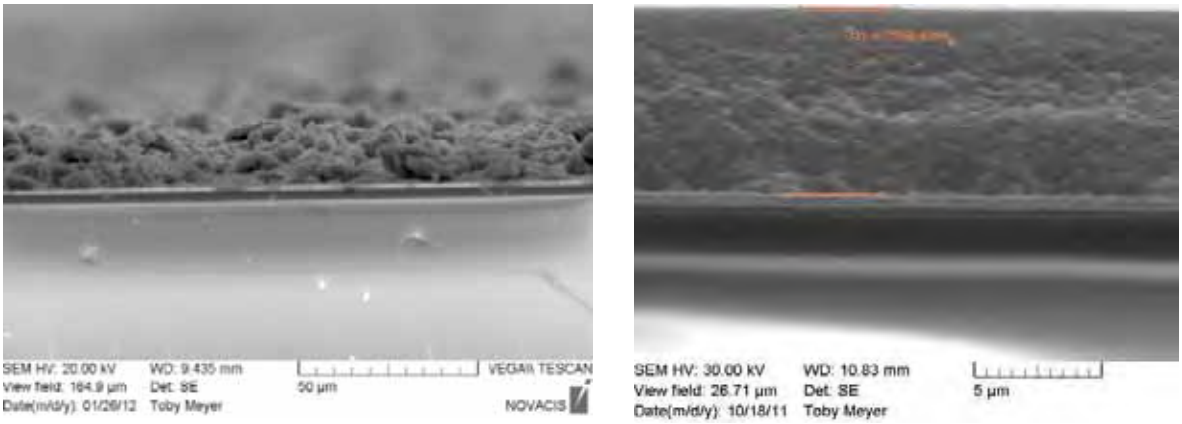
Titania nanorods, given by CNR-IPCF Bari, were investigated in dye sensitized solar cells. These nanorods are 25-30 nm in length, 4 nm in diameter and are oleic acid capped.

A screen printable paste using Solaronix' Ti-Nanoxide T/SP and 25 % in weight of titania nanorods was formulated and used as a precursor of the TiO_2 layer. Several working electrodes were printed and assembled in a complete solar cell in order to evaluate their performances (see table below).

	J	Voc	FF	Eff.
Solaronix T/SP paste	12.36	0.735	0.74	6.76 %
Nanorods based paste	12.31	0.733	0.74	6.67 %

Typical cell performance using titania nanorods (average on 5 cells).

The results were similar to the reference titania layer with no efficiency loss induced by incorporation of these new nanoparticles, which is usually not the case with other type of titania particles. These promising results encouraged us to formulate a screen printable paste based on 100 % of nanorods. Unfortunately due to the oleic acid capping agent the dispersion of nanorods in the organic vehicle was difficult and lead to the formation of aggregates. The latter explain the bad quality of the titania layer formed (see SEM cross section below) and the poor performance of the corresponding test cells.

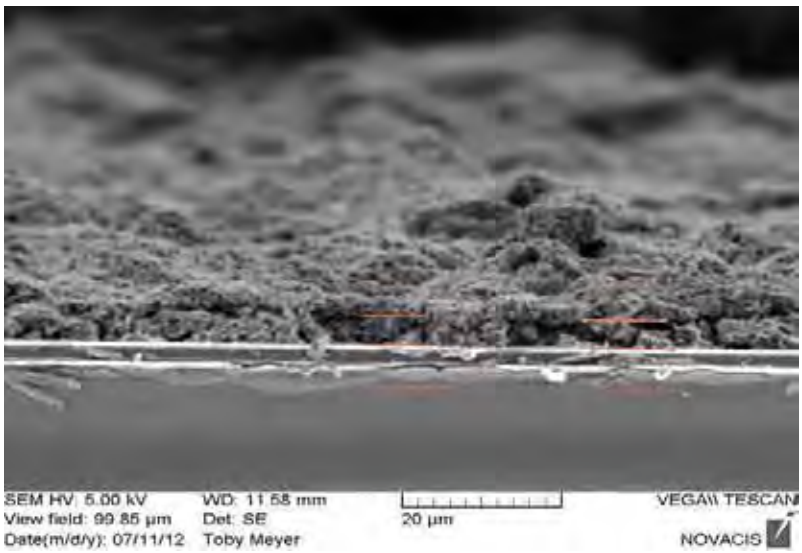


SEM cross section of titania nanorods (on the left) and Solaronix' Ti-Nanoxide T/SP (on the right) based layer.

	J	Voc	FF	Eff.
Solaronix T/SP paste	13.18	0.727	0.70	6.67 %
Nanorods based paste	5.74	0.741	0.73	3.11 %

Photovoltaic performances of the layers using capped nanorods

As capped nanorods were not dispersible in the paste organic vehicle, the capping agent (oleic acid) was removed by a high temperature thermal treatment. The bare nanorods were then dispersed in ethanol. Unfortunately the dispersion was not complete and some aggregates still remained. Several electrodes were prepared using the paste obtained with this ethanolic dispersion. The cells produced with these layers showed good efficiency (around 4.5%) using ionic liquids based electrolyte. This result should be compared to the 3.11% obtained using high efficiency liquid electrolyte and capped nanorods. The quality of the titania layer was investigated (see SEM cross section below). Surprisingly, the layer thickness was lower than expected. This can be explained by the titania content of the paste that was low due to the overtime settling of the aggregate to the bottom of the container. To produce the film only the supernatant and homogeneous part of the paste was used.



Unfortunately it was not possible to increase the layer thickness over 4 µm but using these thin layers; above 7% in efficiency cells were prepared with high efficiency liquid electrolyte. This nice result should be compared to the first results (3.11%) obtained with non-dispersible nanorods.

Electrolytes	J	Voc	FF	Eff.
High efficiency liquid	13.55	0.723	0.72	7.08%
Ionic liquid based	9.57	0.666	0.72	4.59%

Photovoltaic performances of the layers using non capped nanorods.

These results confirm that a good dispersion of nanorods in the vehicle is a key step in the quality of the paste, the layer printed and consequently the cell efficiency.

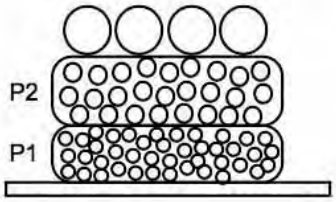
One explanation for the partial dispersion of the heat treated nanorods could be an insufficient heating duration leading to partially capped rods. Some experiments are planned to investigate this issue.
More experiments using capped nanorods and new non polar organic binder are now ongoing in order to produce a homogeneous paste.

In WP5.2, further improvements of the ionic-liquid based laboratory solar cells (036 cm^2) were achieved by using a layering of screen printed TiO_2 having increasing particle sizes:

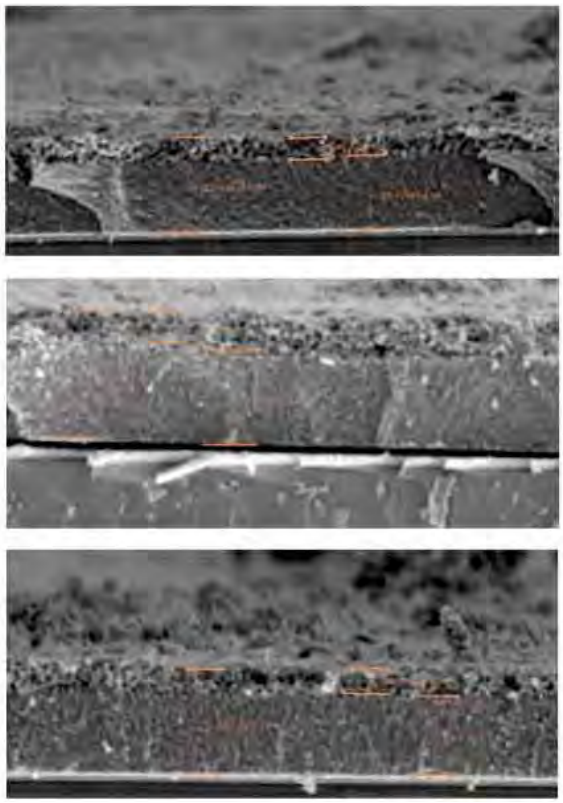
	J	Voc	FF	Eff.
P1 only	12.81	0.651	0.67	**5.60 %**
P2 only	11.50	0.660	0.69	**5.20 %**
P1-P2	15.24	0.642	0.64	**6.30 %**

Dye: C106 0.5 mM in EtOH
D35 0.1 mM in EtOH
CDCA 0.2 mM in EtOH

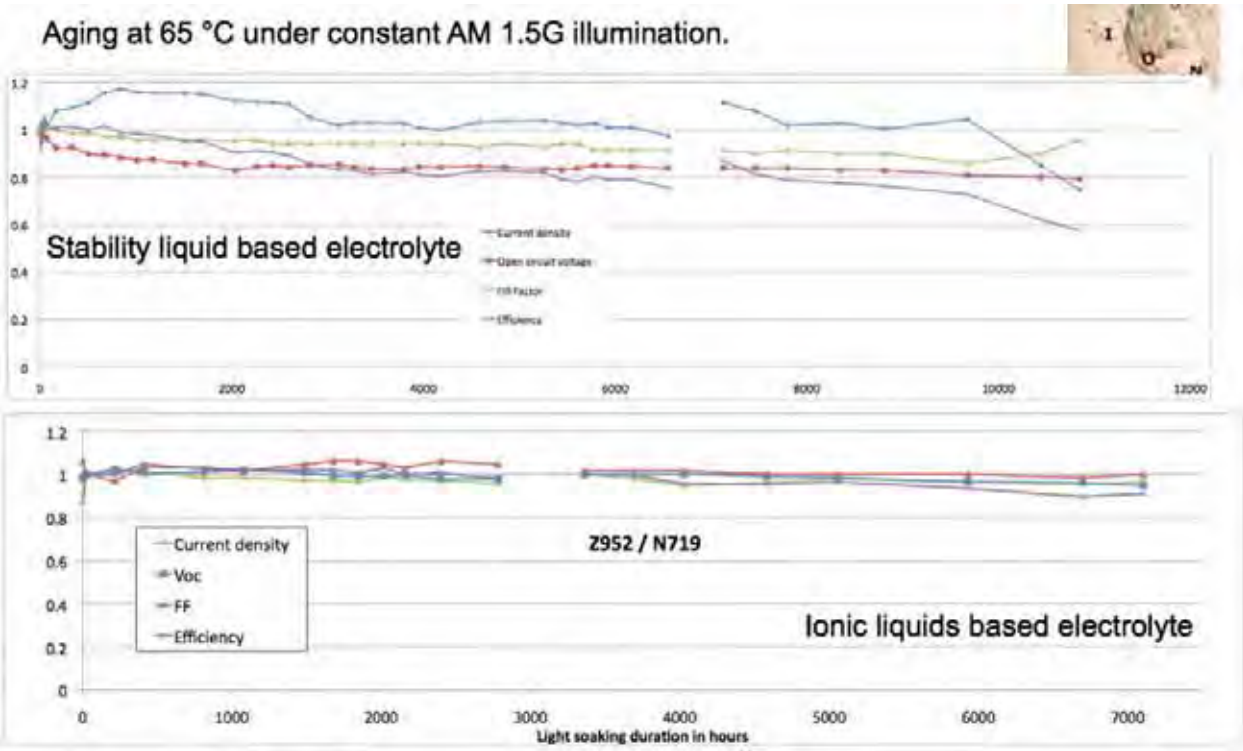
BET
P1: 89 m^2/g - pore size 7 nm
P2: 63 m^2/g - pore size 14 nm



5 cells averages



Moreover the long term stability tests were ongoing by illumination of laboratory cells in continuous artificial sun (1000 W/m2) while keeping the temperature at 65°C.



It seems that the ionic liquid based cells show only a minor change (< 10% of power) after 7000 hr of test, whereas the 3-methoxypropionitrile based ones showed all substantial degradation (> 20 % power loss) after 8000 hr.

National and international cooperation

Running of the 3 years "KTI-Project" N° 10584.1 PFIW-IW with the EMPA Dübendorf (Switzerland) on the topic of near infrared absorbing organic sensitizers.

FP7-Project "INNOVASOL" – coordinated by Dr. Leo Marchese of the SiSTeMI center at the University of Piedmont, Italy.

INNOVASOL aims to increase the efficiency of exitonic solar cells to 15 % by using innovative approaches in cell designs and novel materials (see www.innovasol.eu).

FP7-Project "SOLHYDROMICS" - coordinated by Prof. Guido Saracco at the Politecnico Torino, Italy.

This project aims to build a photoelectrochemical water splitting device based on organic (or biological) catalysts for light collection (PSII system) and hydrogen evolution materials without noble metals (see http://solhydromics.org/).

FP7-Project "CRONOS" - coordinated by Prof. Guido Saracco at the Politecnico Torino, Italy.

This project aims to build a photoelectrochemical water splitting device based on organic (or biological) catalysts for light collection (PSII system) and hydrogen evolution materials without noble metals (see http://solhydromics.org/).

FP7-Project "ARTIPHYCTION" - coordinated by Prof. Guido Saracco at the Politecnico Torino, Italy.

This project aims to build a «Fully artificial photo-electrochemical device for low temperature hydrogen production». Started on May 1st, 2012.

FP7-Project "ADIOS-Ru" - coordinated by Dr. Mashar Bari at the Solarprint, Ireland.

This project aims to take care of the "Advanced Design and Industrialization of Organic Sensitizers without Ruthenium for Dye Sensitised Solar cells". Started on 1st November 2012.

FP7-Project "ECO2CO2" - coordinated by Prof. Guido Saracco at the Politecnico Torino, Italy.

This project aims to build a «Eco-friendly biorefinery fine chemicals from CO_2 photo-catalytic reduction".

Started on December 1st, 2012.

Evaluation 2012 and Outlook 2013

During 2012 stability testing for over 7’000 hours at 65°C under constant artificial sun illumination of ionic liquid filled spot cells show less than 10 % performance loss of the devices under test. This remarkable result opened the way for the production of 35 x 50 cm sized modules filled with ionic liquid, being used in the 300 m^2 facade project for the Swisstech Convention Center at the EPFL campus (to be inaugurated November 2013). The absolute performance of ionic liquid electrolyte cells were also increased to 6.3 % on small test cells (0.36cm^2) by forming a hierarchical pososity within the TiO_2 layer.

References

http://www.cidetec.es/ORION/index.html

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

Bundesamt für Energie BFE

MESOLIGHT

MESOSCOPIC JUNCTIONS FOR LIGHT ENERGY HARVESTING AND CONVERSION

Annual Report 2012

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Project- / Contract Number	MESOLIGHT / 247404
Duration of the Project (from – to)	01.03.2010 – 28.03.2015
Date	10.12.2012

ABSTRACT

In accordance with the goals of the proposal, research has focused on the generation of electric power by mesoscopic solar cells. The key target of the work is to increase the photovoltaic conversion efficiency from 11 percent at the outset of the MESOLIGHT project to 15 percent at the time of its completion, rendering these new solar cells very attractive for applications in large areas of photovoltaic electricity production. At midterm the power conversion efficiency (PCE) reached 12.9 % under standard reporting conditions (AM 1.5 sunlight at 1000 W/m2 and 25oC) providing excellent perspectives to accomplish the targeted performance goals within the time frame of the project.

The work followed largely the original program proposed to enhance substantially the performance of dye sensitized solar cells (DSCs). The emphasis of our research during the first project period was put on the most promising areas comprising i) the theoretically assisted conception and synthesis of new donor-acceptor type molecular sensitizers to extend the spectral response of dye sensitized photovoltaic cells further into the near IR improving the short circuit photocurrent; ii) the coupling of these dyes with cobalt complexes as redox mediators in order to enhance the cell voltage and iii) the introduction of methylammonium lead iodide (CH3NH3PbI3) perovskite nanoparticles as light harvesters in solid state dye sensitized solar cells. The breakthrough was achieved by introducing a Co(II/III) complex based redox electrolyte along with a custom synthesized donor-π-bridge-acceptor zinc porphyrin dye as sensitizer. The same sensitizer/redox electrolyte allowed for very efficient harvesting of ambient light with power conversion efficiency reaching 26 %. A proof of concept (PoC) ERC project was started to exploit commercially this exceptional performance. It appears at this stage that the key findings from our MESOLIGHT project redefine the research and technology landscape in the field of mesoscopic solar cells and ultimately will have a large impact on the field of solar power generation.

Summary of the major achievements since the start of the project 1

1. Research and technological achievements and the impact and use of them

In accordance with the goals of the proposal, research has focused on the generation of electric power by mesoscopic solar cells. The key target of the work is to increase the photovoltaic conversion efficiency from 11 percent at the outset of the MESOLIGHT project to 15 percent at the time of its completion, rendering these new solar cells very attractive for applications in large areas of photovoltaic electricity production. At mid-term the power conversion efficiency (PCE) reached 12.9 % under standard reporting conditions (AM 1.5 sunlight at 1000 W/m2 and 25oC) providing excellent perspectives to accomplish the targeted performance goals within the time frame of the project.

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Detailed results have been reported in some 16 publications that have resulted from our studies since the start of the MESOLIGHT project. A breakthrough was achieved iby replacing the iodide/triiodide redox shuttle by a Co(II/III)tris(bipyridyl) based redox electrolyte and introducing a custom synthesized donor-**π**-bridge-acceptor zinc porphyrin dye as sensitizer (designated YD2-**o**-C8).

Employing a judiciously designed co-sensitizer, coded Y123, along with YD2-o-C8 we reached 12.3 % PCE as reported in our Science paper (Yella et.al Science 334, 629 (2011)). The specific molecular design of YD2-**o**-C8 greatly retards the rate of interfacial back electron transfer from the conduction band of the nanocrystalline TiO2 film to the oxidized cobalt mediator, which enables attainment of strikingly high photovoltages approaching 1 Volt. Because the YD2-**o**-C8 porphyrin harvests sunlight across the whole visible spectrum, large photocurrents are generated. The PCE was further improved to the currently attained value of 12.9 % by developing innovative mesoscopic oxide structures accelerating the transport of the Co-complex through the porous TiO2 layer. Figure 1 shows the photovoltaic performance date of the champion cell.

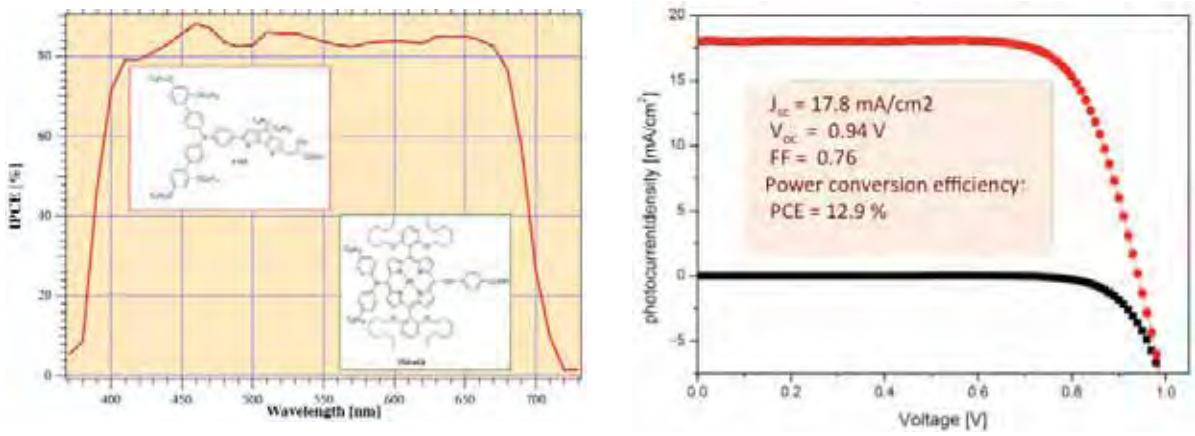

***Figure 1**: Left side. Incident photon to current conversion efficiency as a function of light wavelength for a DSC using Y123 and YD-o-C as sensitizers and cobalt based redox electrolyt. Right: current density in the dark (black curve) and under AM 1.5 sunlight (red curv)e for the same cell.*

A second breakthrough that was achieved during the reporting period concerns the introduction of CH3NH3PbI3 nanoparticles as light harvesters in mesoscopic solar cells where the electrolyte is replaced by a solid hole conductor. These perovskite nanoparticles exhibit very strong absorption below 800 nm (band gap 1.5eV) show a high luminescence yield and are able to conduct electrons as well as holes. This along with near quantitative photo-induced carrier generation makes them very attractive candidates to be used as light harvesters in third generation PV devices.

We have reported PCE values between 9 and 10 % in a first publication on this topic (Nature Scientific Reports 2012, 2, 591). However the performance has since been further improved to PCE values between 12 and 13 %. Substantial further increase in the conversion efficiency is likely on the short term. It is clear already at this stage that the key findings from our MESOLIGHT project redefine the research and technology landscape in the field of mesoscopic solar cells and ultimately will have a large impact on the field.

2. Novel and/or unconventional methodologies.

Two new methodologies have been developed in our laboratory to provide in depth information on the interface separating the mesoscopic oxide support from the molecular or nanoparticle light harvester. Thus we have demonstrated a new in-situ liquid-phase analytical technique for DSCs to quantify the amount, saturation time and adsorption kinetics of dye uptake on flat and a mesoporous TiO2 films using a quartz crystal microbalance with dissipation technique (QCM-D). The Langmuir equilibrium adsorption constant for the sensitizer could also be measured *(Harms et. al Phys. Chem. Chem. Phys., 2012, **14**, 9037-9040)*.

Tests carried out with mesoporous TiO2 film deposited directly on the QCM sensor led to a signal enlargement by two orders of magnitude and a much longer saturation time due to the slow penetration of the sensitizer into the nanoporous oxide film. We have for the first time applied indirect nanoplasmonic sensing (INPS) to study dye molecule adsorption/ impregnation on mesoporous TiO2 films of the kind used as photoanode in dye-sensitized solar cells (DSCs). Au nanoparticles were placed at the hidden, internal interface between the sensor surface and the mesoporous TiO2. This new type of INPS measurement provides a powerful tool to measure and optimize dye impregnation kinetics of DSCs and, from a more general point of view, offers a generic experimental platform to measure adsorption/desorption and diffusion phenomena in solid and mesoporous systems and at internal hidden interfaces *(Gusak et.al Nano Letters, vol. 12, p. 2397-2403, 2012).*

3. Inter and cross disciplinary developments

The scientific advances of MESOLIGHT benefit from close cooperation with theoretical chemists that assist in the design and optimization of sensitizer and electron relays structures enhancing the cells performance. Intense cooperation has been established with several groups in particular with the group of Professor Ursula Roethlisberger a colleague from EPFL and Dr. Filippo die Angelis from the Istituto di Scienze e Tecnologie Molecolari del CNR Perugia.

4. Knowledge and technology transfer

Widespread knowledge dissemination has occurred through numerous publications and public presentation as well as conference participation by the principal investigator and his group. These are listed in the annex of this report. Technology transfer has taken place through cooperation with European industry. Importantly as the Proof of Concept (PoC) proposal IDSC on indoor dye sensitized solar cells (IDCS) was submitted to the ERC and obtained funding (grant agreement no 310230). Of the numerous photovoltaic technologies, dye sensitized solar cells (DSC) are uniquely well fit to efficiently harvest indoor and ambient light. While typical silicon based photovoltaics have a relatively fixed light harvesting spectrum, DSCs are highly tunable by changing the molecular structure of the absorbing dye.

With the same cell configuration as shown in Figure 1 we have obtained power conversion efficiencies of 26% using an Osram 930 lamp as light source. We have associated two industrial partners, i.e. G24 Innovation (UK) and Spinverse (Finland), with the Po project to exploits theses performance advantages of the advanced DSC technology developed under the MESOLIGHT project for ambient light applications

5. Establishment and/or consolidation of the research group

The team constituting the MESOLIGHT research group has by now been well established and has consolidated its efforts to tackle the challenging tasks of the project. It consists of three scientific and one technical collaborator.

Publications partly or wholly resulting from the project

Journal Articles (Author(s), Title, Journal, Year, Open Access? and ERC acknowledgment)

1) Hui-Seon Kim, Chang-Ryul Lee, Jeong-Hyeok, Ki-Beom Lee, Thomas Moehl, Arianna Marchioro, Soo-Jin Moon, Robin Humphry-Baker, Jun-Ho Yum, Jacques E. Moser, Michael Grätzel & Nam-Gyu Park, **Lead Iodide Perovskite Sensitized All-Solid-State Submicron Thin Film Mesoscopic Solar Cell with Efficiency Exceeding 9%,** Scientific Reports, 2, 591 (2012) Open access, ERC ackn YES

2) Thi Thu Trang Pham, Takeru Bessho, Nripan Mathews, Shaik M. Zakeeruddin, Yeng Ming Lam, Subodh Mhaisalkar and Michael Graetzel*, **Light scattering enhancement from submicrometer cavities in the photoanode for dye-sensitized solar cells**, J. Mater. Chem., 22, 16201-16204 (2012), NO, ERC ackn YES

3) Mingkui Wang, Carole Graetzel, Shaik M. Zakeeruddin and Michael Graetzel ***, Recent developments in redox electrolytes for dye-sensitized solar cells**, Energy Environ. Sci., 2012, 5, 9394-9405 (2012), NO, ERC ackn YES

4) Michael Graetzel, René A. J. Janssen, David B. Mitzi & Edward H. Sargent, **Materials interface engineering for solution-processed photovoltaics**, Nature 488, 304, ì312 (2012) DOI :10.1038/ nature11476, NO, ERC ackn YES

5) Barbora Laskova, Marketa Zukalova, Ladislav Kavan, Alison Chou, Paul Liska, Zhang Wei, Liu Bin, Pavel Kubat, Elham Ghadiri, Jacques E. Moser, Michael Graetzel , **Voltage enhancement in dye-sensitized solar cell using (001)-oriented anatase TiO2 nanosheets**, J Solid State Electrochem, 16: 2993-3001 (2012) DOI 10.1007/s10008-012-1729-0 Open access, ERC ackn YES

6) Hauke A. Harms, Nicolas Tetreault,a Viktoria Gusak, Bengt Kasemo and Michael Graetzel*, **In situ investigation of dye adsorption on TiO2 films using a quartz crystal microbalance with a dissipation technique**, Phys. Chem. Chem. Phys., 14, 9037- 9040 (2012) NO, ERC ackn YES

7) Lioz Etgar, Thomas Moehl, Stefanie Gabriel, Stephen G. Hickey, Alexander Eychmuller,and Michael Grätzel, **Light Energy Conversion by Mesoscopic PbS Quantum Dots/TiO2 Heterojunction Solar Cells**, ACS Nano, 6, 3092-3099 (2012), NO, ERC ackn YES

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UPCON

ULTRA-PURE NANOWIRE HETEROSTRUCTURES AND ENERGY CONVERSION

Annual Report 2012

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ABSTRACT

This project investigates the application of nanowires and related heterostructures for next generation solar energy conversion. Nanowires are filamentary crystals with a diameter ranging between few and hundreds of nanometers. This geometry renders them ideal for the collection of the sun radiation and conversion into electricity.

Our work involves a combination of fundamental and applied science. On the fundamental side, our objectives involve the understanding of growth mechanisms of catalyst-free nanowires on cheap substrates such as silicon, as well as the obtaining of novel heterostructures that could help tailor the absorption of the solar spectrum. On the more applied side of the project, it is our objective to fabricate solar cell devices with single and multiple nanowires. Here, one of the goals consists in increasing the device efficiency by learning the fundamentals of light harvesting. Finally, we wanted to use all these results to come up with novel nanowire-based solar cell concepts.

In the following, we present briefly the ***research and technological achievements as well as the impact and use of them***. We separate the results in five different areas:

1. Nanowire growth issues: growth on silicon, in form of arrays

Typically, the growth of GaAs nanowires has been realized on (111) B GaAs substrates. In solar cell applications, a key issue is to use the minimal amount of expensive III-V materials. One way to achieve this is to grow GaAs nanowires on silicon. The challenges of growing on silicon include the lattice mismatch and the fact that Si does not have any polarity, as GaAs nanowires only grow in the (111)B direction and not on the (111)A. The lattice mismatch is partially solved by the efficient lattice relaxation of materials in the nanowire form and was demonstrated in the past. In the initial stages of the project, we had to understand how to induce nucleation with the right polarity, so that nanowires grow perpendicularly to the Si substrates and not in other angles (this would induce shortcuts in the devices). We investigated the initial stages of growth, to finally obtain a 100% yield in the growth of nanowires perpendicular to the substrate [Uccelli 2011, Russo-Averchi 2012].

In order to minimize the amount of material used and maximize light absorption, it is also important to grow nanowires in selected places of the substrate. Thus, we investigated the growth on pre-patterned substrates. The idea here was to cover the substrate with an oxide and to define nanoscale openings where the growth should occur. In order to decouple the effect of the substrate from the pattern, we started studying growth on patterned GaAs substrates [B. Bauer, 2010]. Nanowire growth was obtained in quite similar conditions than on non-patterned substrates. However, the growth presented novel characteristics. We observed that the nanowire growth rate was depending on the distance between the nanoscale holes. This pointed out to an unexpected role of As_4 in the growth of nanowires. Till the date, it was believed that only As_4 molecules impinging on the tip of the nanowire would contribute to growth. Our experiments demonstrated that there is also a contribution from the surrounding area. As a consequence, the effective V/III ratio in the nanoscale holes is extremely different depending on the inter-hole distance, thereby dramatically affecting growth. By turning to growth on patterned Si substrates we realized that the nature of the oxide further affects the effective V/III ratio. Detailed studies on the growth mechanisms and optimization of nanowire arrays on Si are still under way. In parallel, we are currently developing a technique to obtain low-cost large area patterns of nanoscale holes by phase shift lithography [Dalmau-Mallorqui, in progress].

2. Novel heterostructures that improve light absorption

The optimal bandgap for a single junction solar cell lies between 1.2 and 1.4 eV (~GaAs). To further improve the light collection in solar cells, there is the proposal of using quantum dots (QDs) or quantum wells in the absorbing region. These would provide further electron-hole pairs for incident photons with energies below the bandgap. In views of this kind of device, we have investigated the growth of QDs on the nanowire facets that could be incorporated in a nanowire-based radial pn junction device. We started by investigating the growth of InAs QDs on the facets of GaAs nanowires. On (001) oriented GaAs substrates QDs nucleate after the growth of 1.8 monolayers of InAs, as a consequence of the lattice mismatch induced strain. Our GaAs nanowires exhibit facets of the {110} family. When InAs is grown directly on the facets, due to different interface energy with [110] GaAs, InAs does not form QDs but non-uniform layers full of defects. In order to overcome this, we grew a thin AlAs layer which enabled us to obtain InAs QD arrays on the nanowire facets. We investigated the optical properties of the QDs, which resulted to emit about 120 meV below the bandgap of GaAs, as a result of their extremely small size and possible intermixing with GaAs [Uccelli 2010]. We expect to use these QDs in nanowire based radial pn junction devices in a near future.

We have also studied the formation of self-induced InGaAs QDs on the nanowire facets upon growth of InGaAs nanowires under different temperatures [Heiss 2010]. These QDs form upon segregation of In during growth at the nanowire facets. The optical properties have not been investigated yet.

3. Light absorption in nanowires and the impact in photoconversion efficiency

It has been shown recently that light interaction with nanowires differs significantly from the case of thin films. In particular, it has been shown that light absorption can be enhanced and/or reduced for certain wavelengths, as a consequence of the presence of 'leaky mode resonances'. As a consequence, one needs to fully model light interaction for the device design. We have used finite difference time domain simulations for understanding light absorption in nanowires. We have compared the absorption of the solar spectrum in nanowires lying and standing on a substrate. While in the case of lying nanowires the overall absorption can be significantly reduced [Heiss 2011], in the case of standing nanowires we find

a significant increase of the absorption [Demichel, on progress]. Furthermore, the absorption increase in standing nanowires is more important for the wavelengths close to the bandgap, where it is most necessary for the increase of efficiency in the device.

4. Devices

Due to the technical challenges in contacting large arrays of nanowires, we started by characterizing single nanowire p-n junction. We obtained an initial efficiency of 4.5% from a GaAs device. One expects to achieve a better efficiency in a surface passivated device, as surface recombination plays a major role in the device characteristics. For this, we investigated the passivation of GaAs nanowires with AlGaAs (higher bandgap material). The result was extremely promising, as the surface recombination was reduced down to the best values found in the literature for passivated GaAs [Demichel 2010]. The incorporation of passivation layers in the devices and the measurement of surface recombination velocities in real devices are currently under progress.

In order to develop the technique to contact large area devices before we could achieve large III-V nanowire arrays, we started working on large area devices fabricated with Si micro-wires. The Si micro-wires were obtained with a top-down process; the pn junction was obtained by diffusing P in the p-type pillars. After developing the configuration of the top and bottom electrodes, we achieved an overall efficiency of 9.7% in a 5x5 mm^2 device [Dalmau-Mallorqui, 2012].

5. Novel concepts

We have devoted some of our research efforts in finding novel device concepts. Some of the concepts we have been able to realize experimentally and some we have modeled theoretically. Among the novel concepts are the use of plasmons to increase the nanowire efficiency [Colombo 2012], use of up-conversion and down-conversion to increase the photocurrent generated [Demichel, Heiss, in progress].

In the following we address separately further outcomes of the project:

Impact: The research developed in this project has a clear impact in fundamental and applied science, as we have demonstrated novel ways of producing nanoscale materials and how they can have a great impact in solar energy conversion.

Novel and/or unconventional methodologies: Due to the special challenges of the project, we have developed and/or adapted experimental techniques for example to determine: surface recombination velocities in nanowires, carrier concentration and mobility in nanowires by optical means, electrical contacting of nanowire arrays and low-cost fabrication of nanoscale arrays in large surfaces.

Inter and cross disciplinary developments, engineering and physics: This project is clearly interdisciplinary as it works at the interface between materials science, physics and electrical engineering. On one side, one needs to understand the material synthesis and its properties, while on the other side one needs to be able to fabricate functioning devices.

Knowledge and technology transfer: A part of our efforts in fabricating devices has been realized with the Danish company Sunflake. We have transferred some of our knowledge to them so that our developments can be further used in industry.

Establishment and/or consolidation of the research group: We have obtained numerous invitations in international conferences to present the results of the project. Recently we have even obtained an invitation to attend a Nobel Symposium in the area of Nanoscale Energy Converters. This is a workshop in which only selected people could attend it. Our invitation to assist is a proof of recognition in the area.

Summary of the achievements of the project

This project concerns the application of semiconductor nanowires to next generation of solar cells. Nanowires are filamentary crystals with a diameter ranging from few to few hundred of nanometers. Thanks to their morphology, they are ideal objects for an extremely efficient conversion of light to electricity. Additionally, thanks to their small size, they enable us to fabricate solar cell devices with extremely few material (enabling savings in materials).The work includes basic research on the synthesis of nanowires and related heterostructures, the characterization of the optical and electrical properties as well as the realization of solar cell devices. Here below we describe the main results achieved during this first funding period:

Synthesis of nanowires and heterostructures: We have demonstrated the controlled growth of GaAs nanowires on cheap substrates such as silicon. The goal here is to reduce the environmental and costs of the materials used for the solar cells, and at the same time to keep the high efficiency of the device. Furthermore, our initial studies show how nanowires can be grown in arrays, so that the amount of material used can be further controlled. Finally, we have shown how the composition in the nanowires can be changed at the nanoscale to produce quantum dots. Quantum dots enable us to increase the number of photons collected by the nanowire device.

Properties: The properties of the novel nanowire structures have been investigated at the single nanowire level. This enables us to directly correlate the nature of the structure with the properties. We have demonstrated how quantum dots in nanowires result in an increase of the light absorption in the device. We have also shown that we can tune the electrical properties of the nanowires to achieve solar cell devices (single and multiple nanowires).

Devices: We have investigated nanowire based solar cell devices. At the single nanowire level we achieve efficiencies up to 4.5%, while at the multiple nanowire level (arrays) we obtain efficiencies close to 10%. Our theoretical calculations show that indeed the optimal configuration for nanowires is to be vertical with respect to the substrate. In this way, their light collection area is much greater than their own physical size, allowing a large separation between nanowires for a real device. As a consequence, the amount of material used can be reduced up to a factor 40. This constitutes major savings in the production of devices.

As a conclusion, in our project we have made the first steps towards obtaining high efficient and low-cost solar cells. This has been the result of an interdisciplinary work and the combination of both fundamental and applied research.

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NUMERICAL SIMULATION, DESIGN AND FABRICATION OF EXTREMELY THIN ABSORBER SOLAR CELLS

Annual Report 2012

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ABSTRACT

Our joint research focuses on combining both numerical and experimental methods to analyze and improve the optical efficiency of extremely thin absorber (ETA) solar cells. As a first step we produce and measure various reference devices with simplified geometries that are used as benchmark examples. On the computational side we are extending our novel and cutting-edge three-dimensional full-wave optical simulation software OPUS 3-D in such way, that it allows for the numerical simulation of ETA solar cells and returns data that can directly be compared to experimental results. By showing that experimental and numerical data do not only agree for simple structures but for many classes of devices with increasing geometric complexity we aim at establishing a combined framework for the analysis and design of next-generation ETA solar cells. It is a unique approach as the optical characteristics of ETA solar cells are systematically being analyzed by combining elaborate experimental and numerical methods.

Introduction

The overall project goal is the development of a novel framework that – by combining experimental and numerical methods – facilitates the analysis and design of highly efficient ETA solar cells. To this end we aim at proving that our in-house three-dimensional full-wave optical simulation software can reproduce and predict experimentally determined optical characteristics – especially transmission and reflection spectra – of ETA solar cells for a very broad range of designs.

The first part of the project is dedicated to the production and experimental characterization of different reference devices on the one hand, and the extension of the finite-element optical solver software OPUS 3-D on the other hand. In the second part we aim at showing that – for a large variety of device designs and materials – there is good agreement between measured and simulated optical data, in particular, for both reflection and transmission spectra.

To illustrate the applicability of OPUS 3-D for the analysis of a broad range of scattering problems, we benchmark the simulation software with a large variety of standard problems such as planar multi-layer material interfaces or scattering from metallic or dielectric spheres. By showing the excellent agreement between the numerical solutions and the (semi-)analytical reference solutions we illustrate the simulator's validity.

In the next step of the benchmarking procedure, spectrally measured reflection and transmission coefficients, provided by EMPA, are compared to numerical data. This comparison is carried out for planar multi-layer devices with increasing complexity. In all cases excellent agreement between measured and simulated data can be achieved.

A last benchmarking step compares measured and simulated data for a very advanced structure. Here, various ZnO nanowire arrays with different geometries, electro-deposited on a glass substrate, are investigated. Measured and simulated reflection and transmission spectra show, that both the length and the diameter of the nanowires have a very strong but distinct impact on the optical device characteristics. The good agreement between experiment and simulation underlines the simulator's ability to also investigate the characteristics of elaborate nano-structures.

Performed work and achievements

Status report on work package 1: *Fabrication and characterization of sample devices*.

Already finished successfully.

Status report on work package 2: *Extension of software features in the existing simulator opus 3-d.*

During this project the 3-D full-wave finite-element solver OPUS 3-D has been extended substantially. As already indicated in the last report, the most important changes in the kernel are the inclusion of plane wave sources and the implementation of Perfectly Matched Layers (PML) to truncate the simulation domain. Whereas the first modification allows modeling complex scattering and refraction problems, the latter change guarantees both computational efficiency and numerical accuracy. Thorough investigations reveal that reliable and accurate results can only be obtained if PML are employed at the boundaries of the simulation domain. These findings agree very well with what is reported in literature [1]. In addition, the post-processing unit of OPUS 3-D has also been extended and now allows easy computation of reflection, transmission, and absorption coefficients. With these additional features we are able to directly compare measured and simulated data. This is a major achievement because one of the project's main objectives is the development of a computationally efficient software tool whose results can easily be compared to measured data.

It is among the main assets of the simulator that it is not only highly efficient for solving wave propagation problems in large domains, but that it also lends itself very well for the analysis of complicated multi-scale structures that cannot be examined with standard numerical tools (such as Finite-Difference Time-Domain FDTD or Finite Elements FEM). Thus, OPUS 3-D can be employed for the analysis of elaborate structures such as multi-layer devices featuring nanowire arrays working as light diffusors or light scattering centers. Yet, despite of the al- ready highly efficient numerical algorithm that – to further reduce the computation times – has also been parallelized and runs simultaneously on more than 10 processors, it turned out that computation time is still a very critical issue when numerically analyzing advanced multi-scale structures. When computing the light propagation inside such

devices the size of the numerical problem can easily exceed 4 million degrees of freedom, resulting in more than 25 GByte of required memory. If the computational task is then parallelized an efficient speedup can only be achieved if the computational task is equally distributed among all these processors. Especially for the computation of reflection, transmission, and absorption spectra, where a large number of simulations needs to be run in order to cover the entire spectral range, computational efficiency is of utmost importance. To this end, a novel dynamic load-balancing scheme has been implemented that boosts the computational efficiency by another 30% and must therefore be considered as a major achievement of this project.

Status report on work package 3: *Benchmarking with simple reference structures*.

It is the aim of this section to show that OPUS 3-D is not only capable of computing the optical characteristics for a large variety of devices featuring complex geometries, but also, that these results feature high accuracy. Thus, we have chosen a clear and transparent benchmarking procedure that shows the capabilities of the simulator. In a first step, OPUS 3-D was bench- marked with a series of standard problems for which known solutions (either analytical or semi-analytical) exist. This step guarantees high transparency as everybody skilled with Matlab can reproduce and verify the results. In a second step, the simulation results were compared to measured data for various devices with increasing complexity.

Benchmark 1: Reflection and transmission from planar multilayer structures

This benchmark is intended to illustrate that OPUS 3-D correctly computes reflection and transmission spectra for simple layered structures. We have chosen such simple structures as they allow for the easy computation of analytical reference solutions that can be obtained using a simple transfer-matrix method (TMM) approach. The benchmark is carried out for two different device designs. In the first case a plane wave impinges on a glass layer featuring a width of 525 nm, and behind the glass layer there is an infinite layer of air. In the second step, a more complicated multi-layer device that is designed as an anti-reflection filter operating at a wavelength of 570nm is investigated. For both cases figure 1*FIGURE 1* shows the comparison between analytically and numerically computed reflection and transmission coefficients, and in either case there is excellent agreement between the results. This illustrates the simulator's capability to correctly compute transmission, reflection, and absorption spectra for simple planar structures.

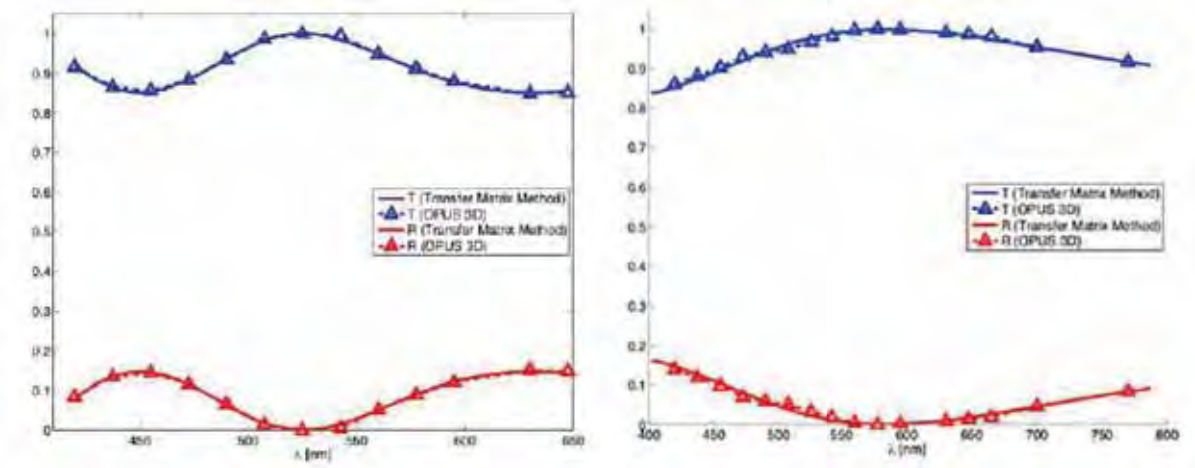


Figure 1: *Comparison between analytical (solid line) and numerical solutions. The red curve is the reflection, the blue curve the transmission coefficient. Left: three-layer-structure. Right: ar-filter.*

Benchmark 2: Scattering from a dielectric sphere

The following benchmark was set up in order to illustrate that OPUS 3-D is very well suited for the analysis of more challenging scattering problems with curved or bent geometries. As depicted in figure 2 we analyze a plane wave that impinges on a dielectric sphere whose radius has a similar order of magnitude as the wavelength.

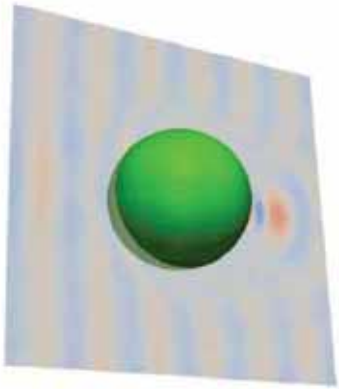
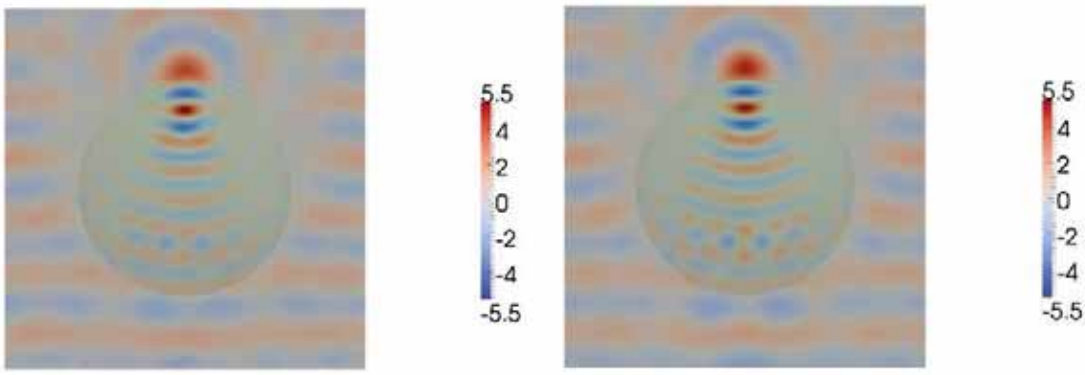


Figure 2: *A plane wave scattered by a dielectric sphere.*

This benchmark is particularly challenging due to the sphere's curved surface. This example has not only been chosen to prove OPUS' ability to efficiently treat complex structures and material interfaces, but also because the Mie series is a well-known semi-analytical reference solution for this problem. This reference solution was computed in Matlab. For the benchmarking procedure both the finite-element solution (OPUS 3-D) and the reference solution (Matlab) were evaluated and compared on a three-dimensional computation domain. Whereas the CPU time for OPUS 3-D ranged around one hour the Matlab solution required a computation time of more than ten hours on the same computer. The excellent agreement between both approaches is illustrated in figure 3– the error ranges around 3%. Similar results were obtained when choosing a metallic sphere instead of a dielectric one.



OPUS 3D

Mie series (Matlab)

Figure 3: *Comparison between opus 3-d solution (left) and semi-analytical reference solution (right).*

Extraction of refractive indices for multi-layer materials

It is one of the project's main goals to illustrate the good agreement between measured and numerically computed optical characteristics for a large class of devices. Yet, prior to comparing measured and computed reflection and transmission coefficients, it is of utmost importance to correctly describe the refractive indices of all involved materials as a function of the wavelength. Determining these values is quite challenging a task. Owing to process variations the structure of the device cannot be exactly determined. In addition, the measured devices typically feature rough surfaces and c omplex scattering structures that can yield in refractive indices that are different from those of bulk materials. Third, it is not always possible to experimentally analyze each material separately, for instance, the FTO, that is always deposited on the glass substrate. Thus we extract the complex indices of refraction from measurements carried out for planar devices. First, we employ a standard Drude-Lorentz

model to describe the refractive index and then utilizing a non-linear Leuvenberg-Marquardt optimization algorithm to determine the model parameters by fitting an analytical transfer-matrix solution to the measured reflection and transmission spectra. The entire procedure is implemented in Matlab, and the resulting data agree very well with what is reported in literature.

Benchmark 3: Comparison with measured data, glass-FTO-structure

After determining the refractive indices, the first comparison between measured and simulated data is carried out for a simple planar reference device. It features a glass substrate covered by a layer of transparent conducting oxide FTO. The FTO layer thickness ranges around 700nm. For a broad wavelength range, from 300nm up 1200nm, the optical characteristics of this structure are analyzed both experimentally and numerically. During the experiment a monochromatic plane wave impinges on the structure and both reflected and absorbed power are measured simultaneously. For a direct comparison to simulated data, the same structure is modeled in OPUS 3-D. The comparison between simulated and measured data is shown in figure 4. The solid lines indicate measured data, the dashed curves show both the computed reflection and transmission spectra. The plot clearly shows the excellent agreement between simulated and measured data for the entire wavelength range.

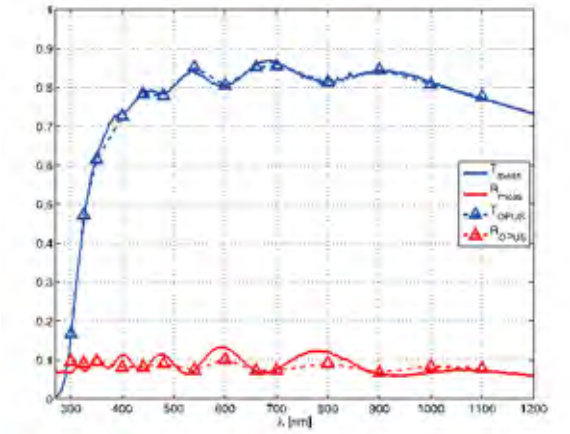


Figure 4: *Comparison between measured (solid) and simulated (dashed) data for a glass-FTO structure. Blue: transmission coefficients, red: reflection coefficients.*

Benchmark 4: Comparison with measured data, glass-ZnO-FTO-structure

Here, a more elaborated device is being analyzed. It is similar to the previous reference device, but this time the structure features an additional compact layer of ZnO with a thickness of 840nm. The benchmarking procedure is identical to Benchmark 3 – for a broad wavelength range we measure and simulate the reflection and absorption spectra. A direct comparison of these data is shown in figure 5. The solid lines indicate measured reflection and transmission coefficients whereas the dashed lines indicate simulation results. Again there is excellent agreement between simulated and measured data over the entire wavelength range.

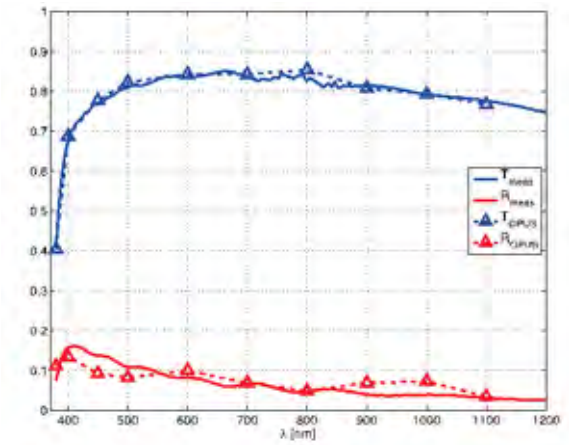


Figure 5: *Comparison between measured (solid) and simulated (dashed) data for a glass-ZnO-FTO structure. Blue: transmission coefficients, red: reflection coefficients.*

Status report on work package 4: *Simulation of more realistic structures and comparison to measured data*

The previous benchmarks illustrated that OPUS 3-D is capable of computing both reflection and transmission spectra in such way that they can easily be compared to measured data. After having shown the simulator's accuracy by comparing the numerical results to either analytical reference solutions or measured data, the following section illustrates how the simulator can help to investigate and under-stand experimental findings that cannot be explained or reproduced with simple one-dimensional or analytical models.

The structure we investigate in the following is a ZnO nanowire array whose detailed description can be found in [3]. A SEM image of the structure is shown in figure 6. Here, various arrays of ZnO nanowires were electro-deposited on glass substrates featuring a conducting SnO2:F layer. In order to control each nanowire dimension separately (diameter and length) we have used our reported methods for electrodeposition of ZnO nanowire arrays with tailored dimensions (see also [4]). These nanowires differed with respect to thickness (diameter from 105 to 330 nm) and length (from 0.5 to 2 µm).

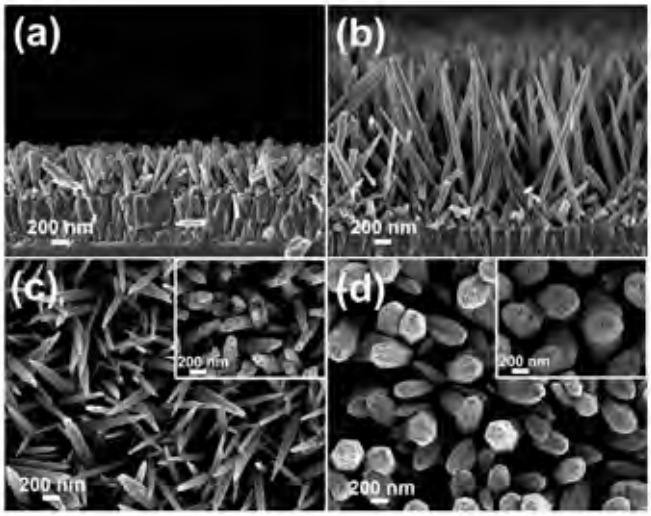


Figure 6: *SEM image of the ZnO nanowire absorber.*

The experiments revealed that both the length of the nanowires and their diameter have a very strong but distinct impact on the reflection and transmission spectra. The measurements show that – leaving the nanowire diameter constant – an increase in nanowire length generally results in significantly higher reflection while leaving the peak reflection wavelength unchanged. In contrast, increasing the width of the nanowires while keeping their length constant not only broadens the reflection spectrum but also leads to a significant red shift of the absorption peak wavelength. Both experimental findings are outlined in figure 7.

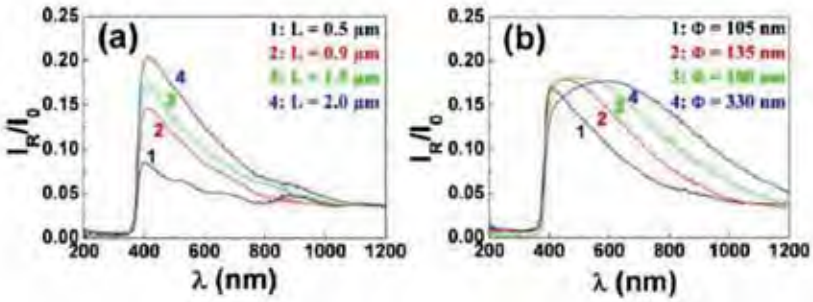


Figure 7*: Measured reflection spectra - impact of length scaling (left) and diameter scaling (right).*

It is the goal of this benchmark to show that a numerical analysis of such nano-wire structures confirms the essential experimental findings. Clearly, this is a problem that cannot be analyzed with simple one-dimensional approaches or ray-optical approximations but mandates the use of 3-D full-wave simulations as the devices feature complex three-dimensional sub-wavelength nanowires. A particular challenge arises during the numerical analysis, as this is a multi-scale problem. On the one hand we have to treat a rather large simulation domain with a size of several wavelengths in any of the three spatial dimensions. On the other hand, the nanowires featuring a diameter ranging around 100nm are

sub-wavelength structures that need to be accounted for. It is the combination of large simulation domains and small sub-wavelength structures that makes the numerical investigation of these structures a most challenging task. Such multi-scale problems cannot be efficiently treated with standard numerical tools such as Finite Elements or Finite-Difference Time-Domain. In both cases the computational cost would be much too high for an efficient numerical treatment.
The computational model used for the numerical analysis with OPUS 3-D is depicted in figure 8. Similar to what was done on the experimental side we modified both length and diameter of the nanowires and computed the reflection and transmission coefficient for a large wavelength interval ranging from 400nm to 1000nm. The efficient numerical model guaranteed moderate computational requirements even for very detailed and accurate models. All numerical problems featured between 2'500'000 and 4'500'000 degrees of freedom, which translated to a memory consumption of some 25 GByte. Employing the newly developed load balancing scheme the computation time ranged around 80 minutes when distributed to 12 CPUs.

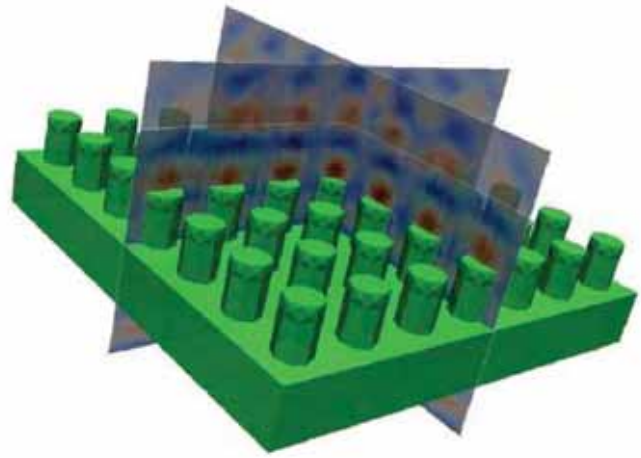


Figure 8: *Simulation model to investigate the impact of the nanowire geometry on the optical characteristics.*

The key findings of the simulations are illustrated in figure 9. The left plot shows how the reflection spectrum evolves when the diameter of the nanowires is kept constant at 200 nm whereas the length increases from 500 nm to 1500 nm. Similar to what is observed during the measurements we see that the reflection coefficient strongly increases for wavelengths between 400 nm and 600 nm whilst the spectral position of the reflection peak remains approximately constant at about 500 nm. This is in excellent agreement with measured data. If – on the other hand – the length of the nanowires is kept constant at 1500 nm whereas their diameter is increased from 200 nm to 290 nm the simulation reveals two significant changes in the reflection spectrum. These changes are depicted in figure 9. First, the increasing width leads to a broader reflection spectrum. Second, the new absorption spectrum shows a clear red shift – its peak wavelength shifts from 500 nm to 600 nm. Again, this is in very good agreement with measured data.

Summing up, a comparison to the measured results clearly shows that both key findings – the increase of reflection with increasing length and both the red shift and the broadening of the spectrum with increasing width – can be reproduced and analyzed using numerical simulations. Here, we have good agreement not only qualitatively, but also quantitatively.

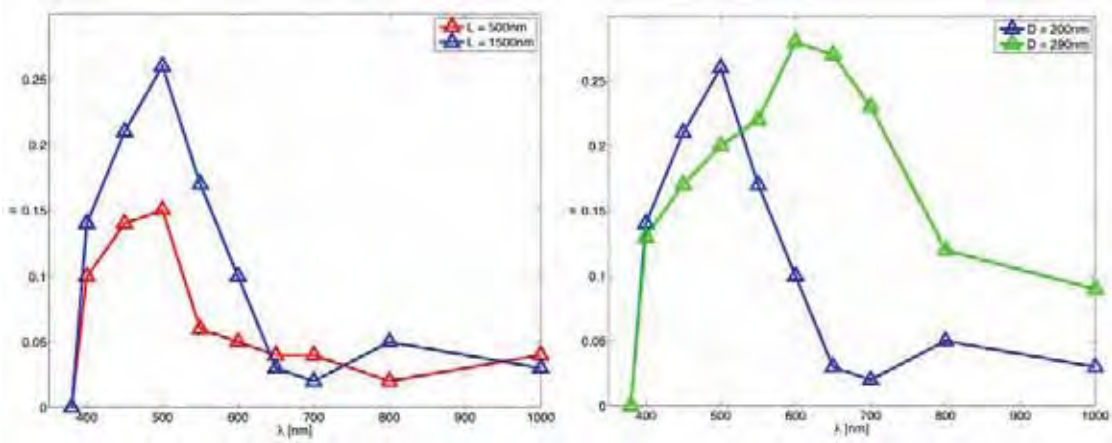


Figure 9: *Simulation results - impact of length scaling (left) and diameter scaling (right).*

National collaboration

As already outlined in the last report, the success of the entire project is strongly related to the efficient and fruitful national collaboration between EMPA Thun and the Zurich University of Applied Sciences. The communication and cooperation strategy has not changed since the last report. Thus, all work packages that could be carried out independently were split between the partners. Other tasks that required far-reaching strategic discussions were decided upon by all partners in order to achieve the best possible results.

In addition, this research project has also arisen strong international interest. The project team was approached by the editor of an international innovation magazine and invited to publish an article about their work that is to appear in a special edition focusing on cutting edge Swiss research. This article will be available for more than 30'000 readers in Europe and the INCO countries and is to appear during the next couple of months.

Conclusion and outlook

We have successfully demonstrated that our novel simulation software OPUS 3-D is well suited for the numerical analysis of elaborate ETA solar cell structures. By showing the good agreement between measured and simulated optical data for a broad variety of designs we could illustrate that our approach – combining measured and simulated data – is well suited for the analysis and design of next-generation ETA solar cells. Among the next possible steps are the analysis and design of even more complex structures such as solar cells featuring urchin-like nanostructures or the transition to combined electro-optical simulations.

In addition, this research project has also arisen strong international interest. The project team was approached by an international innovation magazine and invited to publish an article about their work that is to appear in a special edition focusing on cutting edge Swiss research. This article will be available for more than 30'000 readers in Europe and the INCO countries.

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des transports, de l'énergie et de la communication DETEC

Office fédéral de l'énergie OFEN

SOLHYDROMICS

NANODESIGNED ELECTROCHEMICAL CONVERTER OF SOLAR ENERGY INTO HYDROGEN HOSTING NATURAL ENZYMES OR THEIR MIMICS

Annual Report 2012

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Project- / Contract Number	SOLHYDROMICS / 227192
Duration of the Project (from – to)	01.01.2009 – 31.06.2012
Date	02.02.2013

ABSTRACT

The main objective is to leapfrog current limitations of third-generation PV devices through a drastic improvement of the materials used for assembling XSCs.

The first step is the substitution of the liquid electrolytes, currently used in dye sensitized solar cells, with solid-state hole conductors. In parallel, semiconductor quantum dots (QDs) with tuned band gap, designed to enhance the photon capture efficiency, will replace the organic dyes as light absorbers.

A striking improvement is expected from multi exciton generation (MEG) effects, overcoming the Shockley-Queisser efficiency limit of 31% for the PV conversion. In a second step, highly innovative QDs with supramolecular hierarchical nanostructure will be designed and synthesized: the QDs will be covered by self-assembled monolayers of amphiphilic dye molecules, mimicking the photosynthetic antenna system. The dye molecules will act as molecular relays (MRs), which connect the QDs to the transparent conductive oxide (TCO). Novel TCO architectures will be developed for efficient interface energy transfer and electron diffusion.

Six academic institutions guarantee an interdisciplinary research, based on top level theoretical and experimental approaches.

The high degree of knowledge of solid-state physics and chemistry, nanoscience and nanotechnology of the researchers assures that the new concepts and the objectives proposed will be successfully developed/pursued.

Fiat research center and Solaronix, a SME leader in the XSCs production, will provide proof-of-concept prototypes to validate the innovative materials developed by the academic partners. Materials and technological solutions of INNOVASOL are original and will pave the way for future generation XSCs alternative to devices so far developed both inside and outside Europe.

Aims of the project

SOLHYDROMICS aims to build a photochemical water splitting device using either natural or artificial catalysts. Leaves and algae can split water into oxygen and hydrogen at ambient conditions exploiting sun light. Prof. James Barber, one of the key participants of the SOLHYDROMICS project, was the recipient of the international Italgas prize in 2005 for his studies on Photosystem II, the enzyme that governs this process. In photosynthesis, the reducing equivalents derived from H_2O splitting are used to reduce CO_2 giving rise to the various organic compounds of living organisms including those which provide fuel (biomass, sugars, vegetable oils as well as being the origin of the fossil fuels). However, in certain types of photosynthetic organisms and under some conditions a specific enzyme, hydrogenase, can by-pass the CO2 fixation process and can lead to non-negligible H2 formation. The main goal of SOLHYDROMICS will be the development of an artificial device capable of splitting water to produce hydrogen at ambient temperature composed of:

- An anode exposed to sunlight carrying Photosystem II or a PSII-like chemical mimic. Initially, PSII from microalgae known as cyanobacteria will be isolated with high water splitting activity, and immobilized for attachment to the electrically conducting membrane. In this way the generation of electrons and protons from water at the anodic surface will use the natural light harvesting system, charge separation machinery and water oxidation site of PSII. In the longer term synthetic metal-clusters will be explored which can bring about light-driven directional charge separation, thus mimicking the natural photosynthetic reaction centre, and use the oxidizing potential of the “hole” to split water on a specifically tailored electrochemically active catalyst.
- A cathode will carry a hydrogenase or an artificial hydrogenase catalyst in order to recombine protons and electrons into molecular hydrogen. Here again, the initial studies will involve immobilizing the natural enzymes, including those with low sensitivity to oxygen. Also, as for the water splitting site on the anodic side of the membrane, the longer term goal will be to synthesis a catalytic site which mimics hydrogenase activity in order to produce hydrogen gas.
- A membrane enabling transport of both electrons and protons via e.g. carbon nanotubes or TiO_2 connecting the two electrodes and ion-exchange resins like e.g. Nafion or SPEEK, respectively. The membrane will have to be tailored to provide the minimum transfer resistance so as to achieve maximum conversion efficiencies. Previous experiences of some of the partners showed that Nafion can play a role both as an enzyme immobilization medium over electrode materials and as solvated proton conductor (like in PEM fuel cells). This will offer a wonderful opportunity to design a system that can readily catch the protons where they are generated and drive them by diffusion towards the cathodic electrode where H_2 will form, due to the injection of excited electrons derived from the chlorophyll / dye dependent photo-activated water splitting reaction.

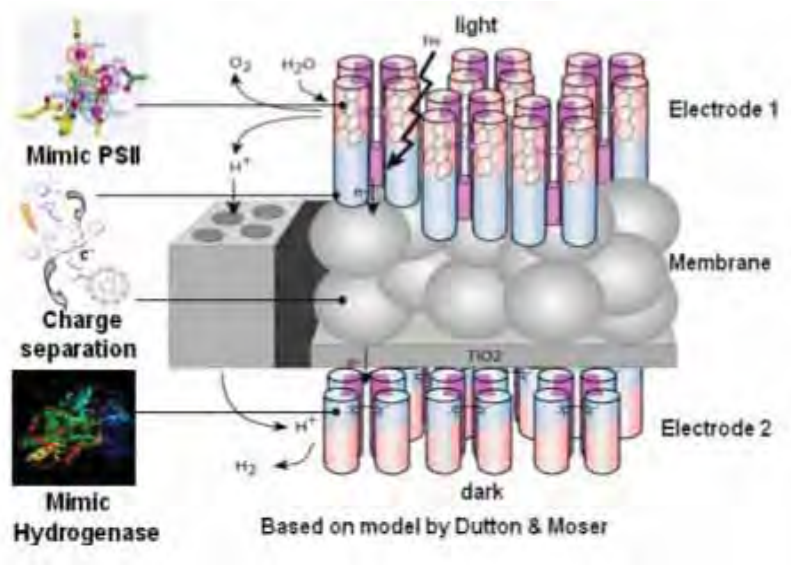


Figure B. 1.1.1 *Scheme of the SOLHYDROMICS device concept, based on the original idea by Dutton & Moser (personal communication to J. Barber).*

Technical Objectives

The main technical and scientific objectives of the SOLHYDROMICS project are:

- Development of an innovative device capable of using sunlight to produce hydrogen from water splitting in a most cost effective way with routes based on photovoltaics coupled with electrochemically driven catalysis. An ambitious efficiency target is 10% conversion of solar energy into pure hydrogen which is considered to be feasible based on preliminary calculations by the proponents.
- The device must be robust with long operational times. A target of 1 week continuous operation is envisaged for a first generation SOLHYDROMICS prototype based on natural enzymes, whilst a 1 month continuous operation is targeted for the second generation one based on stable enzyme mimics. Subsequent technology improvements, beyond the proposed project should lead to a lifetime of years.
- To disclose wide potential application opportunities, the above targets must be reached without using expensive noble metals or materials and via assembling techniques amenable for mass production.
- The potential of this artificial solar energy conversion route will also be assessed in comparison to intensive micro-algal growth systems aimed at producing hydrogen or vegetable oils as fuels.

Work package No	Work package title	Type of activity	Lead participant	Person months	Start month	End month
1000	Coordination and management	MGT	POLITO	19	1	36
2000	Light-driven water splitting electrode	RTD	IMPERIAL	95	1	30
3000	Hydrogen evolution electrode	RTD	BIODIV	95	1	30
4000	Membrane and membrane-electrode-assembly development	RTD	GKSS	88	1	42
5000	Design, construction and testing of SOLHYDROMICS prototypes	RTD	SLX	48	1	42
6000	Modelling, LCA and energy scenarios studies	RTD	HST	68	1	42
	TOTAL			**413**		

Table B.1.3. *Work package list of the Solhydromics project.*

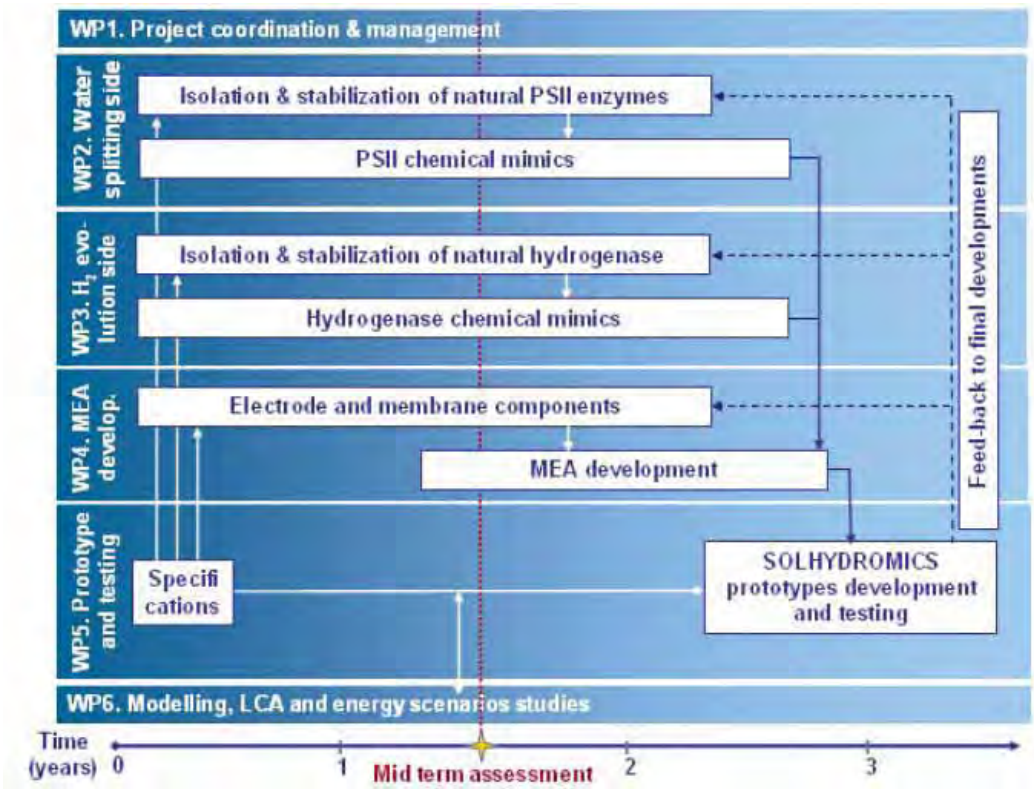


Table B.1.4. *Graphical presentation of the components of the SOLHYDROMICS work plan showing their interdependencies (Pert diagram). N.B.: some WP titles are indicated in contracted form.*

Project partners & role of Solaronix

The SOLHYDROMICS consortium if formed of 6 partners of 4 EU Member States (Italy, Belgium, Germany and United Kingdom) and one partner of an Associated Country (Switzerland).
Two large academic partners, POLITO and Imperial College, and the german research institute GKSS complement 4 high tech SME's, namely Biodiversity, Hysytech, Nanocyl and Solaronix as partners for this ambitious 42 months project.

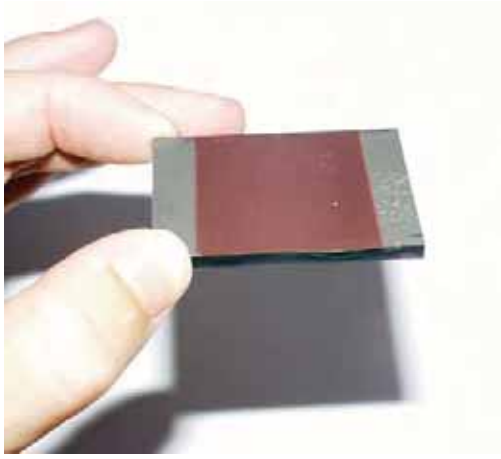
The role of Solaronix is to provide to the partners the critical membrane elements to support the photocatalyst on the anode and/or cathode side of the device. Moreover tuned electrode materials are supplied to the project partners. Solaronix may also be active in formulating and printing the photo-active materials supplied by the academic institutions.

No	Organisation name	Logo	Short name	Type	Nation	Key investigators	Main roles in the project	References/patents
1	**Politecnico di Torino**		POLITO	HES	I	Prof. G. Saracco Prof. E. Garrone Prof. E. Tresso Prof. A. Tagliaferro	Mimics development, membrane dev., modelling	Garrone et al. (2007) *Phys Chem Chem Phys* 9, 1421 Saracco et al. (2007) *Appl.Cata. B.* 70, 525. Tresso et al. (2007) *Solid State Electr.* 51, 1067. Tagliaferro et al (2007) *J. Cryst. Growth* 310,477.
2	**Imperial College London**	Imperial College London	IMPERIAL	HES	UK	Prof. J. Barber Prof. G. Gilardi	PSII and hydrogenase purification and electrode dev.	Barber et al. (2004) *Science* 303, 1831. Barber et al. (2000) *Nature Struct. Biol.* 7, 44. Gilardi et al (2004) *J. Am. Chem. Soc.* 126, 5040. Gilardi et al (2002) *Biosens. Bioelectr.* 17, 133.
3	**GKSS Research Centre on Polymers**	GKSS	GKSS	RES	D	Dr. S. Nunes	Membrane and MEA development	S. P. Nunes and K. V. Peinemann, Eds, Membranes for Energy Conversion, Wiley-VCH, 2008. Nunes et al. (2008) *J. Power Sourc.* 175, 49. Nunes et al. (2007) *J. Membr. Sci.* 295, 121. Nunes et al. (2006) *J. Membr. Sci.* 279, 70.
4	**Biodiversity SpA**	Biodiversity	BIODIV	SME	I	Dr. N. Rota	Electrode development, enzyme stabilisation	The company produces and sells new technologies and products to be used in molecular analysis and diagnostics based on RTD in advanced fields as biochemistry, genomics, proteomics, biotechnology and nanotechnology (www.biodiv.it).
5	Solaronix SA	SOLARONIX "in sun we trust"	SLX	SME	CH	Dr. T. Meyer	Membrane development, percolation of TiO_2	World supplier of nanocristalline TiO_2, ruthenium bipyridine complexes and electrolytes, mainly for the dye solar cell community since 1996. Producer of light soaking test equipment & solar simulators via unique "sulfur-plasma" lamp (www.solaronix.com)
6	**Nanocyl SA**	nanocyl	NCYL	SME	B	Dr. F. Luizi	Membrane development, percolation of CNTs	Nanocyl is focusing on the commercialization of carbon nanotube-based products, useful in producing synthetic materials and manufacturing equipments for the automotive and electronic industries (www.nanocyl.com).
7	**HySyTech srl**	HYSYTECH	HST	SME	I	Ing. M. Antonini Ing. A. Saldivia	Modelling and system development	The company produces and sells hydrogen production and exploitation systems based on patents as WO Patent WO/2005/117,176 by Antonini et al.; PCT/EP2004/051207 by Antonini et al., etc. (www.hysytech.com)

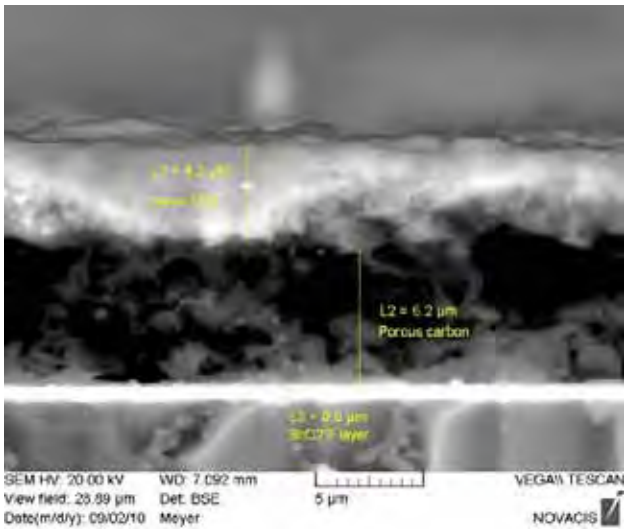
Work carried out and results achieved

First tests were made with all printed electrodes having nano-TiO_2 deposited on top of a electrically highly conducting Elcocarb C/SP porous carbon electrode as model structure for an photo-electrolyzer system. The idea is to provide ultimately a free-standing membrane assembly consisting of ca. 20-50 µm porous carbon impregnated with a proton conductor (SPEEK or Nafion type) topped with a 1 to 10 µm thick mesoporous TiO_2 electrode colored with the light absorbing dye.

Free-standing carbon/TiO_2 electrodes of sizes up to 10x10 cm can be elegantly made using our chemical release layer technique developed earlier in the project.



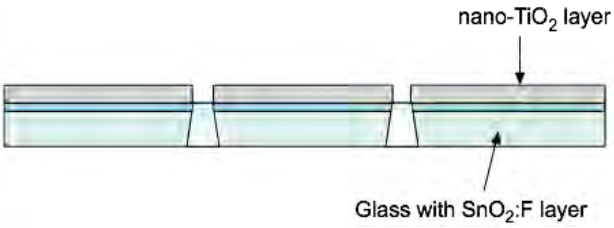
Ruthenium dye colored mesoporous TiO_2 printed on top of a robust and conductive (~ 10 ohm/ square) Elcocarb C/SP porous carbon layer deposed on a supporting glass substrate.



SEM picture showing the cross section of the ~ 6 µm thick Elcocarb C/SP and the ~ 4 µm thick TiO_2 electrode stack printed onto a SnO_2:F coated glass as substrate.

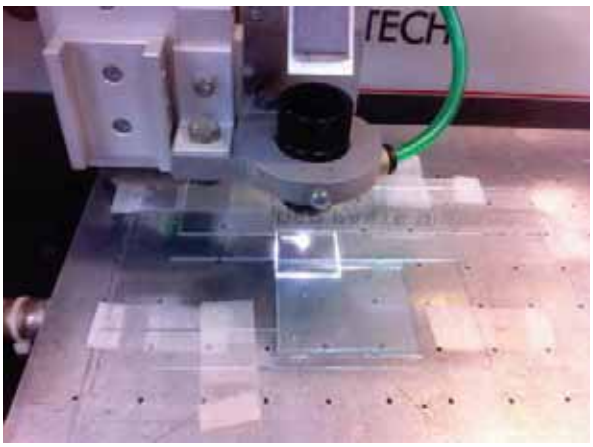
The envisaged photoelectrolyzer may require a bipolar electrode made of an electrically conductive transparent substrate material allowing ionic conduction across its thickness.

A model of such a bipolar electrode was built using a one sided FTO coated glass having holes filled with the proton exchange material.

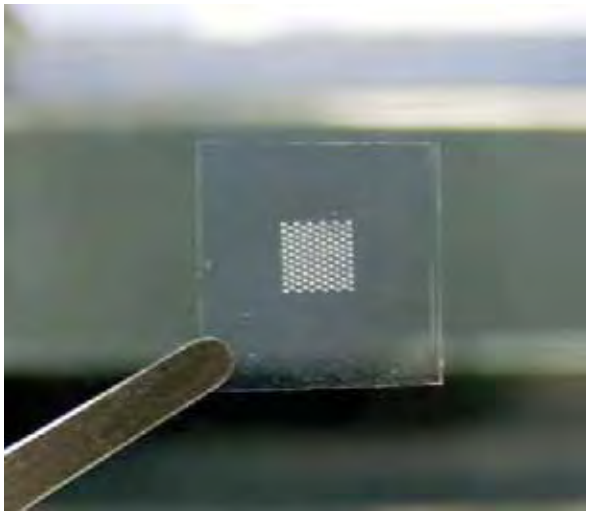


The idea is to coat this micro-drilled glass with nano-TiO_2 on the FTO coated side as photo-electrode, and that the conical holes are filled up with for example Nafion® for proton conduction. Note that the glass is only 100 µm thick and two of such glasses laminated together form a bipolar electrode.

The idea is to form an array of micro-drilled holes into a conductive coated glass substrate:

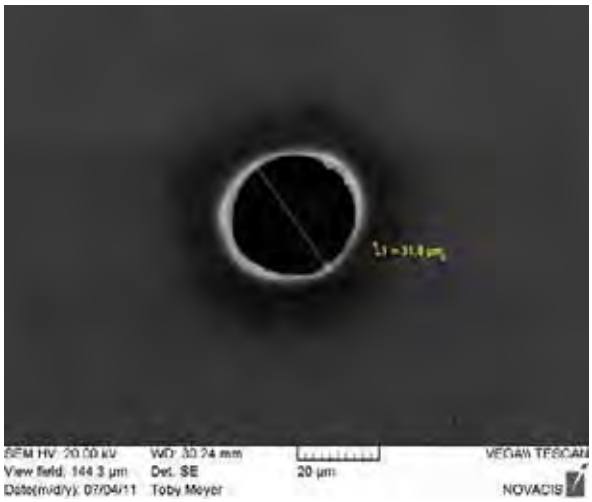


CO_2-Laser drilling of a 100 µm thin 15 x 15 mm sized glass plate.



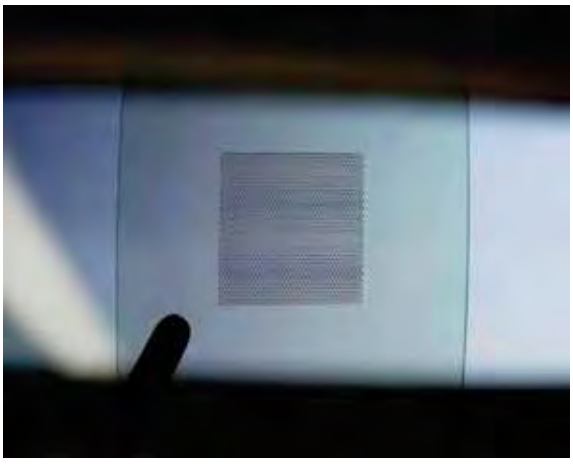
The 100 µm thin Schott AF32eco glass is coated with a fluorine doped tin oxide (FTO) layer, having a surface conductivity of ca 40-70 ohm/sq for these samples.

Optical micrograph of a 110 µm diameter CO_2 laser drilled hole in a 100 µm thick aluminoborosilicate glass - first trials.

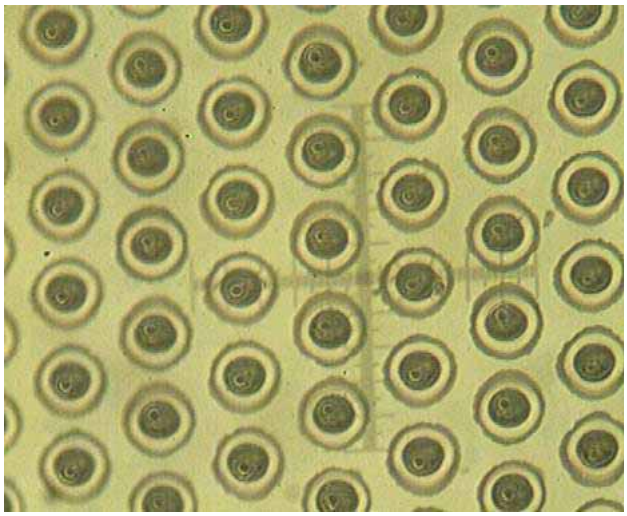


SEM picture showing an improved hole with a diameter of ca. 35 µm being CO_2 laser drilled into FTO coated 100 µm thick thick aluminoborosilicate glass.

Using 150 µm thick quartz glass as substrate it was possible to form micro-hole arrays having up to 1’659 holes on a 10 x 10 mm surface.

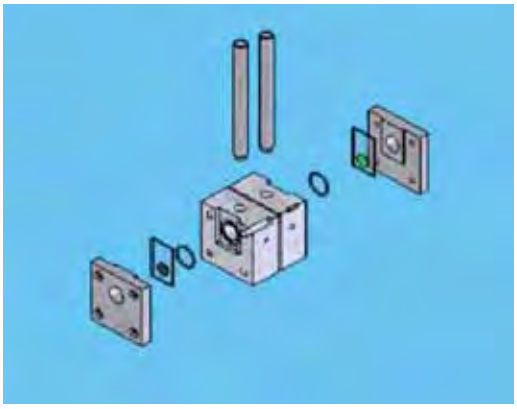


Laser drilled microholes array on a 100 µm thin 25 x 25 mm sized quartz plate.



Optical microscope view from the SnO_2:F side. Holes ~ 30 µm ø.

Finally, various versions of a small electrolyzer unit were designed by CAD, a version for 6 mm diameter TiO2 electrodes on 12 x 20 mm glass holders is shown in the exploded view below:



The device is ca. 5 x 5 x 5 cm in size (without the access pipes) and fits well into a solar simulator. The working electrode (marked in green in the drawing) and the counter-electrode are both removable, as well as the proton exchange membrane located in between the 2 electrode holders.

National and international cooperation

Running of the 3 years "KTI-Project" N° 10584.1 PFIW-IW with the EMPA Dübendorf (Switzerland) on the topic of near infrared absorbing organic sensitizers.

FP7-Project "INNOVASOL" – coordinated by Dr. Leo Marchese of the SiSTeMI center at the University of Piedmont, Italy.

INNOVASOL aims to increase the efficiency of exitonic solar cells to 15 % by using innovative approaches in cell designs and novel materials (see www.innovasol.eu).

FP7-Project "ORION" – coordinated by Dr. David Mecerreyes at the CIDETEC, San Sebastian, Spain. This project investigates the development of a new family of functional inorganic-organic hybrid materials (for example metal oxide – ionic liquid) characterized by an ordered morphology (see http://www.cidetec.es/ORION/index.html).

FP7-Project "CRONOS" - coordinated by Prof. Stefano Sanvito at the CRANN of the Trinity College Dublin, Ireland. The project aims to investigate the "Time dynamics and ContROl in naNOStructures for magnetic recording and energy applications", see http://www.cronostheory.eu/

FP7-Project "ARTIPHYCTION" - coordinated by Prof. Guido Saracco at the Politecnico Torino, Italy.

This project aims to build a «Fully artificial photo-electrochemical device for low temperature hydrogen production». Started on 1st May 2012.

FP7-Project "ADIOS-Ru" - coordinated by Dr. Mazhar Bari at the Solarprint, Ireland.

This project aims to take care of the "Advanced Design and Industrialization of Organic Sensitizers without Ruthenium for Dye Sensitized Solar cells". Started on 1st November 2012.

FP7-Project "ECO2CO2" - coordinated by Prof. Guido Saracco at the Politecnico Torino, Italy.

This project aims to build a «Eco-friendly biorefinery fine chemicals from CO_2 photo-catalytic reduction".

Started on December 1st, 2012.

Evaluation 2012

SOLHYDROMICS ended in June 2012 and it was demonstrated that the Solaronix membranes worked in a second generation photoelectrolyzer unit, having a artificial catalyst (APCo5 developed by POLITO) at the oxygen evolution side and a platinum electrode for the hydrogen evolution electrode.

A follow-up project «Artiphyction» and a similar project called ECO2CO2 have been granted and both have started at the end of 2012. These 2 projects will also use the original membrane technology and the materials developed during the SOLHYDROMICS works.

References

http://www.solhydromics.com

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Département fédéral de l'environnement,
des transports, de l'énergie et de la communication DETEC

Office fédéral de l'énergie OFEN

OPTIMIZED METHODS FOR INCREASED PERFORMANCE PHOTOVOLTAIC CELLS BY NANOPARTICLES INTEGRATION (OPTINOGEN)

Annual Report 2012

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Project- / Contract Number	OPTINOGEN / 10.264
Duration of the Project (from – to)	01.11.2011 – 30.04.2013
Date	17.10.2012

ABSTRACT

The project targets the optimization and the development of new improved methods for enhancing of the overall performance and stability of nanocomposite solar cells (NSC) by introducing new physical principles such as e.g. plasmonic and quantum phenomena into functionality of NSCs with metal nanoparticles (NP), and new strategies of stabilization of the active nanocomposite layer morphology. Research focuses mainly on the method of NP implementation, on different types of NP to be used and on the material investigation.

Firstly, a consistent state-of-the-art in the field of NP integration into the photovoltaic cells was performed. This research covers many aspects of the nanoparticle based photovoltaic cells starting from simulation of the idealized systems through nanoparticle synthesis routs to the implementation into the real system. The main attention was focused on the thin film organic photovoltaic (OPV) based on the organic semiconductors (e.g. poly(hexylthiophene), PCBM(6,6-phenyl-C61butyric acid methyl ester).

Possible ways of integration of the NP in the OPV (thin film organic photovoltaic) architecture were identified and divided into two groups with regards to the routes of NP synthesis and to their further manipulation.

In the second step research was focused mainly on two aspects: NP synthesis and NP distribution in the active layers of OPV. Several batches of silver NP were obtained with size distribution 80 -120 nm with spherical and cubic shapes and further transferred to the final solution of active material.

Simultaneously to the NP synthesis, there were obtained continuous thin layers of titanium oxide follow the titanium oxide sol-gel precursor synthesis.

Finally active materials containing Ag NP were prepared in form of continuous films and the nanoparticles distribution was further investigated.

Project objectives

The energy demand increases due to the incessantly raising world population and improving standards of living. The need to develop and deploy large-scale, cost-effective, renewable energy is becoming important. The storage and conversion of sunlight into electricity during times of day with little sunshine is still a sticking point when it comes to optimizing solar cell function and appeal.

The nanocomposite solar cells (NSC) based on the organic-organic and the hybrid organic-inorganic nanocomposites represent a class of photovoltaic (PV) devices which promise breakthrough advances towards a large scale exploitation of renewable energy sources. Low weight, good mechanical properties enabling integration with various surfaces, and the possibility of large-scale manufacturing by the low-cost screen-printing and related technologies are the key advantages of NSCs, which fulfil the forward-looking demands for launching new low-energy-consumption, environmentally-friendly technologies and products that enhance spreading the sustainable energy conversion processes at a low ratio cost per watt generated. However, the highest PV conversion efficiency of polymer NSCs achieved so far is ca. 5 %, or ca. 7 % if they are used in the tandem arrangement; this value should be increased to above 10 % for NSCs can enter the real market as truly competitive large-scale products. Also the stability of NSCs should be improved.

The increase in the PV conversion efficiency of organic (OSC) and dye sensitized solar cells (DSSC, dubbed 'Graetzel cells') has stopped at values 5.4% for OSC (Plextronics [1]) and 11.1% for DSSC (Sharp [2]). The observed low PV conversion efficiency of real solar cells should be ascribed to drawbacks associated with the preceding (photoexcitation) and consecutive (transport and collecting charges) partial processes of the overall PV energy conversion.

A degradation of NSC components is mostly prevented by encapsulation that, however, does not prevent morphology changes at elevated temperature. Figure of merit for the economic effectiveness is the power efficiency of 10% with lifetime of 10 years and the highest power conversion efficiency achieved is about 7%. Several improvements of the NSCs overall power efficiency are foreseen based on the already established principles: synthesis of a low band gap polymer ([3]), fabrication of series tandem cell, using optical spacer. The Grätzel cells type DSSCs used with TiO_2 or ZnO n-type semiconductor reach power efficiency about 12%. The liquid electrolyte used in this type of cells can be replaced by a solid-state electrolyte or directly by a semi conductive polymer. To increase the efficiency, the length, spacing and aspect ratio of the inorganic semiconductor nanostructure should be improved.

The project targets the optimization and the development of new improved methods for enhancing of the overall performance and stability of NSCs by introducing new physical principles such as e.g. plasmonic and quantum phenomena into functionality of NSCs with metal nanoparticles, and new strategies of stabilization of the active nanocomposite layer morphology. In the frame of the project, simulations and calculations will be conducted and confirmed by relevant experimental research in laboratory environment. Thus, the overall conversion efficiency will be improved and the reliability increased.

Due to the unique optical, electronic and magnetic properties noble metal (such as Ag and Au) nanoparticles (NP) were proposed to improve performance. Some authors ([4]) reported on the incorporation of very thin Ag and Au layers into the series tandem PV structure. Apparently, such layers provide efficient recombination centers for charge carriers to make the tandem structure functional but, additionally, they may cause an optical field enhancement.

Unfortunately, a combination of several effects does not correspond to the best figure of advantages for each system; somehow the system needs compromise to achieve the best performance. Therefore, an introduction of new physical principles is necessary to overcome present limits. High performances can be reasonably achieved only by use of optimized methods; thus one of the goals of this project is the optimization and the development of new improved methods for enhancing the overall performance and stability of NSCs by implementation of standard flow charts of the whole process of nanoparticles integration into the photovoltaic cell manufacturing, validated by tests.

Thus, the purpose of the project is to carry out further researches in the field leading to enhance the properties of photovoltaic cells based on nanoparticles and to overcome some of the challenges still unsolved. Researches will focus mainly on the method of nanoparticles implementation, on different types of nanoparticles to be used, on the material investigation.

The main deliverables of the project are:

1. Summary of current methods used for nanoparticles integration in photovoltaic cells
2. Flow chart of the whole process for different types of nanoparticles integration
3. Report on optimization of the current methods and of different components of the PV cells
4. Report on validation of the new proposals for optimization
5. Nanoparticles integration steps and procedure using new optimized methods
6. Nanoparticles integration performance and definition of the tests
7. Final report on results of the tests and identification of potential improvements of the nano-particles integration.

Work performed and results

Based on the literature search of current methods used for enhancing the overall performance and stability of different types of NSCs by nanoparticles integration a complete state-of-the-art was performed that allows to define the next step for further investigation.

The overview covers such aspects of the nanoparticle (NP) integration in photovoltaic cell as:

- place of implementation,
- types and size of the NP used,
- method of NP synthesis and their further functionalization steps (if any),
- type of the semiconductors used,
- structure and architecture of the final cell,
- observed improvement of the cell performance.

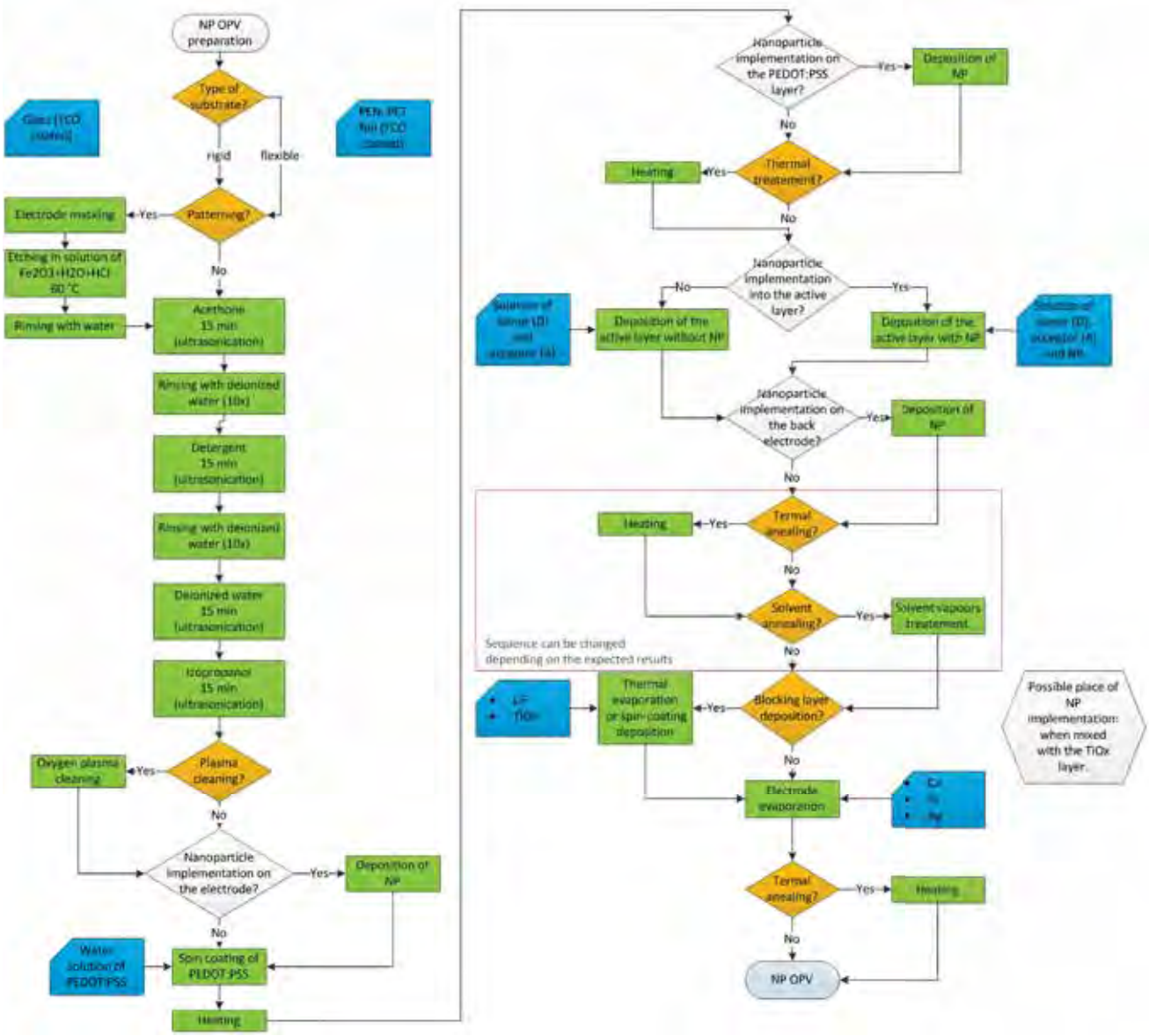
One of the most important aspects of this work was finding of existing incoherentness in the scientific communications, especially when size, shape and the material of the nanoparticles are reported for implementation in deferent organic donor-acceptor systems (e.g. P3HT/PCBM). Based on this research it can be summarized that some of the identified problems need deeper understanding and further investigation. Some of them are:

- influence of the nanoparticle size on the charge carrier transport in the solar cell - NP with bigger radius are identified to be better hole transporting medium then smaller ones used in the same system,
- experimental works are dedicated mostly to the spherical nanoparticles of different size - different shapes (especially cubic ones) are considered only in simulation works,
- instead of the nanoparticle implementation itself, one should be fully convinced about keeping high standards for other device preparation steps.

The model system for further investigation was proposed based on the most common architecture for OPV, where the layers are arranged as follows:

- glass substrate coated with transparent conducting oxide (e.g. indium thin oxide),
- poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS) layer,
- organic donor-acceptor active layer,
- titanium oxide (TiO_X) exciton blocking layer,
- metal electrode.

Such architecture and the available methods of layers deposition give a wide range of possibilities of NP integration in the OPV. A sketch of a fabrication process for organic photovoltaic with noble metal NP has been proposed and summarized. The possible routes of implementation of the NP were gathered and presented on the flow chart (Scheme 1) for the visualisation of the solar cell preparation and integration of different types of nanoparticles. The flow chart allows choosing many possible routs of OPV preparation with use of variety of available substrates, concerning both the bottom-up or top-down NP synthesis routes and deciding on the place of NP integration during the production. Apart from NP integration also other known methods of OPV efficiency enhancing are included into this chart e.g. solvent and temperature annealing steps.



***Scheme 1**: Flow chart for nanoparticles integration in organic photovoltaic cell.*

Generally, there were indicated three main possible places of NP integration for enhancing the overall performance and stability of the cell:

- at the anode site,
- in the bulk of the active layer,
- at the cathode site.

Concerning this assumption there were proposed two deferent routes of noble metal NP synthesis:

1. As first step, the synthesis of un-functionalized silver NP was chosen. There are water soluble that should allow to mix them with the PEDOT:PSS layer as well as with the TiO_X layer. This should give an opportunity to the model PV system with NP placed at the beginning (anode) as well as on the end (cathode) of light path in the device. The NP can be immobilized in the adequate layer in one preparation step or settled in a separate step on the layer interphase e.g. at the interphase of TCO/PEDOT:PSS, PEDOT:PSS/semiconductor layer or semiconductor layer/TiO_X.

   The chosen synthesis for the silver nanoparticle is a seed mediated grown one, detailed in the work of Zhang et all [5]. This synthesis allows controlling the size on Ag NP from 5 nm (for the seeds) up to 200 nm. The main advantage is that this control is accomplished by the time of the reaction. Furthermore, it is relatively easy to up-scale reaction that is important for up-scaling the overall cell production. On the other hand it allows synthesizing both spherical and cubic NP. That opens the doors for a better understanding and possible comparison with simulation works on the absorption enhancement in thin-film organic solar cells [6].

The preliminary work on this synthesis has started thanks to the cooperation with Adolph Merkle Institute (AMI), University of Fribourg.

2. Second step is the synthesis of the functionalized NP soluble in organic solvents for integration into donor-acceptor layer.

   The main concept of this step is to prepare systematic studies of the NP size effect on the organic solar cell performance as it could help to understand the influence of plasmonic and the light diffraction effects on the overall cell performance and how the synergy of these two effects can be used in the proposed model system. This should help to understand what the real influence of the size of nanoparticles is, especially when they are implemented into the donor-acceptor layer.

Silver nanoparticles (AgNP) were synthesized using two different synthesis routes with use of silver trifluoroacetate (CF_3COOAg) and silver nitrate ($AgNO_3$) as NP precursors. Both of this synthesis allows obtaining spherical AgNP with 80 to 120 nm in diameter; moreover synthesis with $AgNO_3$ under nitrogen atmosphere gives cubic shaped NP. The average NP size and shape was investigated with use of dynamic light scattering (DLS), transmission electron microscopy (TEM) (see figure 1).

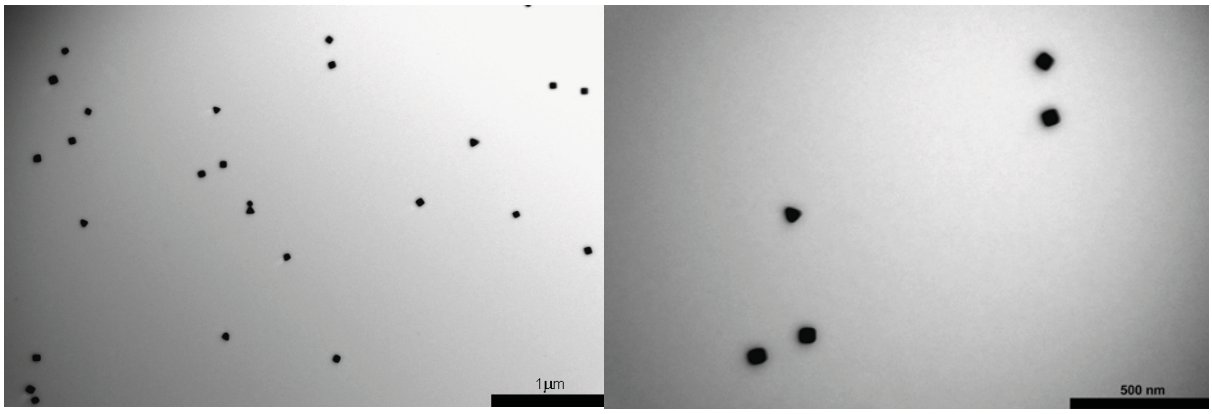


***Figure 1**: TEM image of cubic Ag nanoparticles*

At the first stage, the batch with average 100 nm cubic AgNP was chosen for further investigation. NPs after reaction were cleaned by several sonication and centrifugation cycles using acetone and water. Final concentration of AgNP in water was about 1.9 mg/ml.

Water suspension of AgNP was measured with UV-Vis spectrometer. The plasmonic peak of synthesized NP was observed at 450 nm with additional shape dependent peaks at 350 nm and 380 nm.

In the next step, the NPs were transfered from water to alcohol based solution. In this case, last cleaning was performed in methanol and after removing the supernatant, solution was left to dry in air. AgNP in dry state were further redispersed in both: anhydrous methanol and MiliQ water. In both cases the AgNP were successfully redispersed and exhibit plasmonic peak at same position as for the initial water suspension (450 nm).

From both suspension there were prepared solid samples using drop casting technique – droplet of suspension was left to dry in air on the glass substrate. UV-Vis spectra shows shift of the plasmonic peak in both samples to 442 nm that can be explained by aggregation that occurs during solvent evaporation.

Simultaneously the titanium oxide precursor was synthesized for TiO_X layer that serves as an exciton blocking layer and optical spacer in chosen model of organic photovoltaic cell. All reaction steps were performed under nitrogen and the final reaction product was dissolved in methanol with two volume ratio: 1:30 and 1:200.

The TiOx thin films were prepared by solidification of the initial sol-gel suspension after contact with moisture from the air. Layers were deposited on the glass support with use of the spin coating technique at different spinning speeds (500-1000 rpm).

Next step was to prepared common solution of TiO_X precursor and AgNP that was realized by mixing dissolved precursor together with methanol based NP suspension. The final concentration of TiO_X in all cases was 1:200 when the AgNP concentration was 0.09 mg/ml, 0.19 mg/ml, 0.38 mg/ml and 0.95 mg/ml respectively. All solutions were spin coated with 500 rpm and 1000 rpm on glass forming continuous layers of TiO_X with immobilized AgNP. The AFM investigation (see figure 2) proves isotropic

distribution of NP in the layers. In all cases metal nanoparticles stays over the TiOX layer, that is less than 50 nm in thickness, and are coated with thin titanium oxide shell.

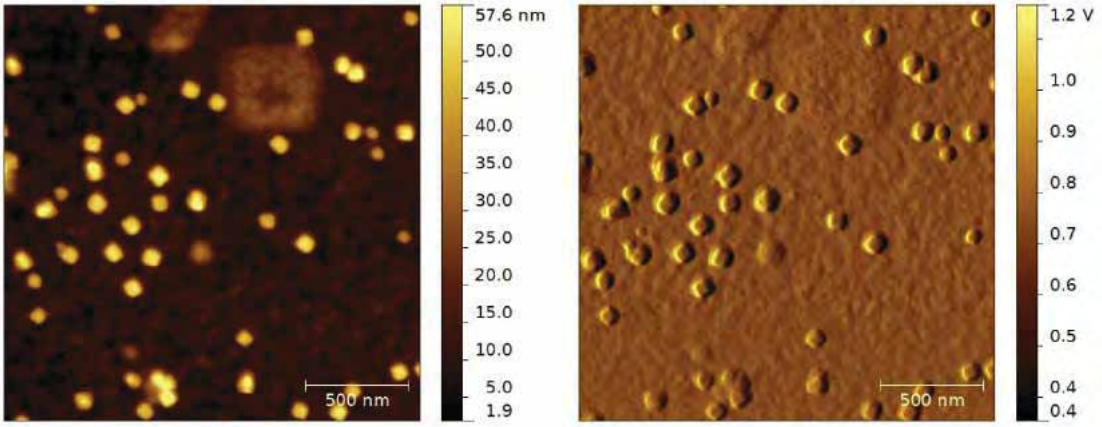


Figure 2: *AFM height (left) and amplitude contrast (right) image of spin-coated layer of AgNP in TiOx.*

Cooperation at the national and international level

The continuous progress of the project is ensured thank to the cooperation (on the national level) with Adolphe Merkle Institut (AMI), University of Fribourg – where all the chemical synthesis are performed under supervision of Prof. Alke Fink who is one of the leaders of the “Bionanotechnology group” at the AMI.

Final cell design, preparation and characterization are performed together with Prof. Marc Jobin and his group at the "Institut des Sciences et Technologies Industrielles" at "Haute école du paysage, d'ingénierie et d'architecture (HEPIA)" in Geneva.

On the international level, there exist continuous collaboration between EIA-FR and Lodz University of Technology (Lodz, Poland) that is the Home institution of Dr. Michal Wiatrowski.

Assessment for 2012 and outlook for 2013

During the project duration the following deliverables have been fulfilled:

1. Summary of current methods used for nanoparticles integration in photovoltaic cells
2. Flow chart of the whole process for different types of nanoparticles integration
3. Identification and proposal of optimization of the current methods and of different components of the PV cells

In the forthcoming year we expect to accomplish the rest of project tasks based on the proposed deliverables:

4. Validation of the new proposals for optimization
5. Nanoparticles integration steps and procedure using new optimized methods
6. Nanoparticles integration performance and definition of the tests
7. Results of the tests and identification of potential improvements of the nanoparticles integration

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LIGHT-IN, LIGHT-OUT: CHEMISTRY FOR SUSTAINABLE ENERGY TECHNOLOGIES

Annual Report 2012

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Project- / Contract Number	LiLo / ERC-2010-AdG
Duration of the Project (from – to)	01.01.2011 – 01.01.2016
Date	01/2013

ABSTRACT

The project is concerned with a c oordinated approach to the development of novel chemical strategies for light harvesting by photovoltaic cells and light generation using light emitting electrochemical cells. Both technologies have proof of principle results from PIs own laboratory and others world-wide.

The bulk of efficient dye sensitized solar cells rely on transition metal complexes as the photoactive component as the majority of traditional organic dyes do not possess long term stability under the operation conditions of the devices. LECs based upon transition metal complexes have been shown to possess lifetimes sufficiently long and efficiencies sufficiently high to become a viable alternative technology to OLEDs in the near future.

The disadvantage of state of the art devices for both technologies is that they are based upon second or third row transition metal complexes. Although these elements are expensive, the principle difficulties arise from their low abundance, which creates significant issues of sustainability if the technology is to be adopted.

The aim of this project is threefold. Firstly, to further optimize the individual technologies using efficiency leading to lower metal requirements. Secondly, to explore the periodic table for metal-containing luminophores based on first row transition metals, with an emphasis upon copper and zinc containing species. The final aspect is related to the utilization of solar derived electrons for water splitting reactions, allowing the generation of hydrogen and/or reaction products of hydrogen with organic species. This latter aspect is related to the mid-term requirement for liquid fuels, regardless of the primary fuel sources utilized.

The program will involve design and synthesis of new materials, device construction and evaluation (in-house and with existing academic and industrial partners) and iterative refinement of structures.

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PYROCELL

Annual Report 2012

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Project- / Contract Number	PYROCELL / GRS-013/09, RS/HES-SO Nr. 21025
Duration of the Project (from – to)	01.01.2010 – 31.01.2012
Date	08.01.2013

ABSTRACT

There are compounds that are semiconductors and do not suffer from any supplying restriction such as Cu_2S or Cu_2O or CuO; the most interesting of them is Pyrite (FeS_2). It is a semiconductor that is difficult to synthesize due to the complex chemistry between Iron and Sulfur. But the following striking factors let appear Pyrite to be a very interesting candidate for solar cells:

- **Abundance: Pyrite's prime materials, Iron (Fe: 50'000 ppm) as well as Sulfur (S: 520 ppm) will neither give rise to speculation nor run into a limited feedstock.**
- Optical properties: Pyrite has an electronic band gap of 0.95 eV, a value which is not ideally adapted to the sun spectrum on the earth and which is a little lower than the one of silicon. However, Pyrite has the highest optical absorption coefficient in the visible light from all known solid-state semiconductors. A Pyrite solar cell absorbs the AM1.5* intensity (Air mass 1.5 corresponds to the light intensity of 800W/m^2 typically at 40° latitude) within a thickness of 600 Å.
- Electrical properties: For Pyrite, drift mobilities of the minority charge carriers as high as 2000 cm^2/Vs are reported. This enhanced mobility favors the migration distance of photogenerated carriers to be longer than the absorption depth of the light.

In the envisaged Pyrite based solar cells, all involved layers are extremely thin and can be deposited at low temperature. Thus, the use of polymer substrates and the serial connection scenarios for solar module manufacturing, known from a-Si:H / µc-Si:H processes, can be applied. Virtually large-scale manufacturing can be carried out using roll to roll processing.

The project “PYROCELL”

The photovoltaic industry is currently booming, partly also based on progress contributed from Swiss researchers in thin-film Silicon, and progress in multicrystalline Silicon solar cells together with new socio-economical frameworks. However, all well established PV technologies have all at least on remaining drawback in a way that the boom occurs as soon as strong subvention scenarios apply, such as the power-law in Germany or the direct cash-flow from the Chinese government to Chinese Companies. Crystalline Silicon suffers from the indirect band-gap that requires huge quantities of Silicon for absorption (slightly corrected by light-trapping) and its cost are stronger influenced from the actual energy costs. Solar cells based on compound semiconductors are also expanding in Ra&D but will always suffer from the abundance of the prime materials looking at Giga-Watt scale, as well as from ecological consideration. Thin-film Silicon is on its way to increase the efficiency and has perhaps the best potential to fulfill future requirements on world-wide PV concepts whenever energy cost and ecologic aspects are the dominating factors for the choice of future energy sources.

There is a compound semiconductor that was proposed in the past and rejected because historical PV funding was exclusively spent to high efficient solar cell projects. Nobody could fabricate a thin-film solar cell of the Pyrite (FeS_2) due to technological reasons: the chemistry between Iron and Sulfur is very complex and a tine semiconductor regime is embedded from pure metallic phase looking at the phase-diagram.

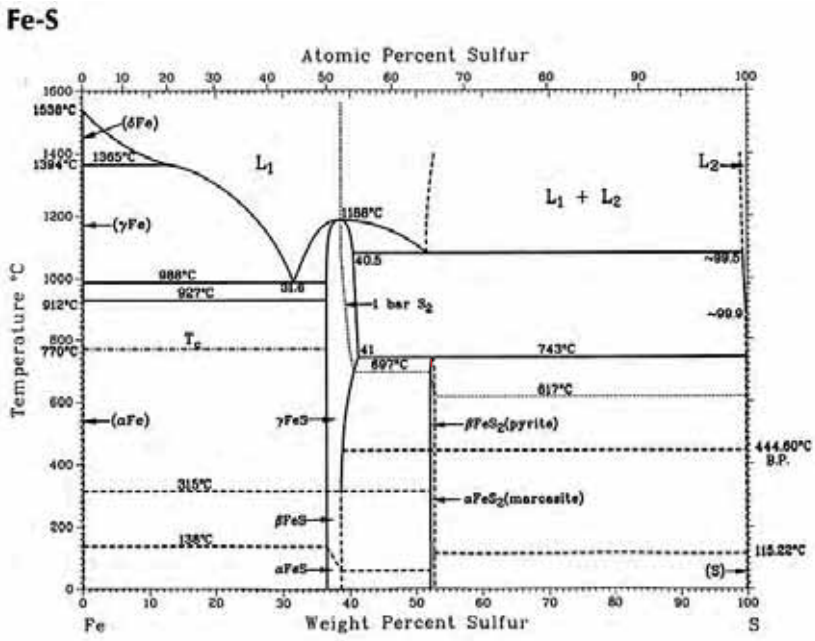

***Figure 1**: Phase-diagram of Fe-S compounds; note the only semiconducting phases are the Pyrite (FeS_2 cubic) and the Marcasite phase (FeS_2 hexagonal). All other phases are metallic.*

The following striking factors let appear Pyrite to be a very interesting candidate for solar cells, looking at actual PV requirements:

- **Abundance:** Pyrite’s prime materials, Iron (Fe: 50000 ppm in Earth’s crust) as well as Sulfur (S: 520 ppm in Earth’s,) will neither give rise to speculation nor run into a limited feedstock.
- **Optical properties**: Pyrite has an electronic band gap of 0.95 eV, a value which is not ideally adapted to the sun spectrum on the earth and which is a little lower than the one of Silicon. However, Pyrite has the highest optical absorption coefficient in the visible light from all known solid-state semiconductors. A Pyrite solar cell absorbs the AM1.5* intensity within a thickness of 600 Å.

  *Air mass 1.5 corresponds to the light intensity of 800W/m^2 typically at 40° latitude.
- **Electrical properties:** For Pyrite, drift mobilities of the minority charge carriers as high as 2000 cm^2/V·s are reported. This enhanced mobility favors the migration distance of photogenerated carriers to be longer than the absorption depth of the light.

The concept of the project PYROCELL was strongly influenced by the fact of grain-boundary passivation or strong auto-selection scenarios of separating metallic phases form high-quality semiconductor phases. The proposed preparation of thin film Pyrite cells includes a variety of different steps (Fig.2); electrochemistry (Al oxidation and Fe template-growth), plasma sulphurization, vacuum process based ZnO deposition (PVD). Manufacturing of thin film Pyrite layers in the so-called Fiber Matrix configuration, whereby the active semiconductor is embedded in the pores of a less than 60 nm thick Al_2O_3 layer. These pores drive the growth of <p> type Pyrite fibers that connect the Al rear contact with the <n> type ZnO window layer on the top, whereby a p/n hetero-junction is formed.

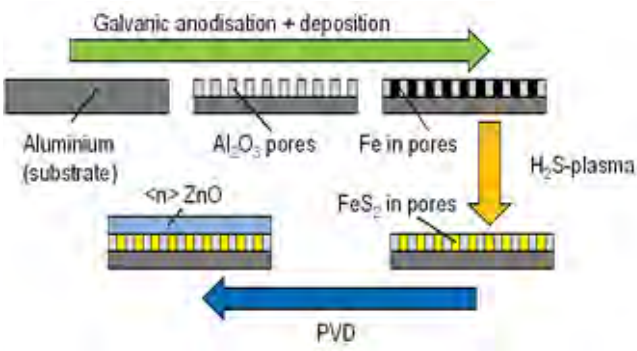

***Figure 2**: Schematic representation of a <p> FeS_2 / <n> ZnO hetero-junction in a Fiber Matrix structure.*

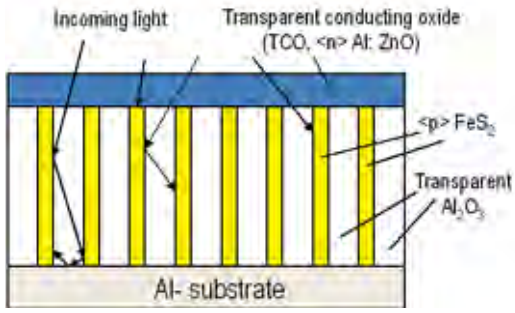

***Figure 3**: Light trapping in a fiber matrix Pyrite thin film solar cell*

The Fiber Matrix structure allows in a later step the so-called reverse-bias annealing procedure whereby metallic components are “burned out” and high-quality semiconductor nano-wires are conserved. If the fiber has high ohmic resistance, it will behave passive. Furthermore, this structure allows light-trapping as diffuse incoming light can be absorbed laterally by the Pyrite fibers (Fig.3).

The overall objective of the project PYROCELL was the achievement of a “diode kind” behavior of a full <p> Pyrite / <n> ZnO heterojunction device ready for electronic characterization (current-voltage, spectral response, etc.) and further optimization. The optimization concerns the growth parameters of the Pyrite fibers on one hand and an electrical post-treatment on the other. In the post-treatment, the junction is reversely biased in order to burn-out fibers that have ohmic behavior. Pyrite-based solar cells could be successfully manufactured as soon as it is possible to deposit thin-film Pyrite exhibiting a diffusion / migration length for minority carriers longer than its AM 1.5 absorption depth that is inferior to 60 nm.

Results

Anodizing of the aluminum electrode

The Al_2O_3 matrix that is planned for the template growth must be developed for the demanded thickness (60 -100 nm).

The first tests of anodizing have been performed on bulk Aluminum. Unfortunately the used parameters could not be applied on films. The pore-size for that thickness could only be achieved by growing a thick layer that was subsequently thinned down to the needed size. Indeed direct growth of a 60 nm layer did never lead to a useful pore structure. In the beginning the anodizing was performed using H_2SO_4 with different conditions of time and temperature. Unfortunately the results were not satisfying. The Al_2O_3 was free from any pores. Better results could have been obtained using a solution of oxalic acide (HOOC-COOH) for the anodizing. It was found that for Al_2O_3 templates as thin as 60 nm no direct continuous growth ending at the desired thickness no porous structure could be obtained. The best results were found for creating first a thick Al_2O_3 layer with a pronounced porous structure and subsequent thinning the layer using phosphoric acid at 30°C. The templates ready for Fe nanopore filling is shown in Fig. 4 showing an REM-micrograph of the up-sight and cross-section:

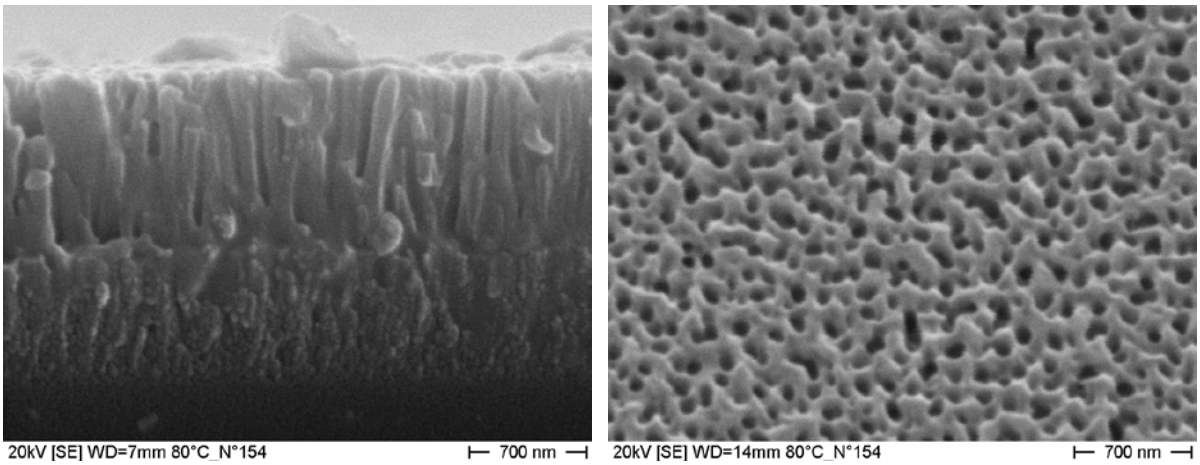

Figure 4: *REM micrograph of the nano-porous template structure of Al_2O_3 obtained from anodizing with oxalic acid (10 seconds at 100V at 80°C) and subsequent phosphoric acid etching of 20min.*

Iron deposition in the pores using a galvanic way

This step may be considered to be difficult due to the limited tools for observation. Electrochemical growth of Iron onto Aluminum at the bottom of the cell turned out to be a problem due to the fact that all pores should be filled in an isotropic way. The effort of electrochemical pre-seeding of the bottoms of the pores using a very thin Zinc layers together with wetting additives combined with AC electro-deposition did not lead to Iron-growth in the vicinity of the pores.

Looking at literature D.Wan et al. [1] describing the formation of Pyrite nanowires, electro-deposition has been performed with pulsed current. The bath contained $FeSO_4$, H_3BO_4, a fluorinated wetting agent and some ascorbic acid to avoid the rapid oxidation of the bath. The pulses were 5ms long and have an intensity of 1.5A. Before doing electro-deposition on Aluminum, a calibration of deposition rate has been performed on a brass substrate during 30 minutes.

The deposition rate was estimated to be 0.66 $\mu m.min^{-1}$. The thickness of porous coating was about 200nm so the deposition time would be 20 seconds to fill the nanopores.

SEM observations showed that Iron is growing in form of nodules at the surface of the sample, without penetrating the nanopores (Fig.5).

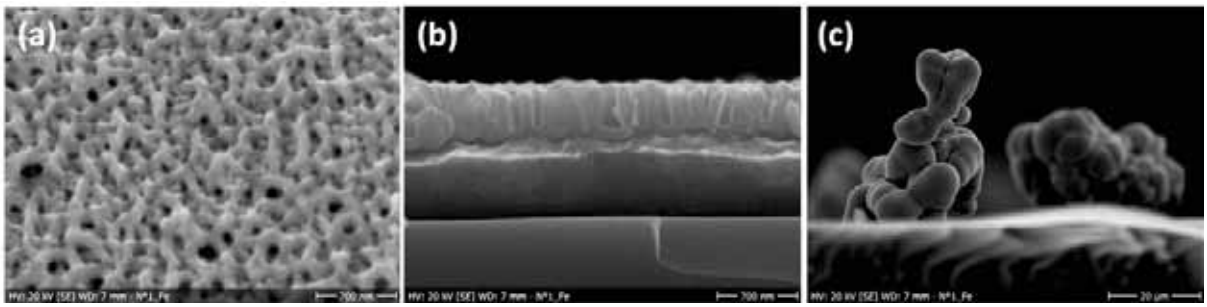

***Figure 5**: (a) Surface of anodized Aluminum with an electro-deposition of Iron (b); the nanopores are not filled with Iron; (c) An Iron nodule.*

Many attempts have been done introducing Iron into anodized Aluminum (Al_2O_3) templates by electro-deposition, in vain so far. EDS analysis confirmed always Iron on the outside of the pores rather than in the pores.

[1] Dongyun Wan & al., Materials Science and Engineering B 122 (2005), pp.156–159

Plasma sulfurisation

Due to the fact that the conversion from Iron to Pyrite was first developed using continuous Iron layers because the Al_2O_3 matrix was not at hand throughout the entire project, all the tests to make a sulphurization of Iron related here have been made on Iron thin films deposed on glass substrate by sputtering. The establishment of the process has been done in a radio frequency (RF) capacitively coupled parallel-plate plasma (CCP) reactor in which Argon gas containing 5% of H_2S was injected at low pressure (10^{-2} -10^{-1} mbar). It was found using RBS- measurements that in this reactor more thermal activation was needed for getting FeS_2 throughout the layer. Better results in terms of dissociation rate of H_2S and better thermal activation could be obtained in an inductively coupled plasma (ICP) reactor. Several systematic diagnostics have been made in the reactor and on the obtained samples like Rutherford Backscattering (RBS), X-Ray Diffraction Spectroscopy (XRD) and Optical Emission Spectroscopy (OES). It was found that the crucial characterization method for following and correcting the preparations was carried out XRD measurements at the Swiss Center for Electronics and Microtechnology (CSEM). With their competence it was possible to suppress the extreme X-ray fluorescence of Iron and to measure the small signals for 60 nm layers.

ICP reactor results

Following those results a new reactor has been built. This one is an inductively coupled plasma (ICP) reactor (Figures 6, 7). This kind of reactor gives a higher plasma density (ionization degree up to 10%) and an almost total depletion of the working gas (100% degree of dissociation). Moreover the reaction can take place in a transparent quartz tube. Thus it allows a heating simultaneously with the H_2S treatment performed with a 1kW infrared lamp.

This set-up allows also an in-situ measurement of the plasma induced Iron-Sulfur reaction to Pyrite. Indeed; as soon as the reaction is complete the Pyrite let pass the infrared light for lower wavelength as the gap of Pyrite (0.95eV=1.3μm) and makes it detectable by an InGaAs photodiode detector (1.2 to 2.6μm spectral response range).The photodiode gives a small current (μA range) which is amplified and transformed to a voltage.

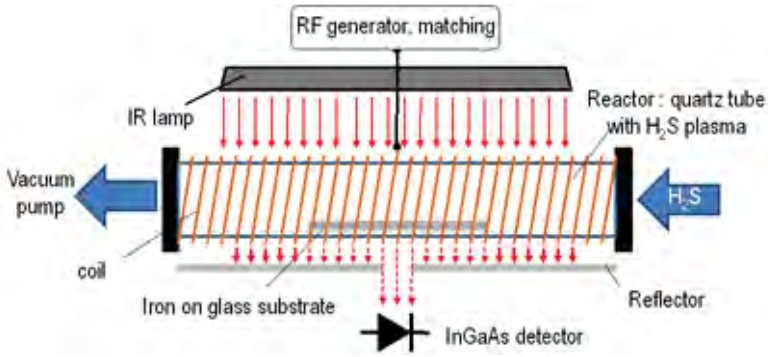

***Figure 6**: Schematic representation of the ICP reactor*

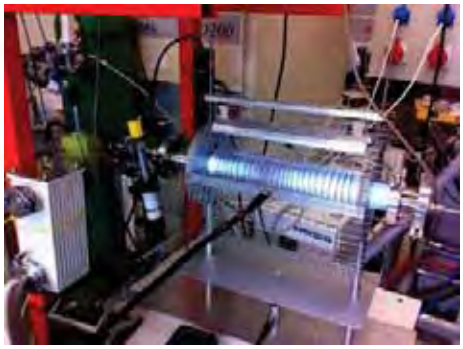

***Figure 7**: ICP reactor under operation*

Measurements of this voltage showed a marked and r apid increase of the infrared light passing through the sample (Fig.8). Indeed, after only 5 minutes of exposure to the H_2S plasma the voltage produced by the amplifier circuit of the InGaAs photodiode has already doubled.

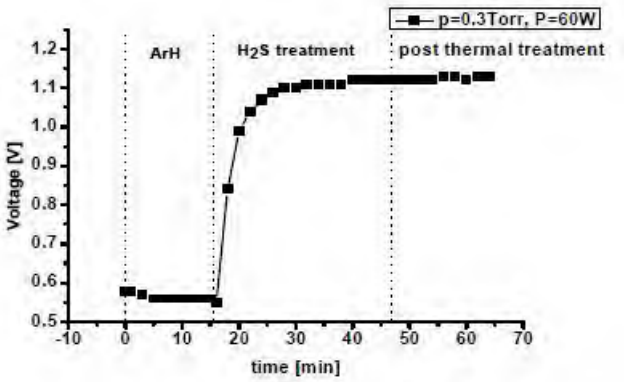

***Figure 8**: Process control using the InGaAs photodiode for monitoring the reaction advancement: 15 min after the beginning of the H_2S plasma treatment, the initially pure Fe layer was converted allowing IR transmission (from the heater) to the photodiode.*

XRD analysis (Fig. 9) of a sample treated under a pressure of 0.1Torr with a power of 80W with 15 minutes of Hydrogen plasma, 15 minutes of H_2S plasma and 15 m inutes of thermal post-treatment (without any plasma) showed a very good conversion in FeS_2. Indeed, 100% of the layer is composed of FeS_2. 32% of it is Pyrite and the rest is Marcasite, which takes form at a lower temperature than the Pyrite. Thus, looking at the phase diagram Fig. 1 indicates that just by increasing the temperature of the layer (by approaching the IR lamp for example) we should enhance the proportion of Pyrite in the thin film.

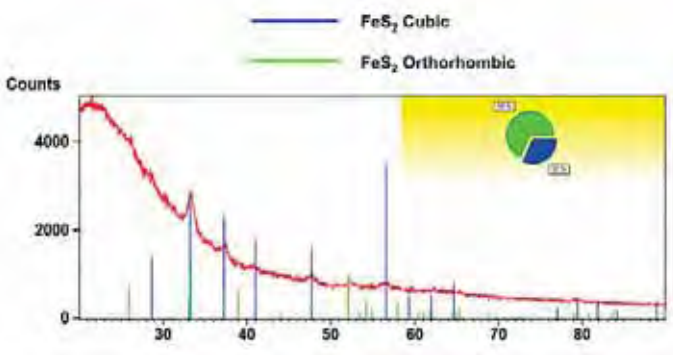

***Figure 9**: XRD analysis of a sample obtained with the ICP reactor under a pressure of 0.1Torr with an injected power of 80W. Under these conditions a conversion rate Fe to FeS_2 at 100% could be obtained, whereby only 32% was the cubic phase Pyrite (wanted) and 68% turned out to be the hexagonal Marcasite (less wanted).*

Together with the Marcasite phase, the presence of Pyrite is well confirmed with ellipsometric analysis. Indeed measurements on samples obtained in the ICP reactor are compared with measurements made on a piece of metallic (natural) Pyrite. We can observe that the refractive index and the attenuation coefficient (Fig.10) are very similar. The difference present in photon energies lower than 1eV can be due to the absorption of the Pyrite gap, which is not present in the metallic Pyrite.

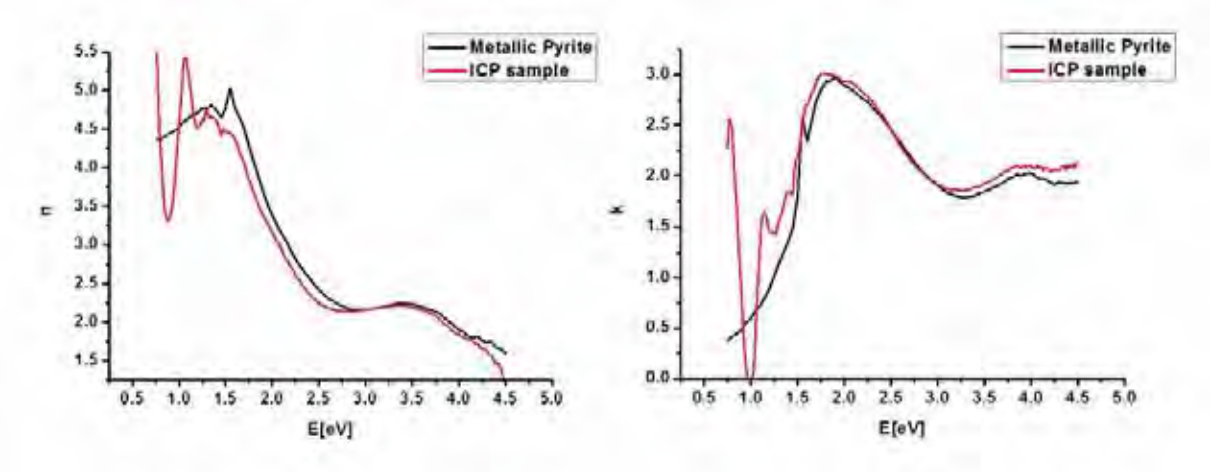

***Figure 10**: Refractive indexes and attenuation coefficients of metallic Pyrite and a sample obtained in the ICP reactor at a pressure of 0.7 Torr with a power of 60W*

In order to investigate more parameters allowing to approach the conditions as indicated by the phase diagram (Fig. 1) XRD analyses have been performed on samples treated at different pressures and with the IR lamp at different distances (thus at different temperatures). Results showed clearly that the higher the pressure is the best the ratio Pyrite/Marcasite is (Fig.12). Moreover increasing the heating gave also a better ratio Pyrite/Marcasite. The best result we obtained was with 0.3 Torr and a higher temperature. The ratio obtained is 49% of Pyrite (Fig.11).

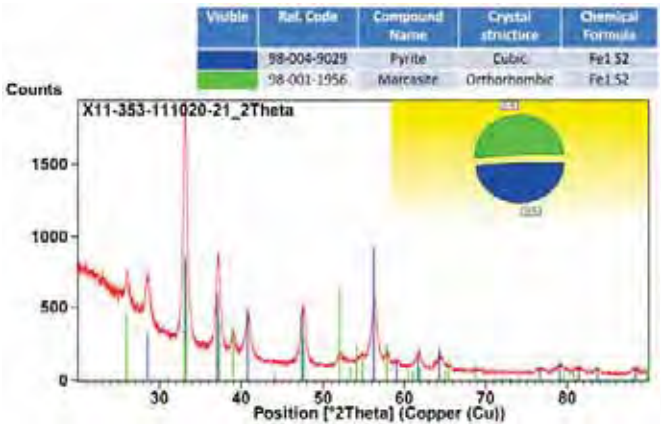

***Figure 11**: XRD analysis of a sample obtained with the ICP reactor under a pressure of 0.3Torr with an injected power of 60W*

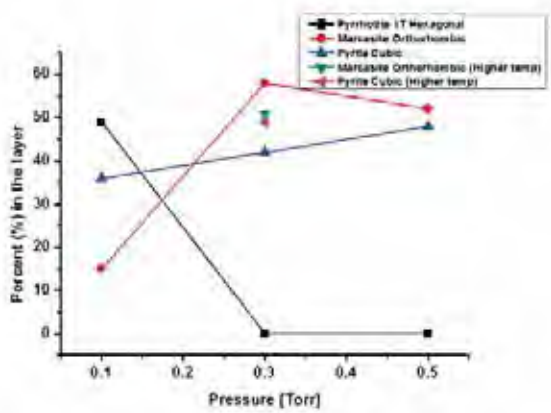

***Figure 12**: Percentages of the different Fe_xS_y-phases present in layers depending on the pressure. The Pyrite phase is favored going to higher pressures*

Fig.12 brings together the different percentages of phase-fractions present in the layers obtained with the ICP reactor as shown in Fig.9. It is observed that at low pressure there is still presence of sub-stoichiometric elements (Pyrrhotite Fe0.95 S1.05), probably due to the lack of sulfur provided in the plasma. By increasing the pressure the Pyrrhotite disappears principally in favor of Marcasite. Then when the pressure reaches 0.5 Torr the ratio Pyrite/Marcasite increases to almost 50%. It is also observed that by increasing the temperature the ratio Pyrite/Marcasite rises obviously.

Optical Emission Spectroscopy made on the H_2S plasma in the ICP reactor at different pressures with 60W and 80 W showed that we have the best ratio Sulfur-Argon (thus the better dissociation) at a pressure of 0.7-0.8Torr for a power of 60W and at a pressure of 0.9Torr for a power of 80W as shown in Fig. 13.

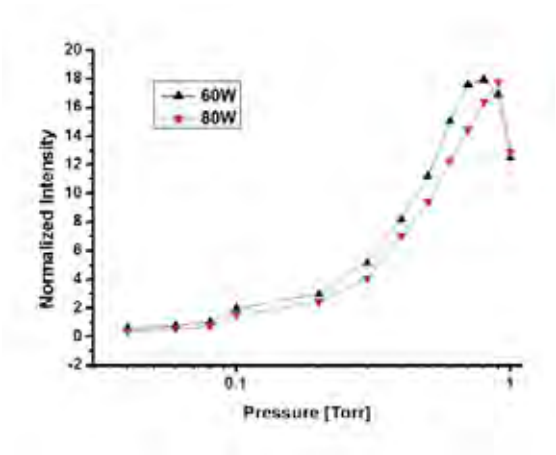

***Figure 13**: OES (optical emission spectroscopy) carried out at the ICP reactor show the Sulfur peak at 504nm normalized by Argon peak at 811nm at different pressures having a pronounced maximum at 0.7-0.8 Torr.*

In order to increase the plasma-density we modified the ICP reactor by reducing the space between the turns of the ICP coil. The sample was then placed at different sites downstream where the plasma appeared mostly homogeneous. XRD analyses have been performed on samples treated at different high pressures (0.7 and 0.9Torr) and with the IR lamp at the closest distance we had already tried. Results showed a good crystallinity and an optimal pressure at 0.7 Torr for the ratio Pyrite/Marcasite. The best result obtained was thus with 0.7 Torr with a ratio of about 90% of Pyrite, the remaining 10% being also FeS_2, but in the form of Marcasite, which is the best result so far Fig.14.

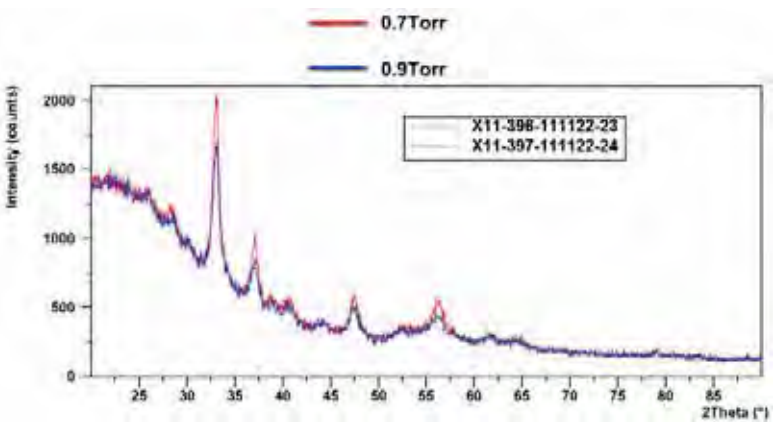

***Figure 14**: XRD analysis of a sample obtained with the ICP reactor with increased coil-density under a pressure of 0.7 Torr and 0.9 Torr with an injected power of 20W.*

The highest Pyrite to Marcasite concentration of 90% could be obtained.

P-N junctions between pyrite and ZnO

Some test cells have been created in order to get an evidence of a photovoltaic comportment. The solar cell test samples consisted a <n> ZnO / <p> FeS2 hetero-junction, whereby the ZnO is just sputtered onto the glass followed by the Iron deposition followed by H_2S plasma treatment. The band structure of the hetero-junction is shown in Fig. 15.

The test cells got many trenches from FS laser in order to separate a large area cell (showing actually many domains and anisotropies); hereby areas can be selected and separately measured. The first layout of test cells with all ohmic contacts (Fig.16) for measuring PV activity of the cell, such as I-V characteristics and Spectral response measurement once a cell is active (measurable V_{oc}).

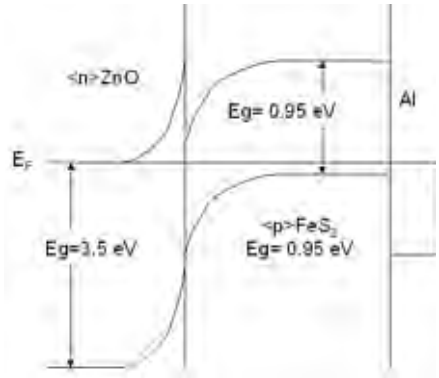

***Figure 15**: Band-structure of a <n> ZnO / <p> FeS_2 heterojunction*

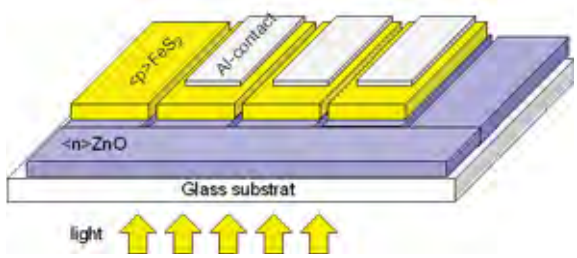

***Figure 16**: Concept of building test structures of <n> ZnO / <p> FeS_2 heterojunction*

Reverse-bias annealing

The process was successfully developed using ITO in Al_2O_3 pores whereby an electronic system containing a constant current density regulation was developed, ready for the treatment of the junctions. The present results have still all ohmic character, this is not surprising because the mechanism of reverse bias annealing using the template-growth structure could not be realized; more technology must be developed for this. Test structures that have been submitted to reverse-bias annealing were completely destroyed due to too many conductive sites.

Conclusions and outlook

Although the ultimate goal of the project, namely obtaining a “diode kind” behavior on a so-called fiber matrix, has not been reached, a lot of progress has been achieved on the way to the Pyrite solar cells. Indeed, the creation of the fiber matrix took more time as expected and the implementation of Iron in the nanopores has proven much more difficult than expected. On the other hand the conversion of Iron into Pyrite using the new reactor-concept (ICP) was the positive outcome. Indeed the presence of Pyrite in trace quickly turned into a layer composed entirely of FeS_2 and which the content of Pyrite is as high as 90%. Moreover the process to cure the non-semiconducting parts of the cell was successfully developed using ITO in Al_2O_3 pores whereby an electronic system containing a constant current density regulation was developed and should be ready for the treatment of real diodes.

With these promising results contacts were made with the Plasma Physics Research Center (CRPP) in the EPFL in order to consider the different activities of the previous project under the aspect of fundamental research. Thus a Sinergia project with the Swiss National Science Foundation (SNSF) has been submitted.

Acknowledgements

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CARACTÉRISATION DES MODULES PHOTOVOLTAÏQUES À COLORANT DE L'ENTREPRISE G2E

Rapport annuel 2012

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Duration of the Project (from – to)	01.10.2012 – 31.12.2014
Date	01.12.2012

ABSTRACT

The company "Glass To Energy" (g2e) in Yverdon is industrializing dye solar panels on the basis of DSC "Grätzel" technology, developed at EPFL.

The panels will be integrated on walls and other building elements.

A solar simulator for measuring the performance of such electrical panels, including an IV measurement tool, is going to be realized.

Then the panels will be installed in real conditions and monitored over a complete year, in order to characterize and have the necessary perspective on this technology.

The project started in October 2012. Since, two electronic loads have been developed for 10x10cm and 60x100cm panels. The schedule is respected.

Résumé

L'entreprise Glass To Energy (g2e), à Yverdon, va industrialiser la fabrication de panneaux solaires à colorant sur la base de la technologie DSC «Grätzel» développée à l'EPFL. Les panneaux seront développés pour être intégrés dans des façades et autres éléments construits.

Dans un premier temps il s'agit de mettre en place un simulateur solaire pour la mesure des performances électriques des panneaux, dit outil de mesure IV, I courant, V tension. Cet outil sera dédié à cette technologie et adapté aux tailles de panneaux réalisés par g2e.

Ensuite il est prévu d'installer des panneaux en condition réelle et de les suivre sur une année complète, afin d'avoir le recul nécessaire sur cette technologie et d'en établir les caractéristiques.

Le projet a démarré en octobre 2012. Depuis, deux charges électroniques ont été développées, spécifiques aux panneaux de taille 10x10cm et aux panneaux de taille 60x100cm. L'avancement respecte le planning prévu.

Buts du projet

L'objectif du projet g2e est de faire un bond dans l'utilisation de la technologie DSC et de développer un produit industriel de grande taille à intégrer dans les façades. Le produit est développé en fonction des besoins du marché en partenariat avec de grands industriels façadiers, les actionnaires. La perspective est pragmatique et délibérément orientée vers des applications concrètes. L'atout principal de cette technologie est sa transparence, sa flexibilité dans le design et le choix des couleurs.

Les panneaux DSC de type industriel issus de la fabrication g2e ne sont pas encore connus, les cellules doivent donc être caractérisées de manière à établir leurs performances.

Dans un premier temps il s'agira de mettre en place un simulateur solaire pour la mesure des performances électriques des panneaux, dit outil de mesure IV, I courant, V tension. Cet outil sera dédié à cette technologie et à cette taille de panneaux.

Ensuite il est prévu d'installer des panneaux en condition réelle et de les suivre sur une année complète, afin d'avoir le recul nécessaire sur cette technologie.

A partir de ces campagnes de données, il sera possible de faire des modèles afin de les rendre exploitables par les logiciels de simulation photovoltaïque classiques de type PVsyst.

Puisque la technique est orientée vers l'intégration aux bâtiments, il s'agira ensuite de créer un logiciel de simulation dédié, pour les acteurs du domaine tels les architectes, les énergéticiens mais aussi des services techniques des administrations ou des entreprises. Le rôle de de la HEIG VD sera ici de constituer la base de donnée nécessaire au futur développement d'un tel logiciel.

Travaux effectués et résultats acquis

Les travaux effectués peuvent être résumés de manière suivante :

- 9.10.12 démarrage du projet (kick-off meeting avec l'entreprise g2e le 8.11.12)
- Octobre à décembre 2012: réalisation des charges électroniques et de l'acquisition

La charge électronique (voir figure 1) est uniquement résistive. Ceci implique qu'elle n'impose aucune tension ni courant à l'objet testé. Elle se comporte comme une résistance variable pouvant varier de 0.1 Ω à environ 30 kΩ. Les limites extrêmes de la charge en tension et courant sont adaptables (physiquement) aux différents types de cellules/panneaux. La plage de travail de la charge dépend de la configuration physique de certains éléments sur la carte électronique. La charge est commandée par le logiciel Labview, depuis le PC branché sur la charge au moyen d'une connexion USB. L'acquisition des résultats se fait par le même canal.

La charge est en cours d'intégration dans le prototype, pour le moment rudimentaire, du simulateur solaire présenté sur la figure 1. Tous les travaux d'intégration de la source lumineuse (caractéristique du spectre, filtrage, homogénéité lumineuse) restent à développer, ainsi que le contrôle en température des cellules « test » de 10x10cm.

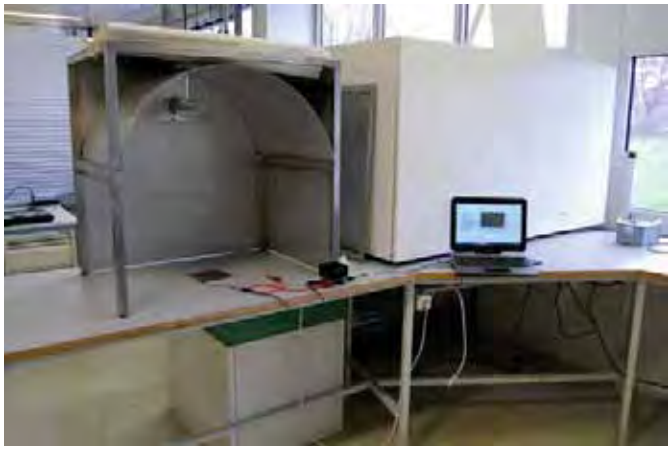

Figure 1: *Prototype de travail avec charge électronique et acquisition sur PC*

Le logiciel d'acquisition basé sur Labview effectue une calibration lors de la première utilisation, puis mesure est réalisée en commençant par détecter quels sont les extrêmes de la cellule à mesurer (Icc et Uoc). Ensuite la caractéristique de la cellule est parcourue en contrôlant la tension, en partant de Uoc jusqu'à 0 V. Sur l'interface PC (voir figure 2), l'utilisateur peut régler les différents paramètres de mesures, permettant certains ajustements selon l'expérience pratique avec les différentes cellules ou conditions d'éclairage.

Figure 2: *Interface utilisateur avec réglages et visualisation de la caractéristique (ici cellule SI)*

Un post-traitement Matlab permet l'édition d'un rapport avec les caractéristiques de la cellule type « catalogue » et la représentation de la caractéristique VI.

Du travail réalisé, certaines conclusions ont déjà pu être tirées pour la suite des travaux, en particulier pour la conception définitive du banc de test ainsi que pour les charges électroniques qui seront réalisées pour chaque panneau de l'installation « outdoor ».

Collaboration nationale

Cette collaboration ainsi que les premiers éléments développée ont été présentés par l'entreprise g2e aux investisseurs et partenaires de l'entreprise, lors de l'assemblée annuelle de l'entreprise.

Collaboration internationale

Aucune collaboration internationale n'a été établie pour le moment dans le cadre de ce projet spécifique.

Évaluation de l’année 2012 et perspectives pour 2013

Le projet ayant démarré fin 2012, seules les charges électroniques pour deux types de panneaux ont pu être développées, ainsi que le logiciel d’acquisition des courbes IV. Celles-ci fonctionnent à satisfaction, et permettent déjà à l’entreprise g2e d’effectuer des contrôles basic. Du travail d’intégration reste nécessaire, particulièrement pour la source lumineuse et le contrôle de température.

Les priorités ont été fixées pour l’année 2013 lors des séances de coordination avec l’entreprise; les développements vont suivre le planning prévu, avec une priorité sur la réalisation de l’installation de test « outdoor » en conditions réelles. Les premiers résultats principaux devraient être dégagés en automne 2013.

Rérérence

http://iese.heig-vd.ch

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ARCHINSOLAR

UNIQUE AND INNOVATIVE SOLUTION OF THIN SILICON FILMS MODULES BUILDING INTEGRATION

Annual Report 2012

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Project- / Contract Number	SI/500474 / SI/500474-01, Swiss Electric Research
Duration of the Project (from – to)	01.04.2010 – 31.03.2013
Date	13.12.2012

ABSTRACT

The ARCHINSOLAR project aims to develop a new generation of photovoltaic elements based on silicon thin films technology (amorphous and micromorph), ultra-reliable and manufacturable at a very low cost, allowing a unique architectural integration, respectful of the built environment, landscape and traditions:

- Innovative colored full size modules were produced using different techniques
- New multi-functional solar tiles with a molded back structure in composite were developed and a cost and life cycle assessment of the composite element was made
- Accelerated-aging reliability tests on small-sized and full size samples were performed in order to ensure a lifetime of over 25 years
- Indoor and outdoor demonstration roofs were constructed at PVLAB to present the new developments.

Goals of the project

The Archinsolar project aims to develop a new generation of photovoltaic (PV) elements based on silicon thin-film technology, which will be ultra-reliable and manufacturable at a very low cost, will allow unique architectural integration, and will be respectful of the built environment and landscape. The objective of the work carried out by the different research partners have been focus on the development of 3 main products:

- Full size (110 x130 cm) thin film based colored modules (orange – terra-cotta)

- Solar tile (110 x 43 cm) with an innovative multifunctional composite back structure

- PVT collector, with a colored PV module

Short project description

The project is divided into three main work packages:

- WP1 “PV engineering design of reliable elements” establishes the design criteria, selects appropriate materials and carries out the first concepts of module design.
- WP2 “Colored filters and multifunctionality” develops the colored films and specific coatings and textures that will modify the visual aspect of the modules as well as the innovative electrical and roof interconnections.
- WP3 “Integration, design, architecture” realizes the architectural implementation and identifies the various constraints (e.g. linked to mounting, security and certification).

Work performed and results achieved in 2012

Terra-cotta like PV modules

Interferential filters

Beginning of 2012, orange thin films of the first generation of developed in 2011 and characterized by energetic losses about 14% have been industrially produced on large glass panes and laminated to real-size (1.10 x 1.30 m^2) PV a-Si modules. The feasibility of the concept has been proven but the lack of angular color stability of the coating has been highlighted (see Figure 1).

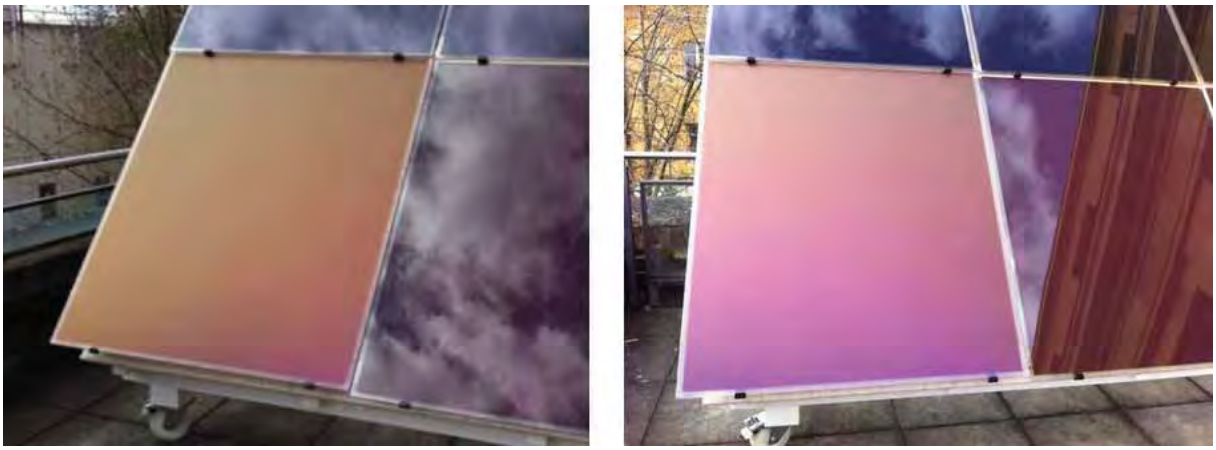

***Figure 1**: Orange glass panes laminated on real-size PV modules (1.10 x 1.30 m^2) on which strong angular dependency of the color is observed.*

Therefore new simulations have been performed in order to improve the color angular stability while preserving the good energetic performances of the coating (losses lower than 15%). New designs of high performance have been identified by computer simulation and described in a PCT application deposited in September 2012.

Some of them have been produced by reactive magnetron sputtering on small glass samples (6x7cm^2) and characterized in terms of solar transmittance and color at LESO. The produced samples are characterized by color coordinates that are close to those of a real tile (x=0.45 and y=0.38 at normal incidence). They also present good color stability for angles of observation up to 60° with respect to normal incidence (see Figure 1).

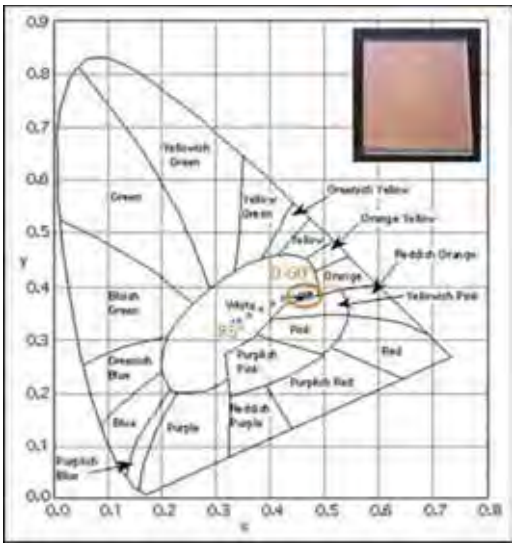

***Figure 2**: Example of color variation of a new orange filter for angle of observation from 0° to 85°. Good color stability is observed up to 60° with respect to normal incidence. For angles higher than 60°, the color desaturates progressively without any change of the dominant color.*

These laboratory samples were then laminated to PV mini-modules to measure the efficiency of the assembly and determine the energetic losses due to the colored reflection of the interferential thin film. They are now being characterized at IMT.

The large-scale industrial production of coatings corresponding to one of those new orange designs has been negotiated with SwissINSO and is expected before the end of the year.

In parallel, alternative front structures, obtained by chemical etching of commercial textured glass have been developed. Photographs of a selection of the most interesting ones are shown in Figure 3.

***Figure 3**: Alternative front structures. Commercial textured glass on the left and same glass treated by chemical etching and combined with an orange colored filter on the right.*

New orange designs combining intense color, good color stability and good energetic efficiency have been identified and produced.

The feasibility of large-scale industrial production of orange interferential multilayered thin films has been proven thanks to SwissINSO.

The production of large colored glass triggered the lamination of LESO's colored glazing with real-size a-Si PV modules has been done at IMT.

Modifying the color by changing the encapsulation material

Another approach has been used to produce terra-cotta like PV modules, based on the encapsulation process. This procedure has been recently published in a patent.

***Figure 4**: Terra-cotta like modules developed at IMT, using a special encapsulation strategy.*

The terra-cotta like color matches exactly the orange color of a selected Braas tile (one of the most installed tile in Suisse romande). A first series of these modules will be produce by a thin film company in January and further installed on the roof of a public monument of the city center of Neuchâtel, as demonstrator. More information on this demonstration site will be given in the final report of the project.

***Figure 5**: Historical building in the city center of Neuchâtel, where 200m^2 of the terra-cotta like modules (IMT process) will be installed.*

Electrical characterization of the colored PV modules

Comparison of front-side and back-side coloring schemes

Semi-transparent amorphous silicon (a-Si) modules with thin absorber were encapsulated at PV-Lab using different encapsulation schemes to change the final module color while losing less than 10% relative of power as compared to a reference module architecture. In order to do so, increase in short-circuit current (I_{sc}) after encapsulation as compared to a reference encapsulation scheme is used to describe the effect of the encapsulation on the module performances.

The color rendering can be tuned by either using a colored (in this case orange) polymer behind the semi-transparent a-Si module or by placing an interferential filter in front of the module. Additionally, textured glass can be placed in front of the module to reduce strongly the angular dependency of the color and to reduce unwanted reflections. The following figure presents the different encapsulation schemes and Table 1 summarizes the tested conditions.

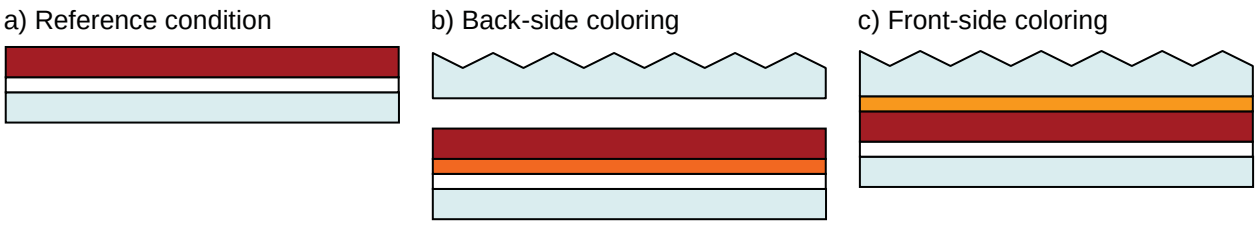

***Figure 6**: Schematic view of the different encapsulation schemes: a) reference condition with from top to bottom; solar cells on glass (reddish), white encapsulant (white) and back-glass (light blue), b) back-side coloring scheme with (optional) textured top glass, solar cells on glass, two types of encapsulant (orange and white) and back-glass, c) front-side coloring with (orange) interferential filter on textured glass, solar cells on glass, white encapsulant and back-glass.*

Name	Coloring	Back encapsulant	Front encapsulant	Front Glass
W	None	PVBw	None	None
WO	Back-side	PVBw + PVBo	None	None
WOO	Back-side	PVBw + 2x PVBo	None	None
WO_Rio	Back-side	PVBw + PVBo	PVBc	Rio Vetro glass
W_F	Front-side	PVBw	PVBc	Orange filter on Rio vetro glass
W_Op	None	PVBw	PVBc	Optiwhite glass
WO_S	Back-side	PVBw + PVBo	PVBc	Albarino S glass

***Table 1**: Encapsualtion schemes tested. Pvbw = white pvb // pvbo = orange pvb // pvbc = clear pvb // optiwhite = solar-grade glass // rio vetro = special etched patterned glass // orange filter = orange interferential filter // albarino s = etched patterned glass.*

An example of typical IV curves obtained before and after encapsulation is shown on figure 7 for the reference configuration presented in figure 6 (W in table 1). One sees clearly the short-circuit gain provided by the encapsulation (in this case due to the back-reflection provided by the white encapsulant layer) that is used for comparison between the different encapsulation schemes.

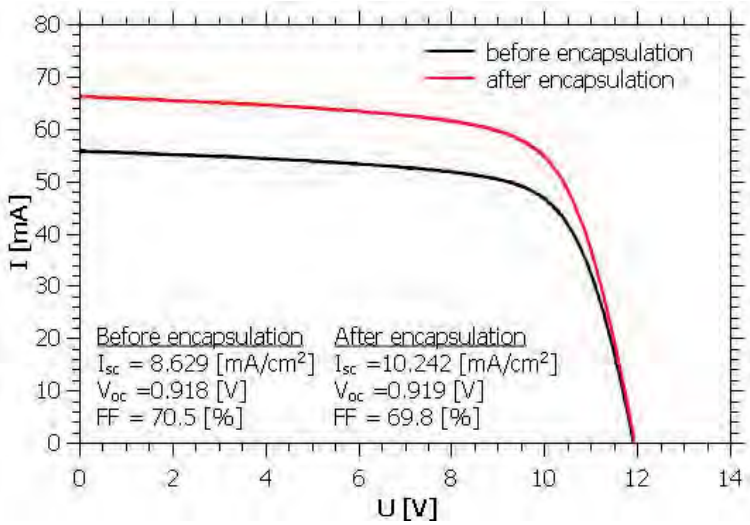

***Figure 7**: IV curves before (black) and after (red) encapsulation for the reference module configuration W. One sees the clear gain in short-circuit current I(V=0) due to reflection of light on the white encapsulant layer.*

Figure 8 presents the results of the electrical characterization in terms of short-circuit current (I_{sc}) gain after encapsulation. One sees clearly that all conditions tested yield to a lower I_{sc} increase than the reference condition. This is expected as the placement of a colored encapsulant layer on the back of the cells lowers the back-reflection effect while placement of an interferential filter in front of the cells reduces the total solar power transmitted to the cells. Knowing that the solar cells on glass before encapsulation have an initial efficiency of 6% and assuming that neither the open-circuit voltage (V_{oc}), nor the fill factor (FF) are influenced by the encapsulation process (as one can see on figure 7), one can calculate a I_{sc} increase threshold that has to be exceeded to yield less than 10% power loss as compared to the reference condition. It can then be seen that for all the developed encapsulation schemes the I_{sc} increase is sufficient to lose less than 10% of the reference efficiency. It is also seen that the front-side coloring (W_F condition) is more efficient electrically than the back-side coloring.

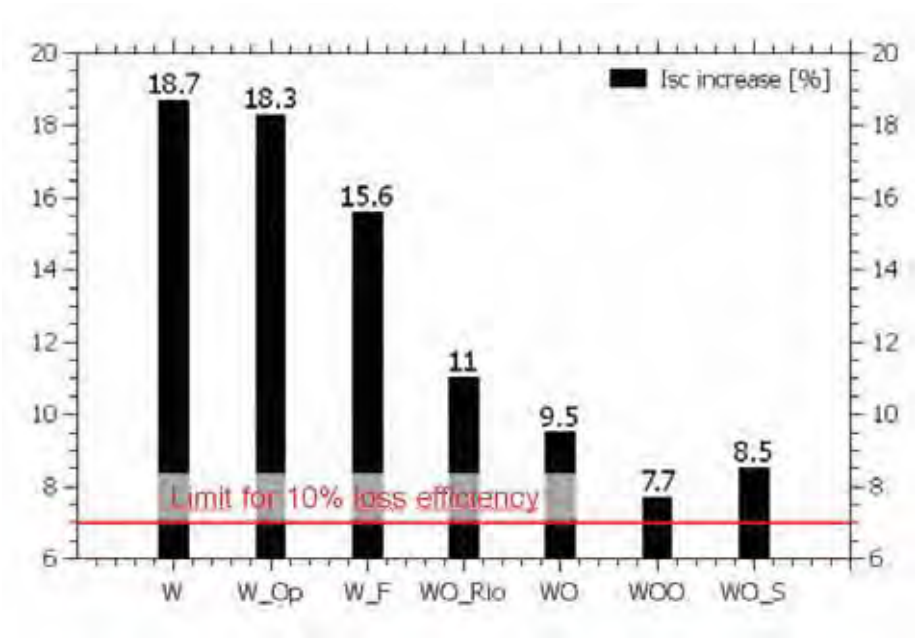

***Figure 8**: Short-circuit gain after encapsulation for all the tested configurations (as described in table 1). Plotted in red is the limit of short-circuit increase threshold that has to be exceeded to obtain an efficiency loss lower than 10% (relative) compared to the reference condition w.*

Optimized interferential filters for front-side coloring

The main issue with front-side coloring schemes is the angular dependency of the appearance. Extensive work has been done by the LESO group at EPFL to produce interferential filters with an improved angle of view stability as compared to the previously mentioned colored filter. Two filters were tested ; "Filter 1" with a light orange color which doesn't change toward different tone but that de-saturates at large angles of view and "Filter 2" with a stronger orange color which do not de-saturate till very large angles of view.

Those filters were applied on amorphous silicon (a-Si) and micromorph (mimo) modules and electrically characterized using EQE and IV measurements. In the case of IV measurements, a textured glass was added on top of the stack to enhance the light trapping.

Results from the electrical characterization for the amorphous module is presented on figures 9 (IV) and figure 10 (EQE). It is seen that application of the colored filters reduces the incoming light leading to a decrease of the short-circuit current. This decrease is stronger for Filter 2 because of the more intense orange reflection (which results in less transmission as can be seen on figure 10).

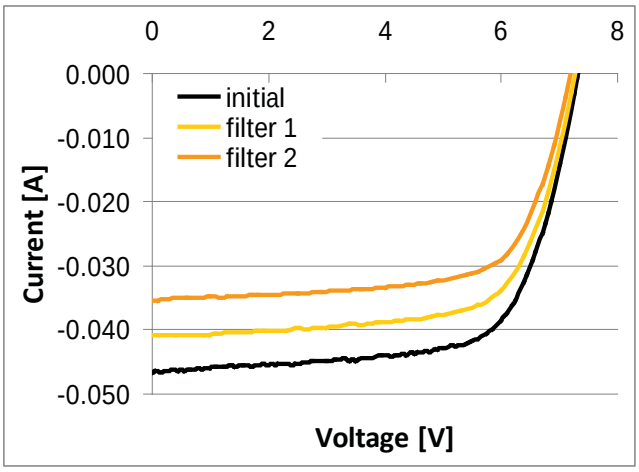

***Figure 9**: IV curves for amorphous modules bare (black) and with filter 1 (light orange) or filter 2 (orange)*

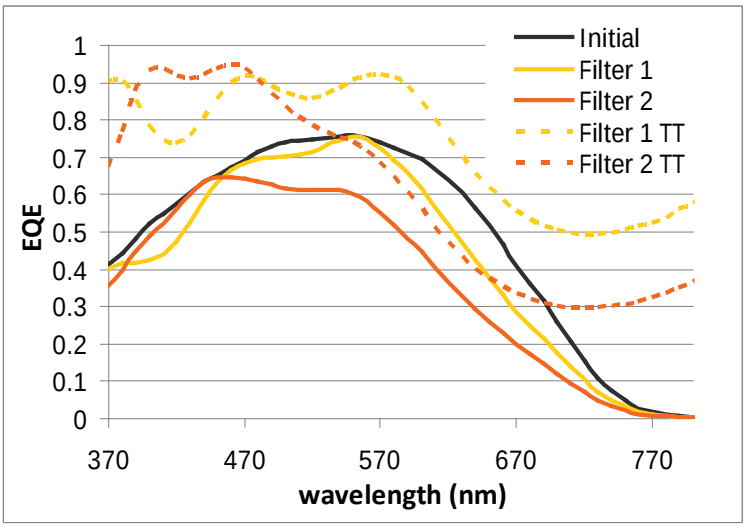

***Figure 10**: EQE measurement for the amorphous module without (black) colored filter and with filter 1 (light orange) or filter 2 (orange), along with the uv-vis-nir total transmission (tt) curves for the two filters (dashed lines)*

When applied to micromorph modules, both filters lead to an appreciable decrease of the short-circuit current that then exceeds the 10% limit, as can be seen on figure 11. The reason for this is given by the EQE curves presented in figure 12 where we see that the orange reflection leads to a strong decrease of the current in the microcrystalline cell, leading to a large current mismatch between the top and bottom cell which is detrimental to the overall efficiency of the device.

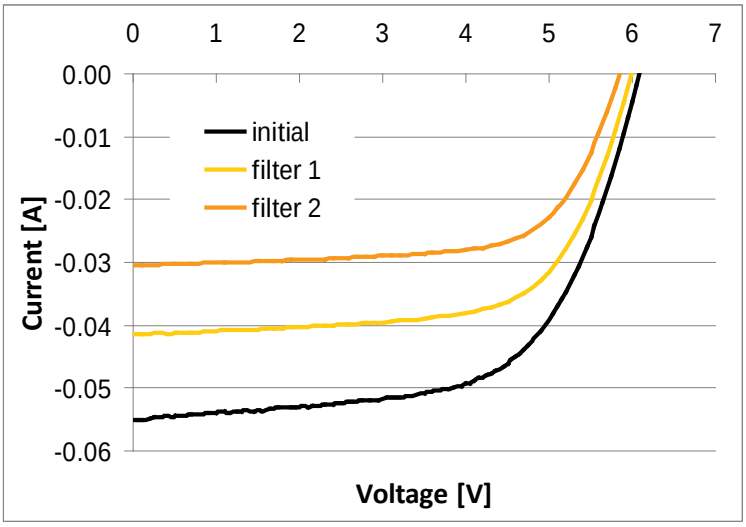

***Figure 11**: IV curves for micromorph modules bare (black) and with filter 1 (light orange) or filter 2 (orange)*

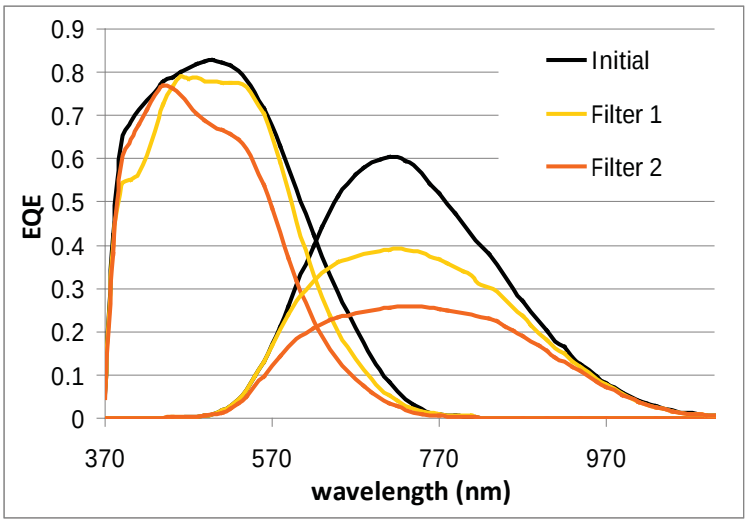

***Figure 12**: EQE measurement for the micromorph module without (black) colored filter and with filter 1 (ligh orange) or filter 2 (orange)*

Table 2 presents the efficiency loss due to placement of Filter 1 or Filter 2 in front of amorphous or micromorph modules. It is observed that only filter 1 does reach the efficiency loss requirements with less than 10% loss.

	Filter 1	Filter 2
Amorphous	-9.4%	-22.5%
Micromorph	-21.2%	-42.3%

***Table 2**: Relative efficiency loss due to the presence of interferential filters for amorphous and micromorph technologies, as calculated from IV measurements*

Conclusions from the electrical analyses

- Both front- and back-side coloring encapsulation schemes that meet ArchinSolar requirements (less than 10% power loss as compared to standard encapsulation scheme) were developed for application with semi-transparent amorphous modules
- Front-side coloring schemes are more efficient electrically but suffers from a strong angle of vision dependency of the color while back-side coloring schemes are less electrically efficient but exhibit more stable colors
- The angle of view dependency of front-side coloring can be improved and a new interferential filter called “Filter 1” has been successfully applied on standard amorphous module
- Due to the strong reflection in the orange-red part of the spectrum, both developed orange filters do not meet the efficiency requirements when applied to micromorph modules.

Architectural integration and design: The Archinsolar solar tile

Prototype analysis

Following the detail design phase of 2011, 6 prototypes have been produced to test the feasibility of the design, and to check the installation and compatibility properties of the Archinsolar tile with the chosen Braas “TEGALIT “system. For this purpose, a real size mock-up roof has been constructed at PV-Lab, combining real TEGALIT tiles and the new prototypes produced by LTC and PV-Lab. This installation allowed confirming the validity of the global concept, but showed some limitations of the prototype. The main issue was due to the kind of technology chosen for the prototype, providing a very good “front” interface with the glass, but lacking the real “thickness” of the cement tile. This was an

accepted option, but asked for a very careful check of the global design to ensure that the next generation will correct this aspect. A few minor details were also identified that needed design modifications.

Following progresses in the various parts of the glass combination design, a new round of global design meetings was started, including LESO, LTC and PV-Lab collaborators. The new design keeps the main characteristics of the first prototype regarding general dimensions and compatibility, but includes several improvements:

- Better coloured glass area covering
- Actual thickness of the tile at all four sides
- Adapted surfaces for better positioning and support on the wooden beams
- Special slots for fixation screws and washers
- Rounded edges for easier manufacturing and hands protection

Multifunctional composite backing element

During the reported period, the cost and life cycle assessment of alternative composite backing solutions initiated in 2011 was completed. A new thermoplastic composite material and a novel direct integrated molding process were introduced as cost-effective solutions to produce solar tiles fully compatible with building integrated PV. A small series of PV module tile demonstrators was produced.

The three main achievements related to the development of a composite backing, namely the costing and environmental analysis, the development of an integrated process based on thermoplastic composites and the production of tile demonstrators, are detailed in following sections.

Cost and life cycle assessment of composite backing solutions

Five different polymer composite materials were selected based on the initial study (see 2011 report), as listed in Table 3. The cost and technical specifications of material constituents are reported in Table 4.

Process	Material	Tile weight (kg)
Reference Al framed glass-glass module tile		8.40
Polyester glass (RTM)	54wt% polyester 46wt% glass fibres	9.22
SMC Compression Moulding	30wt% polyester 30wt% glass fibres 40wt% sodium silicate	9.33
GMT Compression Molding (PP)	67wt% polypropylene 33wt% glass fibres	8.36
Injection Molding	45wt% polypropylene 55wt% glass fibres	8.36
GMT Compression Molding (PVC)	60wt% PVC 40wt% glass fibres	8.37

Table 3: *Composition of the selected composite backing materials and corresponding solar tile weight (RTM: resin transfer molding; SMC: sheet molding compound; GMT: glass mat thermoplastic; PP: polypropylene; PVC: polyvinyl chloride).*

Material	General Cost (CHF/kg)		Density (g/cm³)	Volume/ Panel (cm³)	Mass/ Panel (kg)	Material Cost (CHF/Panel)		Volume Fraction
	lower	upper				lower	upper	
Vinyl Ester	3.0	5.0	1.4	3010	2.95	8.85	14.75	70%
PVC/Glass	3.5	4.5	1.55	2146	3.36	11.64	14.97	30% FVf
PP/Glass	3.0	4.0	1.12	3010	3.37	10.11	13.96	20% FVf
Polypropylene	1.0	2.0	0.91	3010	1.92	1.92	3.84	80%
PVC	2.0	3.5	1.37	3010	2.89	5.77	10.10	70%
Glass Fibers (E-glass)	1.5	3.0	2.55	3010	2.30	3.45	6.91	30%

Table 4*: Cost and technical specifications of composite backing materials.*

The cost and environmental analyses were focused on the production of the solar tile designed in collaboration with LESO-EPFL and PV-LAB-EPFL (Size: 114 cm x 52 cm, Active part: 110 cm x 43.3 cm, Thickness: 6 mm) based on a BRAAS Schweiz AG Tegalit concrete roof tile. Such tile provides a power of 30 W. A production of 100'000 tiles / year (estimation by LESO-EPFL for Western Switzerland) was considered. The production steps included i) the raw materials production, ii) the composite backing manufacturing, iii) the a-Si PV glass panel production and iv) the final lamination.

Figure 13 shows the production cost structure of the composite backing for the five investigated scenarios. It was found to be in the range of 16 to 19 CHF, dominated by the cost of the material. The glass fiber reinforced polypropylene (PP) and polyvinylchloride (PVC) are the less expensive options.

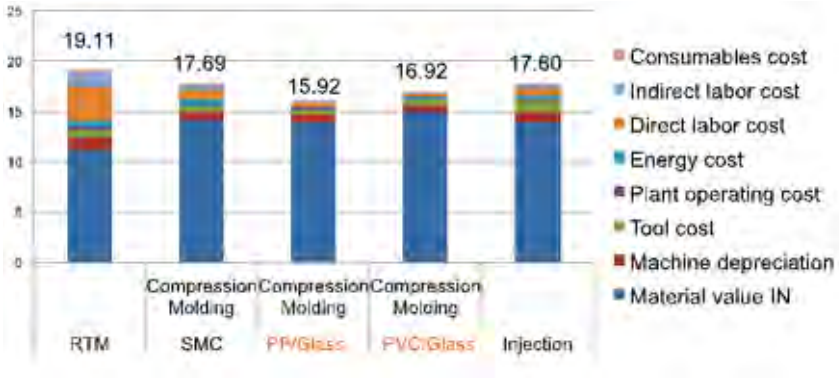

***Figure 13**: Production cost (CHF) of the solar tile with the five composite backing scenarios.*

A screening life cycle inventory was carried out with CO_2 emissions (kg eq.) and energy requirements (MJ of non-renewable primary energy). As shown in Figures 2 and 3, the impact of the PVC/glass backing is the lowest of all considered scenarios, and in fact very close to that of the reference glass/glass module.

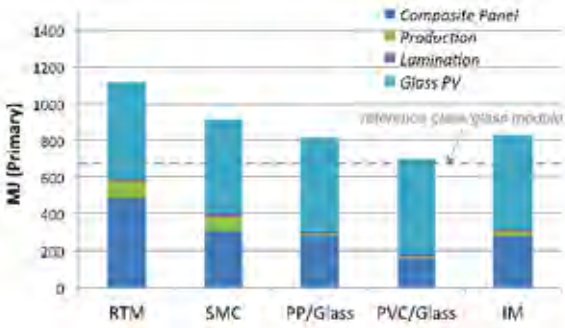

***Figure 14**: Energy requirements during production of the solar tile with the five composite backing scenarios.*

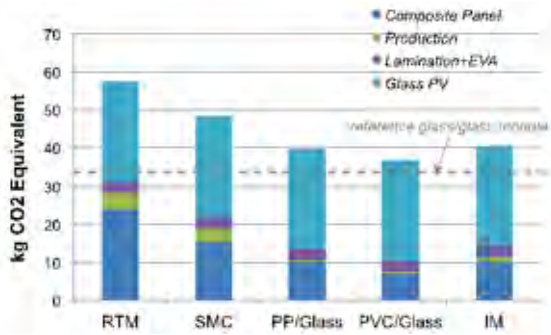

***Figure 15**: CO_2 emissions during production of the solar tile with the five composite backing scenarios.*

Figure 16 summarizes the costing and environmental analysis and compares the composite backing tiles with a reference aluminum framed glass/glass tile. The cost of a glass 'backing' was assumed to be 5 CHF. For comparison the production cost of the Al framed glass/glass reference tile was taken as 45 CHF (incl. frame of 5 CHF and lamination cost of 2.2 CHF).

It is again evident that the PP/glass and PVC/glass thermoplastic composite options are the most interesting. The latter shows a 10% cost increase but similar carbon footprint compared to the reference module. Further cost reduction is expected with increasing volumes beyond 100'000 parts/year.

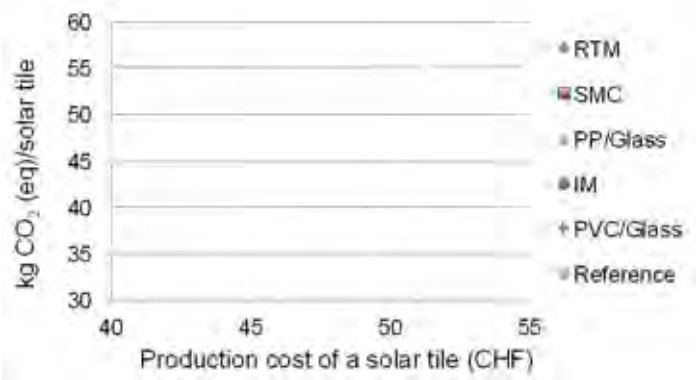

***Figure 16**: CO_2 emissions vs production cost of the solar tile with the five composite backing scenarios.*

Integrated process with glass mat thermoplastic composites

The glass fiber reinforced PP and PVC thermoplastic composites were identified as the most relevant options for large volume production of composite backing structures. These two 'glass mat thermoplastic' (GMT) composites are produced in the form of semi-finished plaques in a first step, and compression molded in the desired shape in a second step. A typical GMT process cycle includes a 1 min. preheating step (IR oven, 200-230°C) followed by a transfer into the mold set at 80°C and the application of pressure (100-300 bar) for 1 min, and a final trimming.

A novel integrated process approach was introduced, in which the lamination step of the glass module to the composite backing (Figure 17a) is suppressed by direct overmolding of the composite backing on the glass with or without adhesive layer (Fig. 17b). The main challenges are i) the risk of breaking the glass due to thermal shock during the molding process and ii) durability issues in case no adhesive is used. Table 5 summarizes the advantages and drawbacks of the standard lamination vs the integrated process method, based on an initial series of processing trials. Several test specimens were produced with intact glass. A molded-in composite frame could moreover be processed, in order to limit the ingress of moisture on the module electrical contacts.

***Figure 17**: Standard lamination (a, left) and integrated process (b, right).*

Process	Features	Pros	Cons	Picture
Standard lamination		- Well-known process	- 3 steps	
Integrated (PP/Glass, 8 bar, 220°C, 30 s)	with adhesive	- 2 steps	- Thermal shock - Degassing of adhesive	
	no adhesive	- 2 steps - Cost reduction	- Thermal shock - Durability?	
	no adhesive, framed	- 2 steps - Cost reduction	- Thermal shock - Durability?	

***Table 5**: Summary of process methods.*

Demonstrators

The production of five PV module demonstrators based on a glass module and a structured composite backing was completed at LTC-EPFL in Dec. 2011 using micromorph glass modules prepared by PVLAB-EPFL. These modules are functional, with a power of 30 W. Figure 18 shows a demonstration roof with 4 solar tiles surrounded by standard Tegalit roof tiles prepared and installed at the PVLAB.

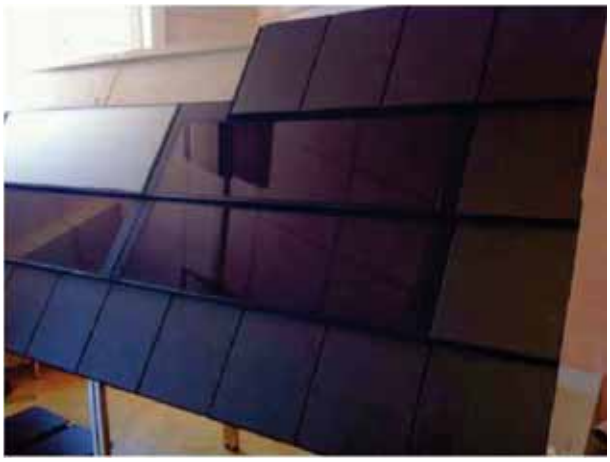

***Figure 18**: Demonstration roof with 4 solar tiles surrounded by standard Tegalit roof tiles.*

Main achievements and future work

To summarize, two optimal composite materials (GMT process) were identified based on cost and environmental assessment with attention paid to composite backing manufacture, PV panel production and lamination. A new composite material (glass fiber reinforced PVC) with superior fire resistance and UV stability and a novel cost effective integrated process method were introduced. Five prototype tiles (power 30 W) were also produced and installed on a demonstration roof.

In the continuation of the project, the integrated process method will be further developed using the new glass reinforced PVC composite. Attention will be paid to the mechanical and thermal design of the glass/composite module assembly, using a combination of experimental and numerical approaches. Focus will also be on optimizing the interface between the glass module and the composite backing in collaboration with PVLAB, and on the production of a new series of tile demonstrators including interference filter glass in collaboration with LESO.

General comments

Consulting with practicing installers gave essentially positive appreciations of the concept, with the major question being the potential price of the final product, question not answered yet.

Another issue was on the fixation solution proposed to compensate for the lighter weight of Archinsolar tile compared to the weight of the 4 TEGALIT tiles it will replace (approx. 12kg vs. 21kg). Most existing system use hooks at the bottom of the tiles. Our analysis shows that the screw system should perform OK, but this has to be checked on the prototypes, as it depend heavily on the final material chosen. A back-up solution already exists in case of unsatisfactory results (see below).

The problematic of fire resistance has not been addressed up to now, as it depends heavily on the kind of substrate the final (commercial) product will be made of. Nevertheless, this is an issue that must be addressed for official certification, together with electricity safety.

An external element has brought mixed feelings amongst the developing team: Braas manufacturer issued mid 2012 a novel product, namely a PV tile, compatible with their TEGALIT tiles system (see Annex 1).

On one hand, having a competitor on the market before we are ready is bad news, even if we don't know yet their pricing position.

On the other hand, there are two positive elements associated:

- There is a market for this kind of product, as this move by a large tile manufacturer demonstrates.
- The analysis conducted to identify the best tile product we should be compatible with was perfectly correct (TEGALIT), as shows the same selection by a manufacturer producing several dozens of tile models.

Their system uses a hook at the bottom of the tile, solution that can be used as back-up if the screws system proves unsatisfactory. Our proposed system has the advantage of no apparent fixation. The Braas PV tile has very visible connections, and that can be a point where Archinsolar will do better.

Next steps will be final analysis of the new prototype series.

Reliability testing

Adhesion testing for Archinsolar modules interfaces

As seen in the previous sections, several interfaces are present in the ArchinSolar module design concepts. All interfaces must be reliable in time. In order to test the quality of the different interfaces, adhesion tests were performed for the different encapsulants and substrates using a specifically developed adhesion test based on the “Compressive-Shear Test” (CST) technique. All adhesion tests were performed before and after degradation in damp-heat (DH) conditions (85°C/85%RH) for 70h.

The matrix of the tested conditions is given in Table 6.

Front / back side module	**Substrate**	**Encapsulant**	**Condition ID**
Front side	glass	Clear PVB	PVBc
Front side	Colored filter	Clear PVB	PVBcCF
Back side	glass	White and orange PVB	PVBow
Back side	TCO on glass	White PVB	PVBwTCO
Back side	TCO on glass	White and orange PVB	PVBowTCO

***Table 6**: Matrix of the tested interfaces*

Figure 19 gives an example of adhesion test result for all front-side interfaces of ArchinSolar modules, before (plain curves) and after (dashed curves) degradation in DH conditions for 70h. It can be seen that adhesion of clear PVB to glass is less efficient before degradation than adhesion of clear PVB to colored filter. However, the adhesion after degradation being similar for the two conditions after degradation, one can state that adhesion of clear PVB to colored filter will be less reliable in time than on glass.

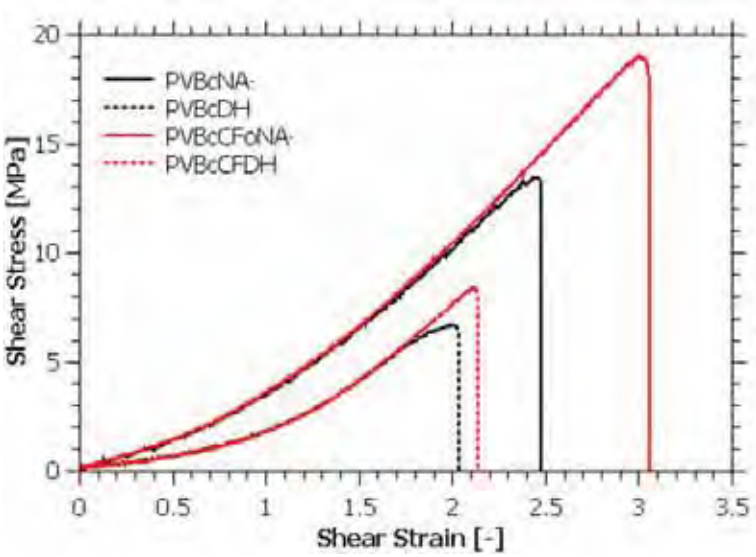

***Figure 19**: Adhesion curves obtained using CST for interfaces in front of archinsolar module stack. Black curves present adhesion of clear PVB (PVBC) on glass while red curves present adhesion of clear PVB to colored filter (CF). Both results before (plain curves) and after (dashed curves) degradation in DH conditions are given.*

Figure 20 presents the results concerning the back-side of ArchinSolar modules, according to the description given in Table 6.

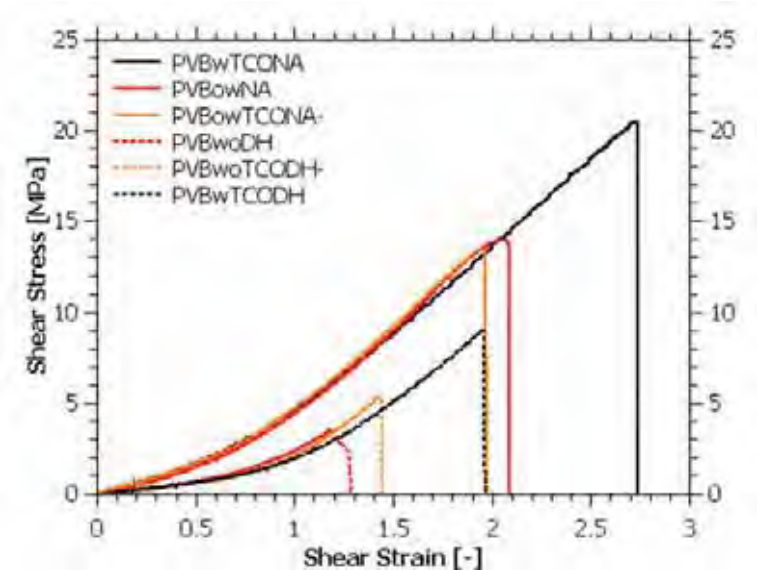

***Figure 20**: Adhesion curves obtained using CST for interfaces in back of archinsolar module stack. Black curves present adhesion of white PVB (PVBW) on TCO, red curves present adhesion of orange and white PVB stacks to glass and orange curves present adhesion of orange and white PVB stacks to TCO. Both results before (plain curves) and after (dashed curves) degradation in DH conditions are given.*

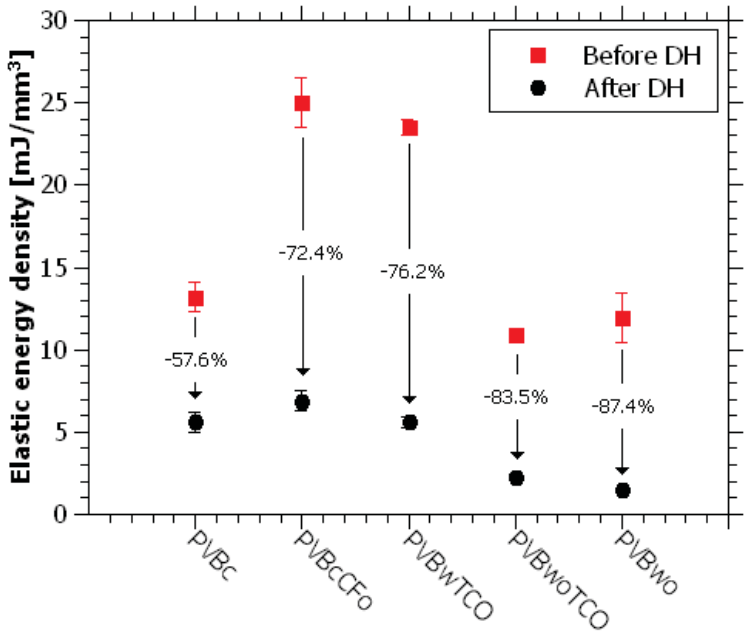

***Figure 21**: Adhesion summary for the different conditions described in table 6.*

Conclusions of the adhesion study

- On the front side of the ArchinSolar modules, adhesion of clear PVB is better on the colored filter than directly on glass before degradation. However, due to the larger relative loss of adhesion after degradation for clear PVB on colored filter, it is stated that this interface is less reliable and should be protected against water ingress.
- Similarly, the white PVB used on the back-side leads to strong initial adhesion which degrades strongly in DH conditions.
- When orange PVB is used (as stacked with white PVB), delamination always occurs on the orange PVB/substrate interface, leading to the conclusion that orange PVB adhesion is usually lower than white PVB adhesion on the tested substrates (glass and TCO)
- Due to the usually large adhesion losses observed after DH degradation, one can state that a moisture blocking layer (edge sealant) must be used in the ArchinSolar module design.

Evaluation of the edge-sealing protection effect

As the need of an edge-sealing agent to protect the interfaces from moisture ingress has been emphasized by the adhesion study presented above, we present here the evaluation of the edge sealing protection potential for two encapsulants; white and clear PVB.

The protection potential of the edge sealant has been evaluated by monitoring the sheet resistance of a ZnO layer deposited on glass, encapsulated using white or clear PVB and placed in a climatic cabinet under DH conditions (85°C / 85%RH). Evolution of the relative sheet resistance increase as compared to the initial ZnO layers value are shown in figure 22 for clear and white PVB with or without edge sealant.

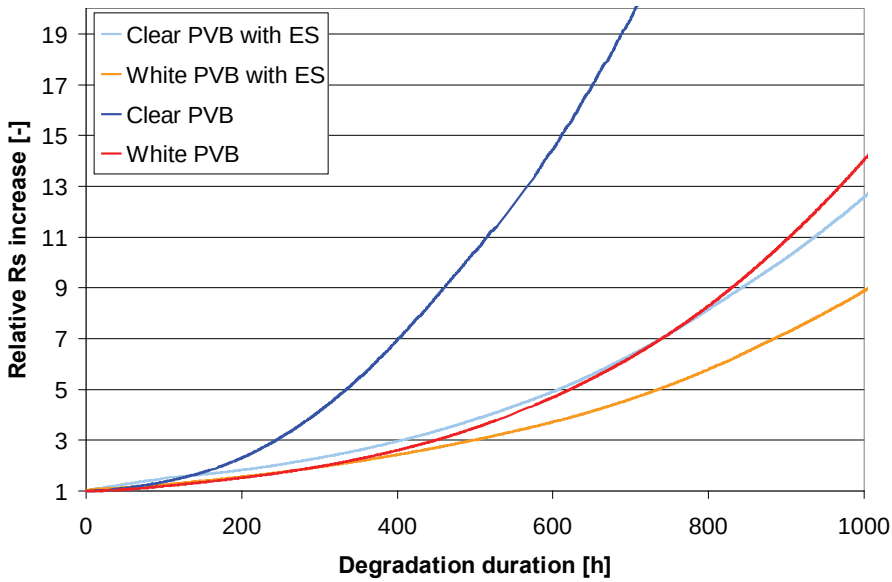

Figure 22: *Relative sheet resistance increase of ZnO layers deposited on glass and encapsulated with clear or white PVB, with or without edge sealant (ES) and placed in a climatic chamber under DH conditions.*

It is clearly seen that addition of an edge sealant lowers the relative sheet resistance increase rate for both clear and white PVB, with a greater effect for the clear PVB. Table 7 summarizes the relative sheet resistance increase of ZnO layers after 1000h of DH degradation when protected with clear and white PVB, with and without edge sealant. The protection factor calculated as the sheet resistance increase ratio between condition without and with edge sealant is also give as an indicator of the edge sealing effectiveness.

	With edge sealant	Without edge sealant	Edge sealant protection factor
White PVB	9	14	1.56
Clear PVB	15	42	2.8

***Table 7**: Relative sheet resistance increase of ZnO layers after 1000 in DH for white and clear PVBs.*

Conclusions on the edge-sealing protection effect

- Edge sealing was shown to be necessary to protect ArchinSolar modules interfaces between encapsulants and module substrates
- It has been demonstrated that addition of an edge-sealing agent reduces the ZnO sheet resistance degradation by a factor of 1.5 to ~3 depending on the encapsulant.
- As a general conclusion, edge sealing should be used in the ArchinSolar module design concept to enhance the long-term reliability

Photovoltaic energy in the building envelop

PVT collector

In Solergie buildings the local generation of low temperature heat and electricity is considered as an additional primary function of the building skin. Mostly the generator is situated on the roof.

This new interpretation of roofs influences the architectural design on different scales: Building element, building, community or city. Considering formal issues, the PV/T is the most sensible element in the system because it is visible from outside and is placed on the most essential part of a house.

The roof integration of a combined photovoltaic (PV) and solar thermal (PT) collector, known as hybrid collector (PV/T), brings the advantages of

- increased electrical performance due to controlled cell cooling by a thermal absorber on the backside of a PV module
- increased thermal performance due to backside insulation by building insulation material
- higher aesthetical value

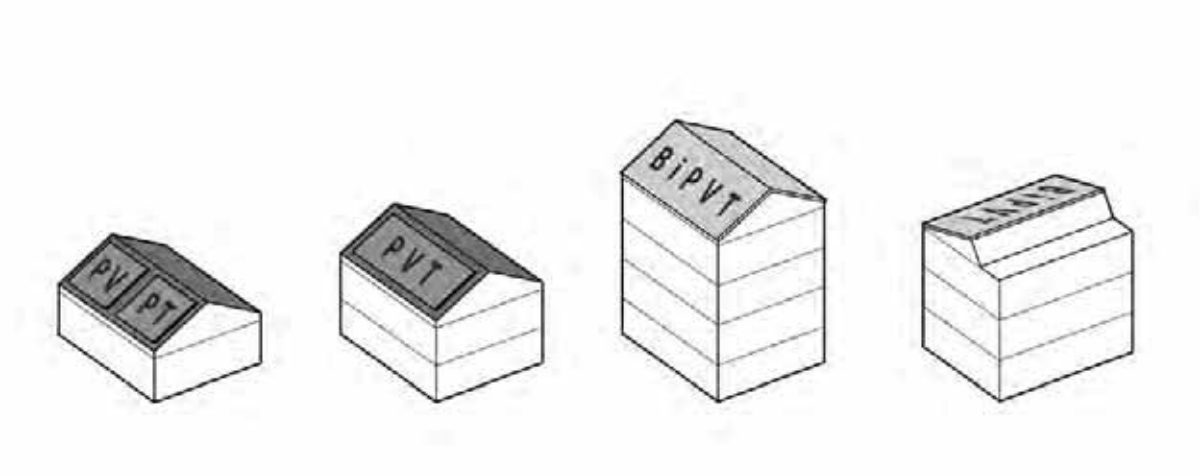

Figure 23: *Photovoltaic and solar thermal installation side by side; roof added installation of combined PV/T as state of the art (24 figures left) and building integrated large size roof element of PV/T (24 figures right)*

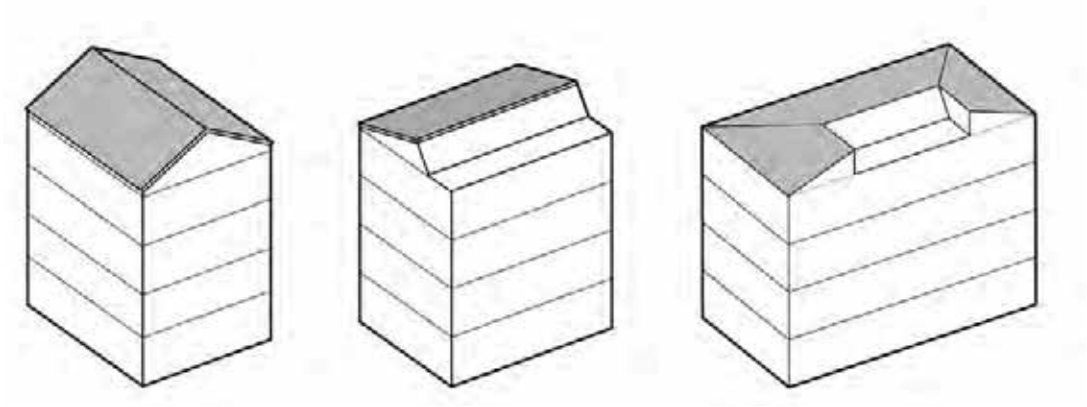

Figure 24*: Constructive and typological freedom of roof design with BiPVT*

A concept of a pre-fabricated large size roof element is being elaborated. The concept aims at simplification of the construction by avoiding redundant layers and multi-functionality of the elements and leads to formal and constructive coherence. The elements allow a flexible design, which is adaptable to different PV-modules (technology). Beside that the large size element also allows a flexible architectural application due to different shapes and colors of the first layer. One of the main goals is a more economical planning, construction and installation process.

The elaborated concept of a new solar roof element consists of following different elements:

- Visible first layer of glass with adaptable color
- Electric generating photovoltaic
- Thermal absorber as base structure of the first layer
- Thermal roof insulation with low u-value and open to vapor diffusion
- Timber frame construction as main structure
- Visible inner covering

The element is being pre-fabricated in an industrial process by robots. The electrical and hydraulic connections are tested in the assembly hall. The pre-fabricated roof elements are transported by transporter to the construction site and put on the roof by crane. This enables a simple and secure installation on the site. The faster installation process enables a decrease of total installation cost.

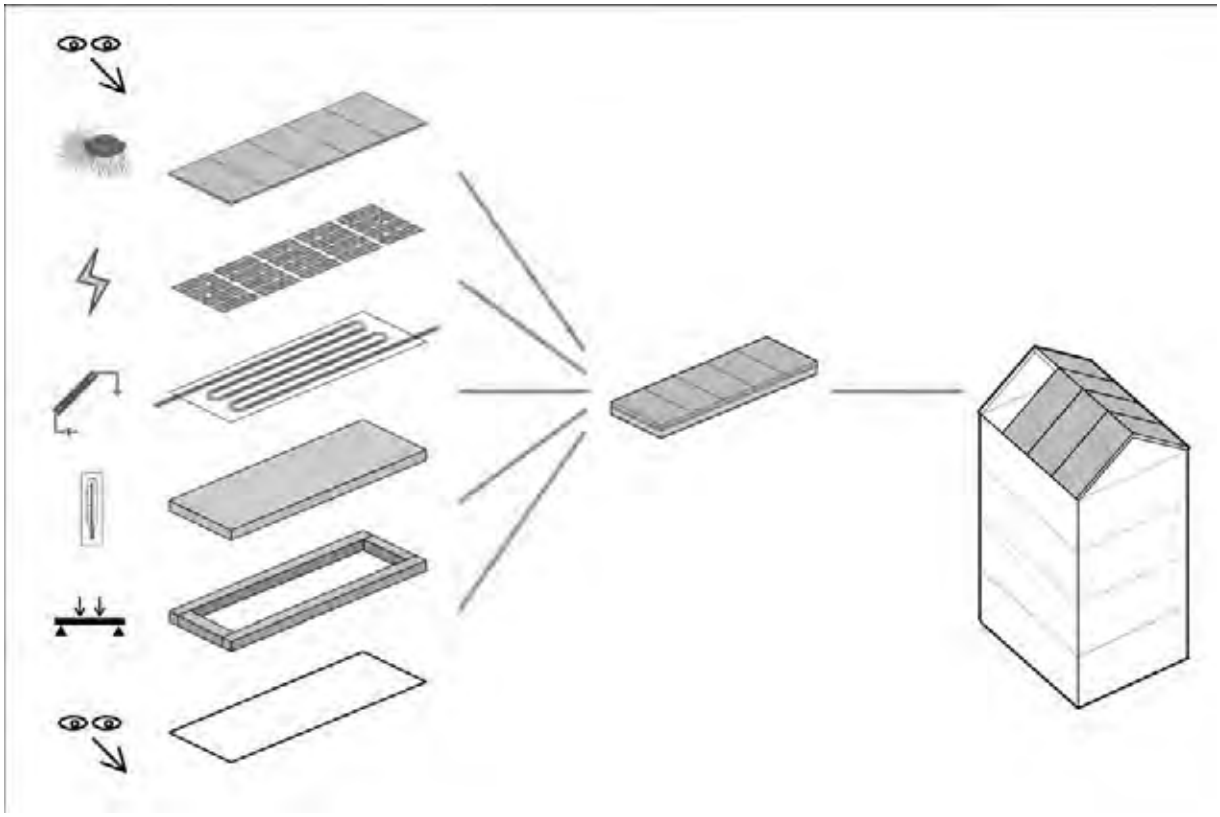

Figure 25*: Components of the building integrated, pre-fabricated large size solar roof element*

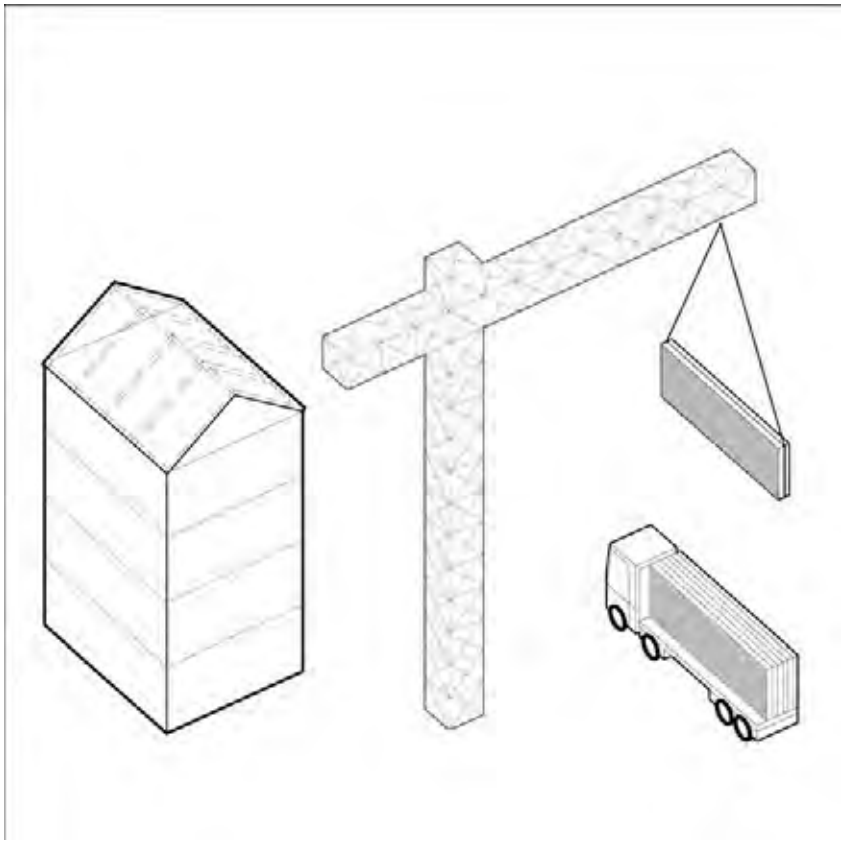

***Figure 26**: Pre-fabricated roof elements are transported by transporter to the construction site and put on the roof by crane*

Moisture Ingress through the PV Modules: Heat & Mass Transfer Study

Airflow around building integrated photovoltaic (BIPV) has a significant impact on their hygrothermal behavior and degradation. The potential of reducing the temperature of BIPV using underneath cavity is experimentally and numerically investigated in literature. Most of the models are over-simplified in terms of modeling the impact of 3D flow over/underneath of PV modules, which can result in a non-uniform surface temperature and consequently a nonhomogenous thermal degradation. Moreover, the simultaneous presence of radiation and convection related to upstream wind, in addition to the combined impact of back-ventilation and surface convection, are barely addressed in literature. However, these simplifications can result in the unrealistic loading climate conditions. Therefore, this study intends to understand the impact of simultaneous flow above and underneath of the PV modules.

For this purpose, a unique experimental setup is developed. Employing a thermography technique and particulate image velocimetry (PIV), the aim of this setup is to monitor the surface temperature of PV modules and flow pattern in presence or absence of an underneath cavity exposed to various upstream wind velocities and radiation intensities. The result of this study in addition with the future development of a simulation model will result in development of recommendations and guidelines for the installation of roof and façade integrated PV modules, e.g. for promoting cavity ventilation in order to reduce the hygrothermal loading of the PV modules.

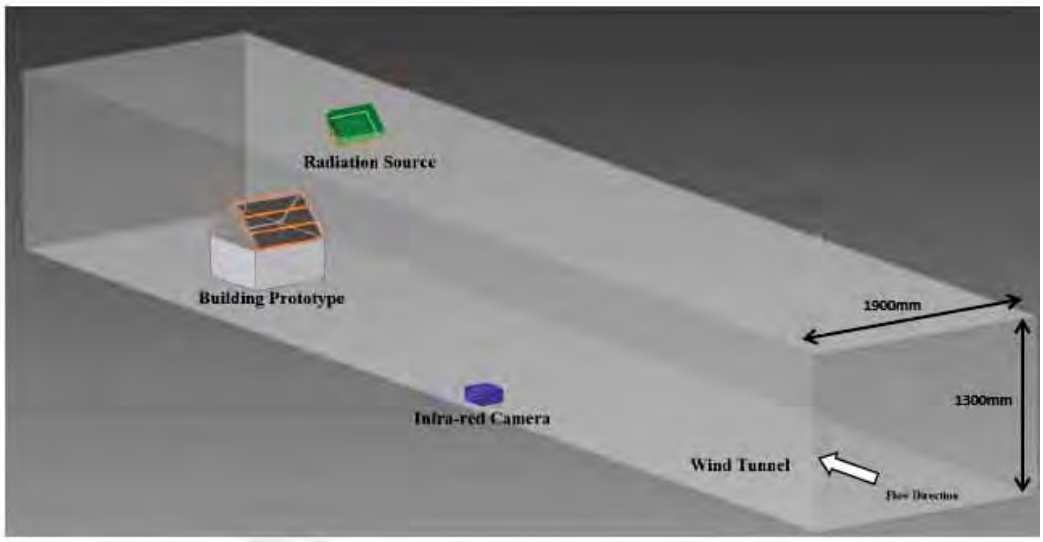

***Figure 27**: Wind tunnel experiment setup*

Figures 27 and 28 depict the unique setup of the developed experiment, including building prototype, radiation source (solar simulator), and monitoring devices (i.e. infrared camera, thermocouples, and thermopiles). The whole setup is placed inside the ETH/Empa wind tunnel; the test section of this tunnel is 1300mm in height and 1900mm in width. The building prototype consists of an insulated Styrofoam structure. The roof is covered with photovoltaic modules. The cavity height can be adjusted as well as type: flat-wise and stepwise installation.

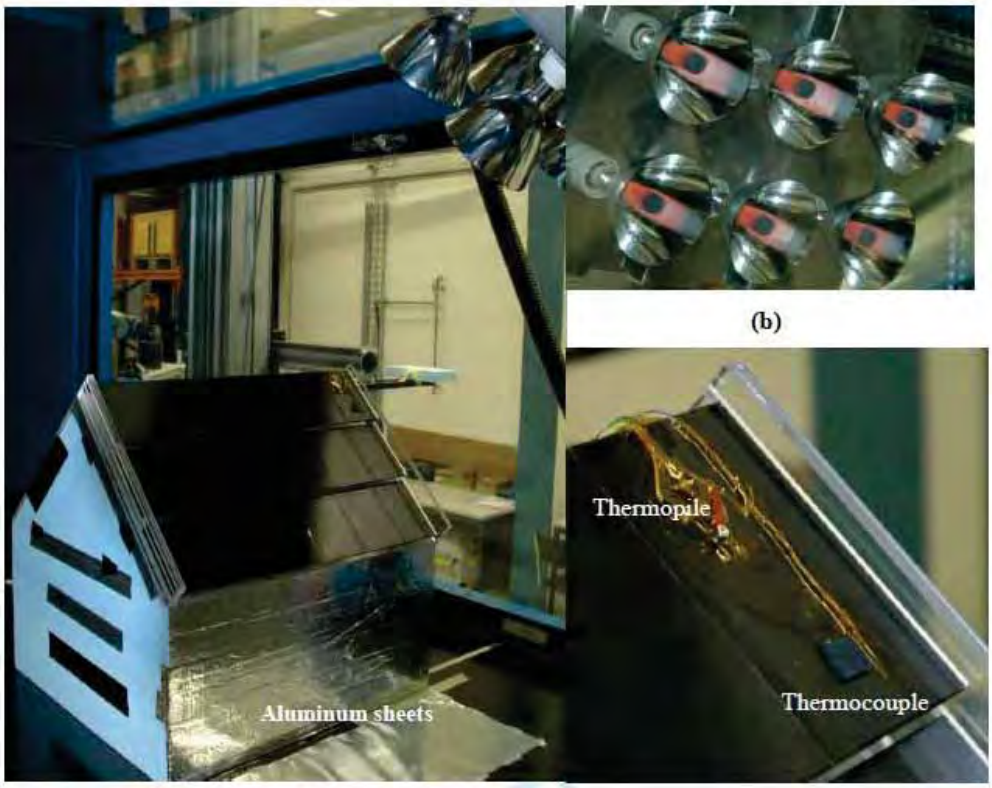

***Figure 28**: (a) building prototype (b) solar simulator (c) thermocouple and thermopile*

Thermography

The setup includes a solar simulator which is positioned in an atmospheric wind tunnel in order to provide a range of various radiation intensities over the BIPV. The approaching upstream wind is controlled in the wind tunnel. The temperatures within the underneath cavity and at the front side of the PV module are monitored with thermocouples and IR camera (Figure 29), respectively. The measurement is repeated under various upstream velocities, radiation intensities, and cavity sizes and arrangements.

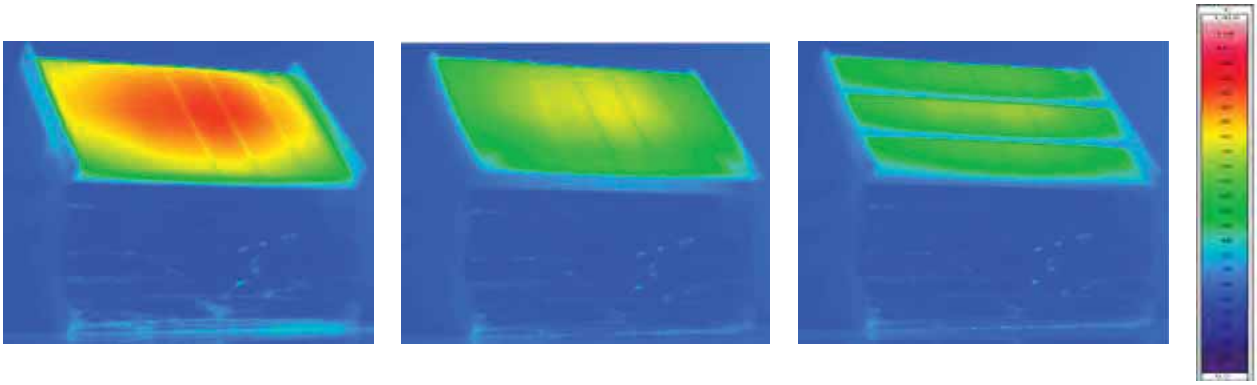

***Figure 29**: Monitored temperature of the BIPV using infrared camera*

Particulate Image Velocimetry

PIV technique is used to visualize the flow underneath and above the cavity. The heat transfer between photovoltaic's modules and airflow can significantly vary due to the contact area and the velocity of the air on the surfaces. The PIV techniques help to understand the local heat transfer distribution on the PV modules. One can use the obtained data to investigate the impact of the PV arrangement, roof declination, and cavity size on the local heat transfer from the PV modules. This helps to modify the current installation of the BIPVs. Also, the PIV technique provides reliable datasets in order to validate the CFD models. For example, Figure 30 shows the flow pattern above and under cavity when the PV module is or is not heated.

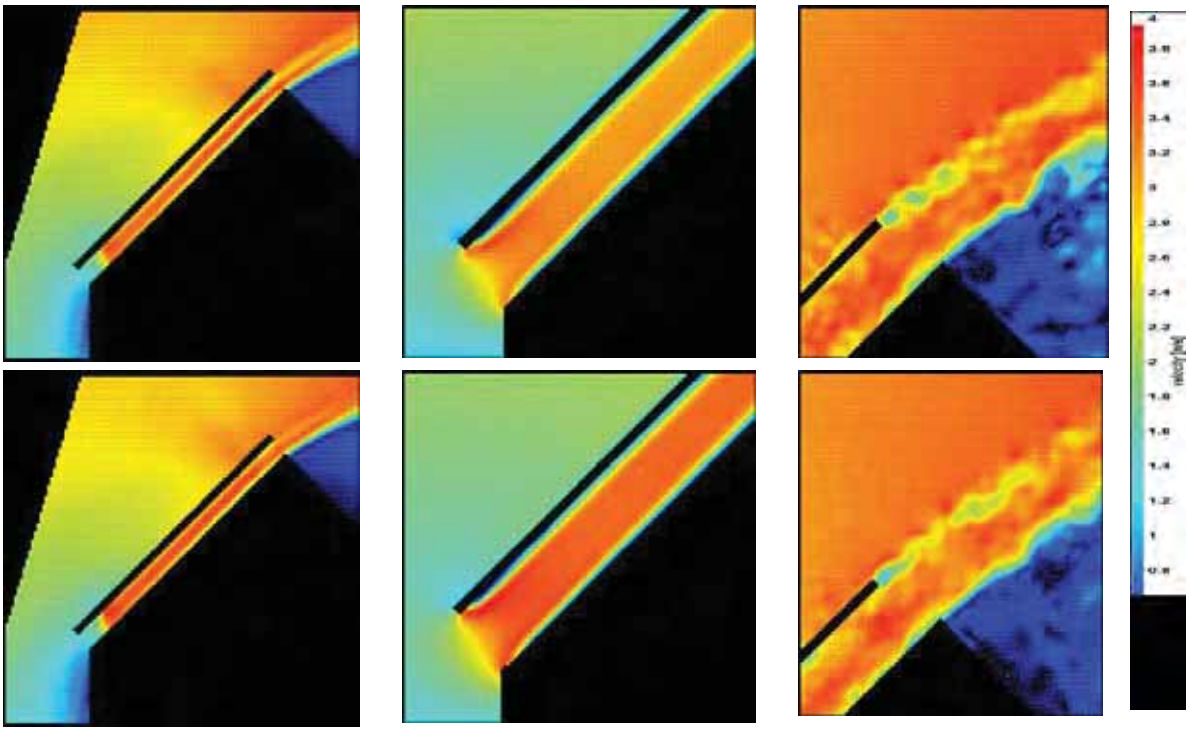

***Figure 30**: (Top) non-heated case (bottom) heated case*

National and international collaborations

In addition to the strong partnership between the scientific partners involved in the project, this project also relies on fruitful collaboration with SwissInso for the production of the colored glasses and with Pramac for the production of the micromorph modules.

Evaluation for year 2012 and perspectives for 2013

In 2012, most project deliverables were met on time. The first terra-cotta modules with both technologies (interferential filters and modified encapsulation process) and a fully integrated solar tile with a back sheet composite were demonstrated. Two patents have been deposited for the colored modules.

Looking ahead, further aesthetic developments will be made by developing new colored filters also on textured patterns of the glass. The emphasis until the end of the project will be to finalize the reliability testing on all the systems developed and finally, a real demonstration roof will be installed in the city center of Neuchâtel, in a close collaboration with the city council of Neuchâtel.

Acknowledgments

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Office fédéral de l'énergie OFEN

OPTIMIZATION OF THIN FILM MODULE TESTING AND PV MODULE ENERGY RATING AT SUPSI

Annual Report 2012

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Date	01.12.2012

ABSTRACT

The project aims to improve the measurement accuracy for thin film technologies through the definition of new test procedures and the up-grade of the test equipment. The focus is on the characterisation of multi-junction devices and the pre-conditioning of thin film modules, which needs to be improved to guarantee a higher comparability and repeatability of power measurements. The results, in combination with long term outdoor data monitoring and modelling activities, will be used to increase the understanding of the performance of thin film modules in comparison to the one of crystalline silicon technologies and to verify the applicability of the present energy rating procedure to thin film modules. Side activities as measurement round robins and collaborations with industry and other test institutes will help in the evaluation of the introduced changes.

The activities of 2012 focused on the indoor characterisation of multi-junction modules, the monitoring and validation of an enhanced energy prediction model for thin film modules:

- A new experimental set-up for the spectral response measurement of large area multi-junction modules was successfully validated and a set of commercial modules characterized.
- The outdoor facility was equipped with a new spectro radiometer. The first monitoring data were used to quantify the spectral effects and validate an advanced energy prediction model based on the average photon energy index (APE).
- A number of international and national collaborations have been established to exchange the acquired know-how within this project with industry and research laboratories.

Aim of the project

Energy yield measurements and predictions of crystalline silicon (c-Si) modules have been investigated intensively over the last years, and a positive degree of predictability has been achieved when reliable indoor measurements were available, indicating the temperature and irradiance dependencies of the module [1], together with an accurate performance determination under standard test conditions (STC). Prerequisites for a module ranking which reflects reality are both a high level of measurement accuracy and quality control measures [2]. The aim of this project is to reach the same level of accuracy for thin film technologies.

Understanding and predicting of the energy yield of thin film modules require much more effort than that for c-Si technologies, and the focus has to be put on spectral and meta-stability issues, both for the determination of indoor as well as outdoor performance.

The activity of the first year focused on the indoor characterisation of thin film multi-junction modules and the monitoring and validation of energy prediction models of thin film modules.

An extension of the existing spectral response measurement set-up [3] to a system with bias light systems allowing the characterisation of multi-junction technologies was therefore required, as well as an extension of the outdoor test facility with a spectrum radiometer for the quantification of spectral effects and the validation of advanced energy prediction models based on the average photon energy introduced by T. Betts from CREST [4].

[1] G. Friesen et al.:, kWh/Wp measurements and predictions of 13 different PV modules, 37th IEEE PVSC, Seattle (USA), June 2011.

[2] S. Dittmann et al.: Energy yield measurements at SUPSI - importance of data quality control and its influence on kWh/Wp inter-comparisons, 26th EPVSEC, Hamburg (D), September 2011.

[3] G. Friesen et al.: Final report ISAAC-TISO test centre, quality and energy yield of photovoltaic modules, period VIII, 2007-2010, www.isaac.supsi.ch.

[4] T. Betts et al. : Investigation of Photovoltaic Device Operation under Varying Spectral Conditions, Loughborough University, 2004

Work carried out and results achieved in 2012

2.1 Test procedures for the characterization of multi-junction devices (WP1)

Spectral response measurement set-up

The spectral response (SR) measurement set-up for multi-junction modules was finalised with the purchase of a set of 145 W coloured LED floodlight by AEON (blue, 475 nm; red, 630 nm; infrared, 850 nm), being able to cover all the multi-junction thin-film technologies on the market to date. Figure 1 shows the experimental set-up and the new bias light system.

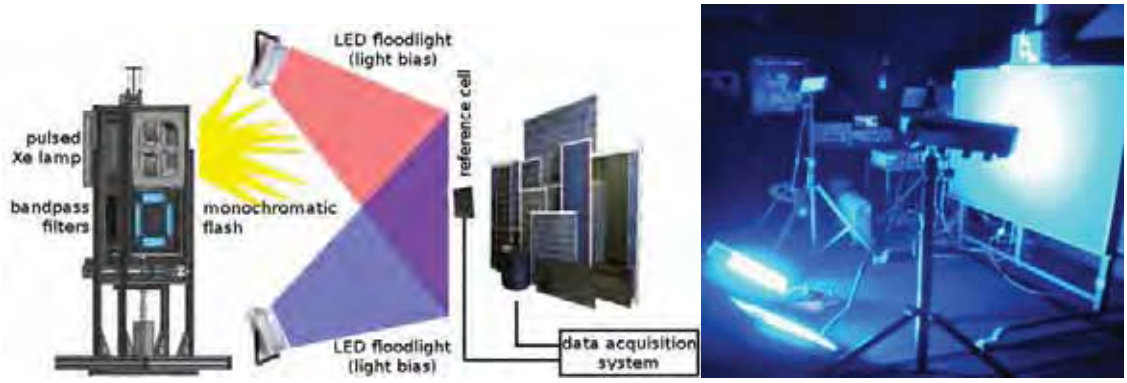

***Figure1**: Measurement set-up with bias light for the measurement of large area modules: (a) the scheme; (b) a picture with blue bias light.*

Several multi-junction modules were tested, both a-Si/a-Si, a-Si/µc-Si and a-Si/a-Si/a-Si. Some results are shown in Figure 2. The figure shows also the dark SR (i.e. the SR measured without bias light). The dark SR was investigated as a tool to detect the effects of low shunt resistances (see figure 2d as an example), that usually affect SR measurements giving rise to non-trivial measurement artefacts.

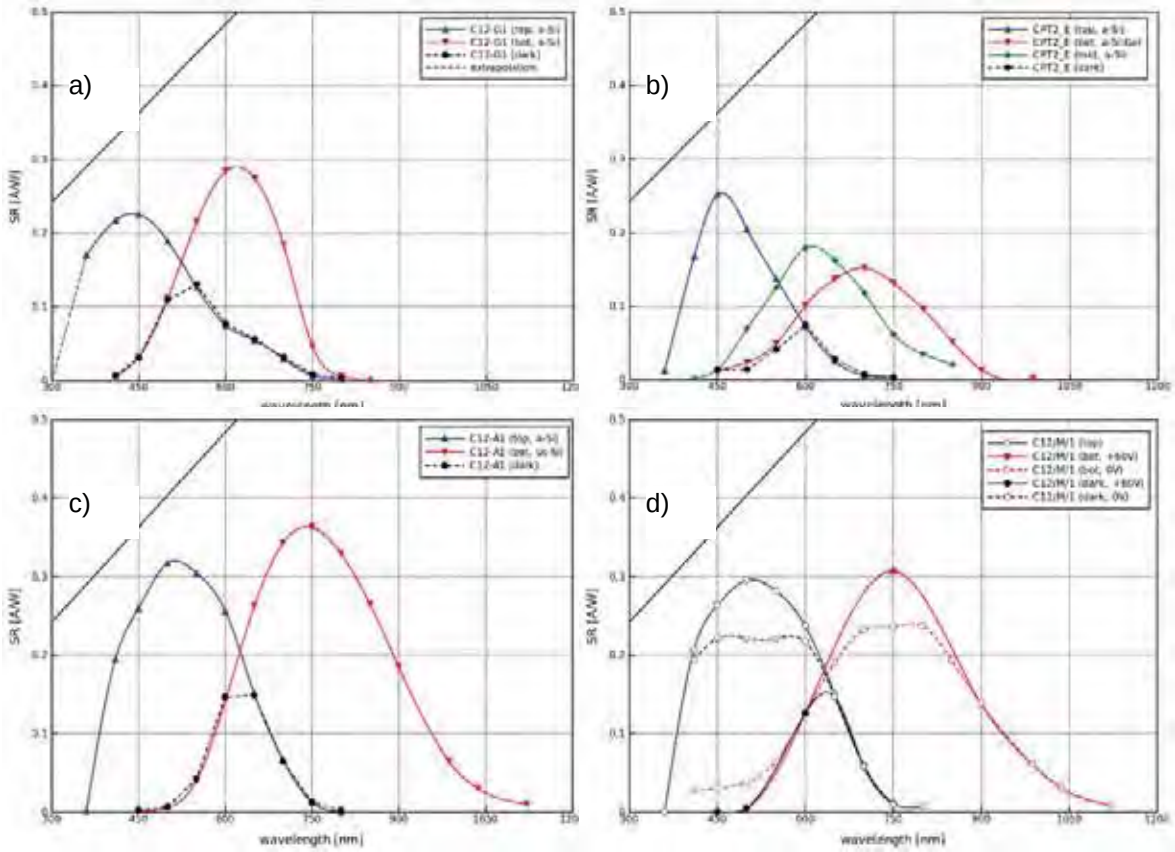

Figure 2: *Examples of SR measurements of commercial size modules: (a) a-Si/a-Si; (b) a-Si/a-Si/a-Si (triple junction module), (c) a-Si/µc-S without shunt losses and d) a-Si/µc-Si with significant shunt losses, detected by the non-zero response of the dark SR at short wavelengths in the absence of additional forward bias voltage (dashed black line).*

A dedicated data acquisition system was developed to acquire SR and external quantum efficiency (EQE) of the testing module. The software has been tested and qualified by the comparison of SR measurements of the PTB-calibrated reference cells. The uncertainty calculation of the new set-up is ongoing.

Procedure for IV characterization of multi-junction modules

The main factor affecting the uncertainty budget in the indoor characterization of multi-junction modules is the spectral mismatch between a solar simulator and the standard reference spectrum AM1.5g. Even a Class AAA simulator may show spectral mismatch giving underestimation of the short-circuit current (and subsequent overestimation of the fill factor) as high as 10%.

The first step that has been investigated towards the development of the most appropriate procedure for the indoor IV characterization was a tool to detect the most appropriate reference cell. Two procedures were studied in parallel:

1. Isc versus spectral irradiance measurement: due to the small variations in spectral irradiance along the 10 ms pulse of the solar simulator, a measurement of the short-circuit current (Isc, corrected to 1000 W/m^2 according to the reading of a given reference cell) may give information on the reference cell that minimizes the uncertainty due to the spectral mismatch.
2. Spectral mismatch calculation: thanks to the SR measurement of the testing module, a spectral mismatch correcting factor can be calculated directly, knowing the spectral irradiance of the solar simulator, the SR of the reference cell in use and the standard reference AM1.5g spectral irradiance.

Figure 3 shows an example of the application of the first method, indicating that the ISE054 ref cell is the most appropriate reference cell in that case.

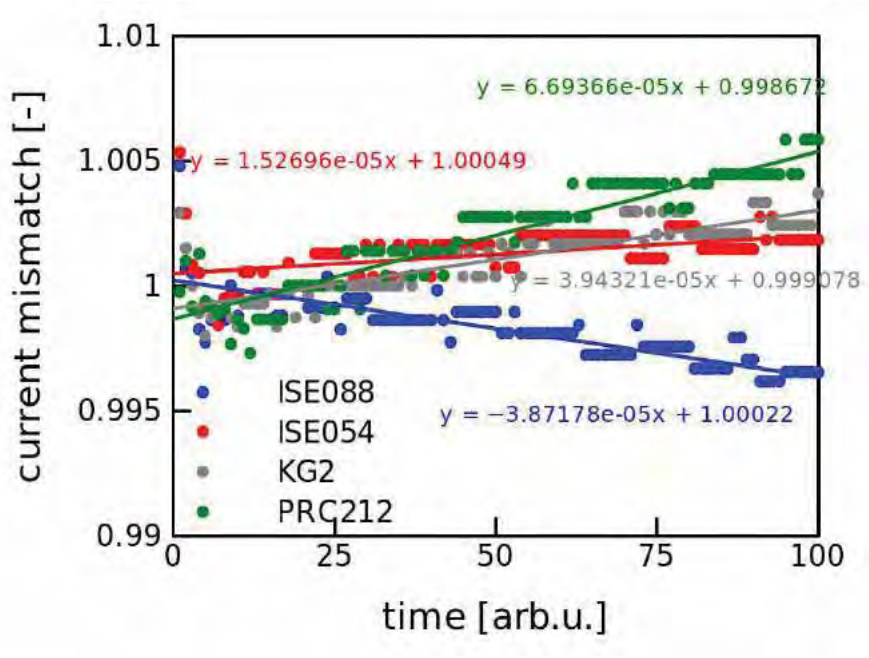

***Figure 3**: Isc versus spectral irradiance measurement, indicating ISE054 as the most appropriate reference cell.*

To apply the second method properly, the spectral irradiance of the solar simulator needs to be measured at each IV characterization. The data acquisition needs then to be implemented to add the spectroradiometer input as shown in figure 4.

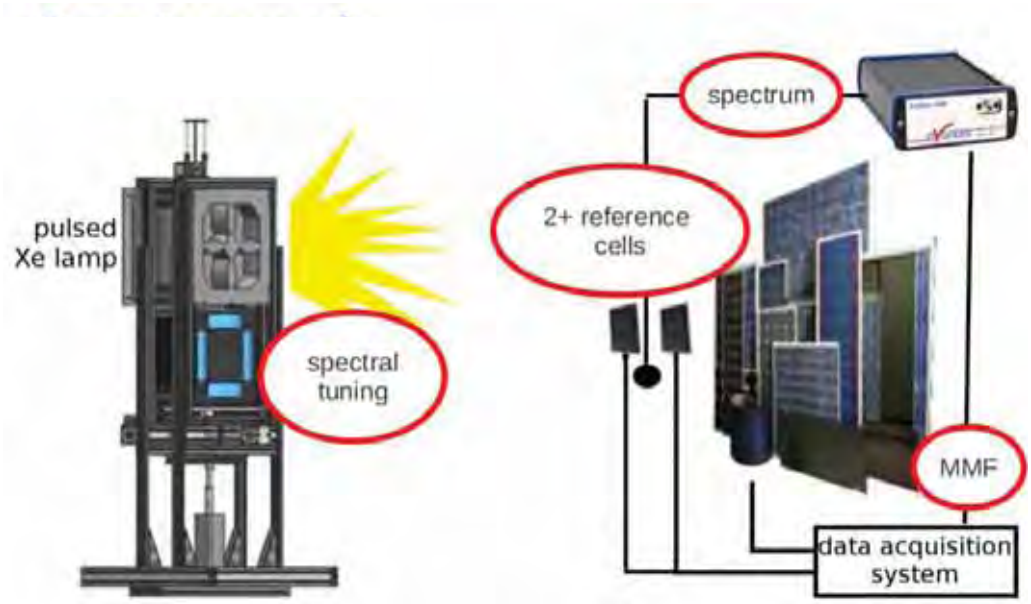

***Figure 4:** The proposed implementation of the data acquisition system for IV characterization of multi-junction modules, with spectral mismatch calculation and tunable spectral irradiance.*

2.2 Inter-comparison of 11 different thin film modules

The focus of the first year of project was on: (1) initial stabilization of thin film modules, (2) energy yield inter-comparisons, (3) energy yield modelling with indoor measured module parameters as input, and (4) the introduction of average photon energy (APE) for the modelling of spectral effects.

Outdoor test facility and test procedure

A measurement campaign (also referred to as “test cycle 12”) which focuses only on thin film module performance was started at SUPSI-ISAAC at the beginning of 2011. A selection of 11 thin film technologies (a-Si, 2 a-Si/a-Si, 4 a-Si/µc-Si, 1 CdTe, 1 CIS, 1 CIGS and 1 CIGSS) have been exposed outdoors, together with some c-Si modules. 2 modules per type are mounted on the outdoor facility (figure 5) and a third one is stored in the dark, keeping it as a reference. The goal is to acquire a minimum of three-year data of the performance, covering the full initial degradation of the amorphous silicon modules (a-Si, approx.1 year), plus 2 years of performance data under so-called stabilised conditions.

***Figure 5**: Picture of the outdoor test facility at ISAAC with the 11 different thin film technologies and 2 c-Si modules for inter-comparison.*

Before their installation on the outdoor test facility, all modules, including the dark-stored reference modules, underwent a set of preliminary laboratory tests (electro luminescence, visual inspection, insulation test and wet leakage test) and a full electrical characterisation with a class AAA solar simulator. The initial electrical performance was measured under standard test conditions (STC), different irradiance levels (100-1000W/m²), temperatures (25-65°C) and spectral wavelengths (360-1170nm). The modules were dismantled at different times of the year (Oct. 2011, Apr. 2012 and Oct. 2012) and measured again together with the dark stored modules in order to detect any changes occurring during outdoor exposure. Outdoors the module power is recorded in minute intervals together with in-plane global irradiance (Kipp & Zone CMP21pyranometer), module temperature and since July 2012 also spectral irradiance (EKO MS-710/712).

Initial stabilisation

The first analysis performed on the test cycle concerned the initial stabilisation of the outdoor exposed modules. Each technology is characterised by a different type of stabilisation process: (1) c-Si by a first light induced degradation (LID), (2) a-Si and µc-Si by the Steabler-Wronski degradation which is partially recovered by thermal annealing and (3) CIS and CdTe by a first positive light soaking effect.

Table 1 summarises the change in STC power between the first indoor measurement (brand-new never exposed modules) and the second measurement in October 2011 for the CIS and CdTe modules and the third measurement in April 2012 for the a-Si technologies. A later measurement has been used as reverence for a-Si and micromorph (µc-Si) modules to be sure that the full Staebler-Wronski degradation has occurred. Whereas the difference measured for the c-Si modules is well within the measurement repeatability, and can therefore be considered as being stable, the CIS and CdTe modules showed an increase in power of 1-5%, which occurred in the very first days to weeks of outdoor exposure.

	Change in STC Power
REF (c-Si)	-0.7%
MOD1 (CIS/CdTe)	4.0%
MOD2 (CIS/CdTe)	4.7%
MOD3 (CIS/CdTe)	2.8%
MOD4 (CIS/CdTe)	0.7%
MOD5 (a-Si 1j.)	-25.9%
MOD6 (a-Si 2.j)	-18.8%
MOD7 (a-Si 2.j)	-16.4%
MOD8 (µ-Si)	-18.9%
MOD9 (µ-Si)	-14.3%
MOD10 (µ-Si)	-13.7%
MOD11 (µ-Si)	-13.9%

***Table 1**: Percent of degradation or recovery (measured with solar simulator) for each module technology.* meas in spring 2012*

As expected, all a-Si modules demonstrated the typical initial degradation, which ranged from approximately 26% for the single junction technology to a little bit less for double junction a-Si (a-Si/a-Si) and down to 14 % for micromorph (a-Si/µc-Si) modules. Once stabilised the inter-comparison of energy yield was started.

Energy Yield inter-comparison (module ranking Jan-Aug 2012)

The coloured bars in Figure 6 show the total energy production (in percent of kWh/Wp) each technology produced within the first 8 months of 2012, compared to the c-Si reference module. Differences of up to +/-6% with respect to the c-Si module have been measured. The standard amorphous technologies (a-Si and a-Si/a-Si) and CdTe are over-performing c-Si of ±4-6%, whereas CIS and a-Si/µc-Si modules produces 2-5% less. A full year ranking will be available in January 2013.

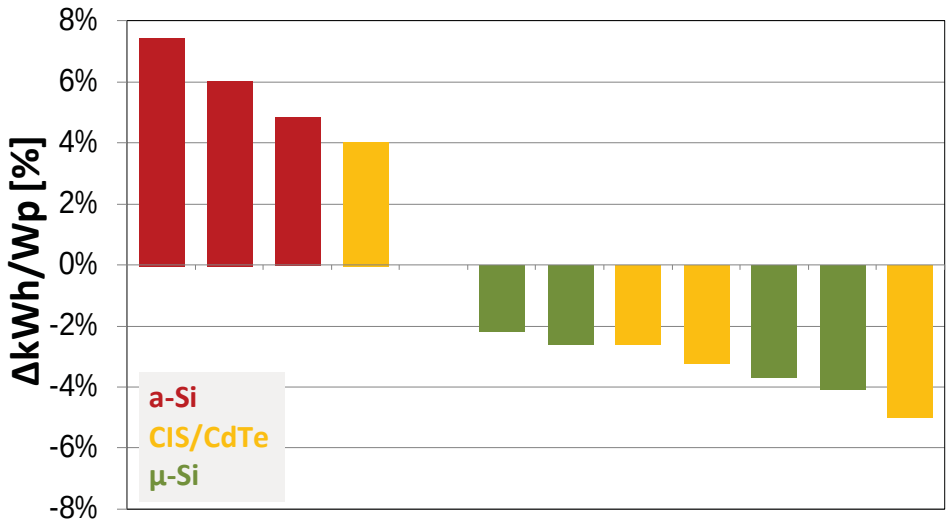

Figure 6: *Differences in percent of energy yield of all thin film modules compared with the c-Si reference module. Indicated in red are single and double junction amorphous silicon, in green a-Si/µc-Si silicon and in yellow CIS and CdTe.*

The ranking shown here is of course strongly influenced by the reference power used for the calculation of the kWh/Wp and has to be therefore considered. When using the indoor measured STC power, as done here, the ranking depends both on the measurement accuracy (kWh and STC power) and on the time stability. Whereas the measurement uncertainty of the kWh is below ±1%, the uncertainty for the thin film technologies can vary between ±3-5% depending on the type of module and test procedure. A ranking with a higher precision should be achieved by: (1) the full implementation of new measurement procedures (see 2.1) for the characterisation of multi-junction technologies, (2) the quantification of the annealing effect occurring within a-Si under real operating conditions, and (3) the definition of more reliable procedures for the stabilisation of CIS and CdTe modules. These topics are investigated within this project and will be considered in future rankings. The first year of the project focused on a first validation of energy prediction models and the impact of single input parameters.

Energy Yield predictions starting from indoor and outdoor measured module parameters

Most commercial software tools require the following inputs to model the energy output: (1) STC power, (2) efficiency over irradiance η(G) and (3) the temperature coefficient $\gamma = P_{max}(T)$. These values are generally measured with a solar simulator. The first validation study performed here aimed to identify the limits of the standard approach, especially for thin film technologies and to extend the approach by the introduction of a parameter describing spectral effects.

Spectral modelling is based on the average photon energy (APE). The APE index (in eV) is calculated according to equation 1 by using the spectral irradiance data measured every minute with a spectroradiometer mounted in-plane to the modules. The index is defined as the ratio of the integrated irradiance to the integrated photon flux density, and gives an idea of how red- or blue-shifted the spectrum is. An index of 1.634eV is achieved for the standard AM 1.5g when the integrals are performed between 350 and 1600nm.

$$APE = \int G(\lambda)d\lambda \Big/ q\int \Phi(\lambda)d\lambda \qquad [eq\,1]$$

Equation 2 describes the module power Pm in dependence of the in-plane irradiance (G), the module temperature (T_{mod}), the average photon energy (APE) and the interpolating coefficients a,b,c,d and e.

$$Pm = \left[a \cdot G + b \cdot G \cdot \ln(G/1000) + c \cdot G \cdot \ln^2(G/1000)\right] \cdot \left[1 + d \cdot (T_{mod} - 25)\right] \cdot \left[1 + e \cdot (APE - 1.634)\right] \quad [eq\,2]$$

The module parameters a, b, c and d are extracted from the indoor measurements performed after stabilisation. The parameter e is extracted from outdoor measurements by plotting the temperature and irradiance corrected P_{max} values (1000W/m and 25°C) versus the calculated APE. Only P_{max} values between 950W/m² and 1050W/m² and stable conditions are therefore considered. The slope of the linear interpolation gives the parameter e. The narrower the spectral response of the module technology is, the stronger is the spectral dependency and consequentially the larger is e. The interpolated module parameters (a, b, c ,d and e) are then used to calculate the energy output. Figure 7 shows the differences between measured and calculated energy yield.

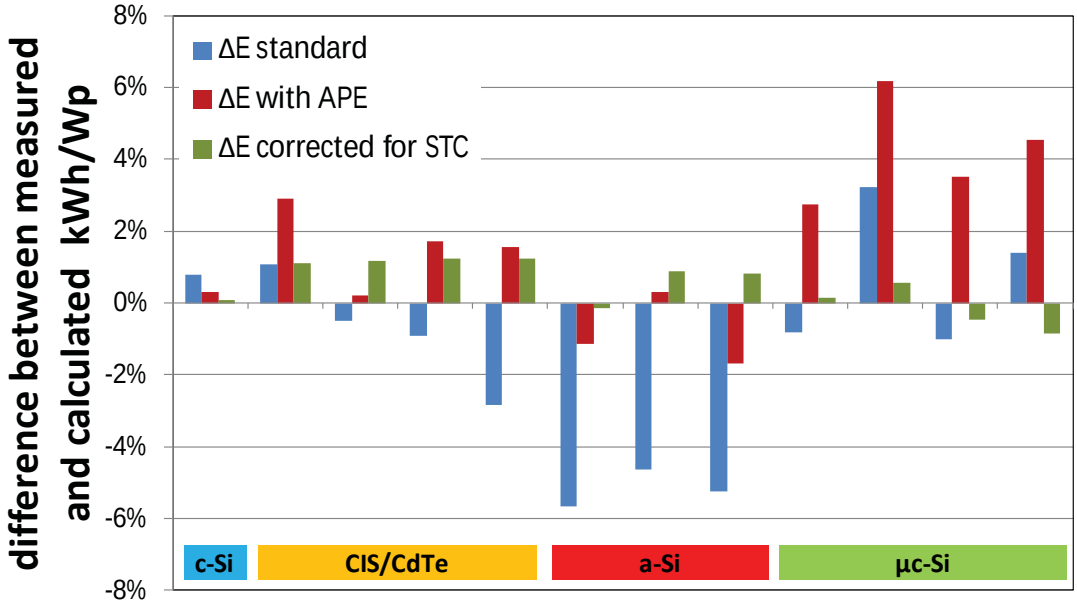

Figure 7: *Differences between measured and predicted energy yield for the 3 months July–Sept 2012. Legend: (blue bars) basic approach considering only the parameters a, b, c and d, (red bars) advanced modelling with APE, (green bars) advanced modelling with index and STC power extracted from the linear interpolation of P_{max} versus APE.*

The graph shows that in order to increase the accuracy with respect to the standard approach, as used by most commercial tools, one needs to consider spectral effects and improve the accuracy of STC power. When doing both, an accuracy of ±1% is achieved. The spectral effect contributes with up to 4% for a-Si (single and multi-junction), a little bit less for a-Si/µc-Si and below 1% for CIS and CdTe. For c-Si and broadband CIS technologies the effect is almost negligible. The technology most influenced by an error in STC power is the a-Si/µc-Si.

National/International collaboration within the project

- Measurement of multi-junction modules with Oerlikon Solar (now TEL Solar). The results showed significant agreement in the performance of a testing module, once the appropriate reference cell is chosen according to one of the methods illustrated above.
- Measurement of single junction thin film and c-Si modules with Fraunhofer ISE (STC power, temperature coefficients, irradiance dependency and SR).
- International measurement inter-comparison campaign of spectroradiometers for a correct estimation of solar spectral irradiance data, organised by RSE and in cooperation with ESTI, ENEL and Universidad Politecnica de Madrid, among others.
- Validation of PVSYST modelling approach in collaboration with André Mermoud.

Summary and outlook 2013

The new experimental set-up for the SR measurement of large area multi-junction modules was successfully validated and the 6 multi-junction reference modules of test cycle 12 characterized. A second measurement of the stabilized modules is foreseen in 2013.

The results helped to highlight certain critical aspects that are frequently observed in this kind of measurements, such as current-limitation and low shunt resistances. A procedure for the correct selection of the bias voltage to be applied during measurement was also defined.

The finalisation of the operating procedure and the calculation of the measurement uncertainty of the STC power of multi-junction modules is ongoing together with a validation of the results, via round robins and indoor-outdoor measurement intercomparisons.

APE has been successfully integrated into a standard energy prediction approach and accuracies of ±1% have been achieved, when starting from in-plane irradiance and module temperature together with a set of high quality module input information (STC power, η(G), γ and P(APE)).

Further validation over a longer period, together with an investigation of how to determine the APE dependency also from short-term outdoor or indoor measurements, is still ongoing.

Compared to c-Si modules, the input parameters of thin film technologies resulted in being less stable over time, and in some cases significant differences between modules of the same type have been observed.

Some discrepancies between indoor and outdoor STC characterization have been identified for some of the thin film technologies. Investigations to reduce this spread and further improving future energy predictions are ongoing. The three main issues identified are: (1) meta-stabilities in CIS and CdTe modules, (2) current-limitation within sub-cells due to spectral mismatch and (3) new module parameters capable of predicting seasonal variations of STC power within a-Si based technologies.

Moreover future work will include angle of incidence effects, the change of energy prediction when introducing irradiance dependent temperature coefficients and modelling of module temperature.

List of publications 2012

M. Pravettoni, “To Bias or Not to Bias? A 'How-To' Guide for Spectral Response Measurements of Thin Film Multi-Junction Photovoltaic Modules” MRS Proceedings, 1426, pp 81-86. doi:10.1557/opl. 2012.838.

M. Pravettoni at al., “A Filtered Pulsed Solar Simulator for Spectral Response Measurements of Multi-junction Modules of Commercial Size” Proceedings of the 27th European Photovoltaic Solar Energy Conference, Frankfurt, 2012.

G. Friesen at al. “Detailed analysis of thin film module performance based on indoor and outdoor tests” Proceedings of the 27th European Photovoltaic Solar Energy Conference, Frankfurt, 2012.

M. Marzoli at al. “PV module parameters determination for system simulation” Proceedings of the 27th European Photovoltaic Solar Energy Conference, Frankfurt, 2012.

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DEFEKTANALYSEN AN PV MODULEN MIT ELEKTROLUMINESZENZAUFNAHMEN UND DEREN KLASSIFIZIERUNG

Annual Report 2012

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Project- / Contract Number	INNO-IW / 12349.1
Duration of the Project (from – to)	01.03.2011 – 01.03.2012
Date	12.12.2012

ABSTRACT

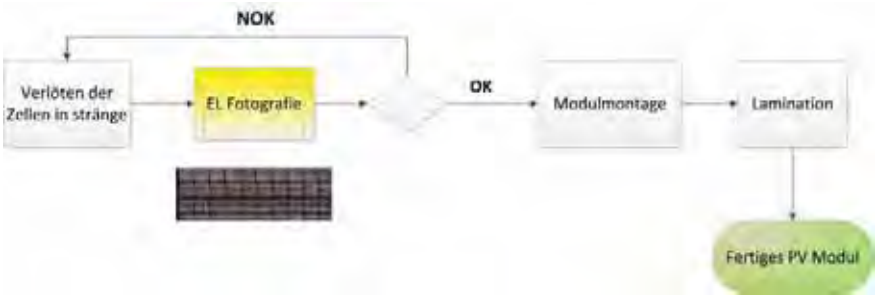
This project aims to improve the quality control of PV module production. For this purpose the electro-luminescent photography is used in the production line. The quality control is performed after the soldering of the string and before the lamination process. This quality control step allows the repair of strings with soldered cracked cells replacing them with new ones and the final quality of the PV module increase.

Projektziel

Für PV Module, deren Leistung über 25 Jahre von den Herstellern für den Betrieb im Freien garantiert werden, ist eine 100% Qualitätskontrolle des Endproduktes erstrebenswert. Aktuell wird die Qualitätskontrolle der PV Module durch eine Leistungsmessung, der elektrische Isolation und einer Sichtkontrolle durchgeführt.

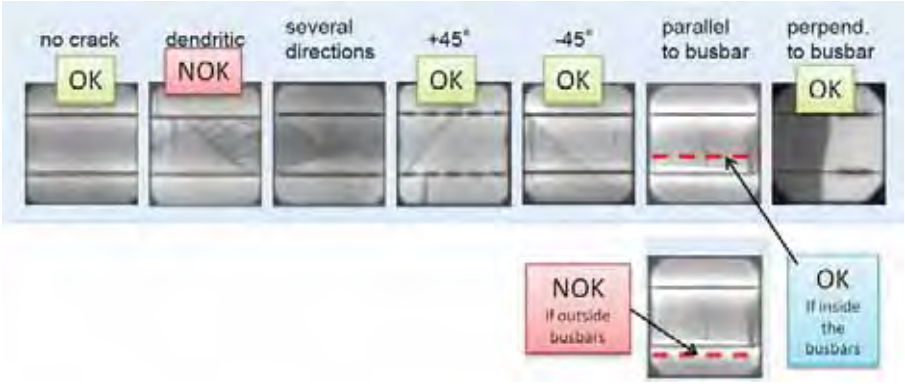
Durchgeführte Arbeiten und Ergebnisse

Die Elektrolumineszenz - Photographie (EL) ermöglicht es, mechanische Fehler in den Zellen wie Mikrorisse und schlecht verarbeitete Lötstellen festzustellen. Die Einführung der EL in die inline Qualitätskontrolle ermöglicht es daher, fehlerhafte PV Zellen vor der Endmontage bzw. der Laminierung auszusortieren. Die Qualitätskontrolle mit der EL wird nach dem verlöten der Strings und vor der Laminierung durchgeführt, sodass defekte Zellen im verlöteten Strang ersetz werden können.



Ablauf der EL Qualitätskontrolle in der PV Produktionslinie

Es werden Zellen mit den in der folgenden Abbildung aussortiert und defekte Lötstellen, welche durch eine überhöhte Temperatur in der EL erkennbar sind.



Klassifizierung der Zellrisse (1)

Da in dem Laminierungsprozess nur Stränge mit guten Zellen verarbeitet werden, wird die Qualität der fertigen PV Module verbessert. Es werden auch der Ausschuss verringert und die Leistungsschwankungen der PV Module minimiert.

(1) S. Kajari Schröder – Crack statistic on cristalline Si PV Modules – IEA Task 13 Workshop.

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Bundesamt für Energie BFE

PHOTOVOLTAIK IM VERBUND MIT DÄMM-STOFF FOAMGLAS

Annual Report 2012

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Project- / Contract Number	SI/500582 / SI/500582-01
Duration of the Project (from – to)	01.12.2012 – 31.12.2013
Date	7.12.2012

ABSTRACT

As a pure electrical power producer, the photovoltaic technologies are established. The development of “In-roof-systems” has proved to be effective. Besides the electrical power production, In-roof-systems serve also as roof panels and water protection. Unknown are systems, where the photovoltaic in addition to the power production and the water protection has the function of thermal insulation. The scope of this project is the development and realisation of building integrated photovoltaic (BIPV) including the feature of thermal insulation. A pilot plant with modules combined of photovoltaic modules and Foamglas insulation shall be build.

The project “Photovoltaic with Foamglas insulation” was initiated in spring 2010 and was started officially in December 2010. In 2011, the market requirements and main concepts have been elaborated. In 2012 the concepts have been detailed and proved in various tests. Furthermore, a pilot Project has been evaluated and then the planning has been executed. Following results were achieved in 2012:

- Evaluation of the adhesive between PV module and Foamglas insulation
- Testing the adhesive a) concerning handling, b) in the climate chamber, c) under traction test
- Cabling solutions
- Sealing and module replacement solutions
- Long term outdoor test regarding the efficiency of amorphous silicon (a-Si) insulated modules compared to non-insulated modules
- Concepts for flat roof solutions
- Evaluation and planning of a pilot project

Short summary of the targets for 2013:

- Building the pilot project in the very early 2013 including setting up the recording of measures
- Analysis an interpretation of the results of the measures
- Review of the plant cost and efficiency

Einleitung

Das Ende 2010 gestartete BFE Pilot- und Demonstrationsprojekt mit den Partnern Pittsburgh Corning AG, Basler & Hofmann AG und SUPSI hat 2011 Anforderungen und Konzepte für eine Verbindung des Dämmstoffes Foamglas mit PV Modulen erarbeitet. 2012 wurden die Konzepte detaillierter ausgearbeitet und Tests und Prüfungen durchgeführt. Weiter wurde eine Pilotanalage ausgesucht und die Planung durchgeführt. Anfangs 2013 soll die Anlage erstellt werden und die Messresultate Ende 2013 ausgewertet werden.

Marktanforderungen

In der folgenden Tabelle sind die im 2011 geschätzten Marktpreise Deutschland für die komplette Gebäudehülle inkl. PV-Unterkonstruktion, Material und Arbeit. Die Bezugsgrösse der folgenden Komponenten ist 200 m^2:

- Dämmung, Dampfsperre
- Dichtung
- Witterungsschutz
- PV-Befestigungssystem ohne PV Module (PVUK)

Die Preise stellen für die Entwicklung von Lösungskonzepten die Zielgrösse dar, welche unterschritten werden muss, damit das Produkt auf dem Markt Sinn macht.

Marktpreis Neubau	***Starke Dämmung***	***Mittlere Dämmung***	***Leichte Dämmung***
Fassade	*U: 0.15* *126.00 EUR/m^2*	*U: 0.24* *115.00 EUR/m^2*	*U: 0.35* *110.00 EUR/m^2*
Flachdach Beton	*U: 0.15* *156.00 EUR/m^2*	*U: 0.20* *141.00 EUR/m^2*	*U: 0.30* *125.00 EUR/m^2*
Flachdach Leichtbau *(Trapez, Holz)*	*U: 0.15* *153.50 EUR/m^2*	*U: 0.20* *138.50 EUR/m^2*	*U: 0.30* *122.50 EUR/m^2*
Schrägdach *unten Holz, oben Ziegel*	*U: 0.15* *126.50 EUR/m^2*	*U: 0.20* *120.00 EUR/m^2*	*U: 0.30* *111.70 EUR/m^2*
Schrägdach *unten Beton,* *oben Falzblech*	*U: 0.15* *156.00 EUR/m^2*	*U: 0.20* *138.50 EUR/m^2*	*U: 0.30* *138.50 EUR/m^2*
Schrägdach *unten Trapezschale,* *oben Falzblech*	*U: 0.15* *100.50 EUR/m^2*	*U: 0.20* *94.00 EUR/m^2*	*U: 0.30* *85.70 EUR/m^2*
Schrägdach Sandwich	*U: 0.15* *70.00 EUR/m^2*	*U: 0.20* *64.00 EUR/m^2*	*U: 0.30* *60.00 EUR/m^2*

Tabelle 1: *Überschicht Abschätzung Marktpreise für Isolation, Witterungsschutz und PV Montagesystem*

Fokussierung auf Applikationen

Aufgrund einer breiten Konzeptstudie und der Marktpreissituation wurden die Potentiale für eine PV Lösung mit Foamglas auf folgende Felder fokussiert:

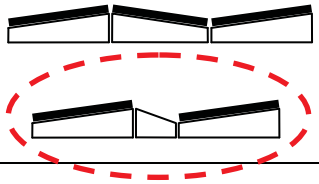
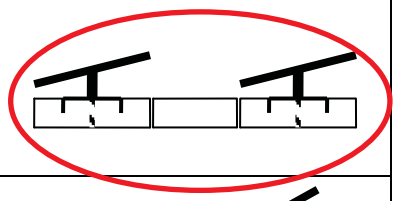
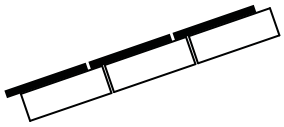
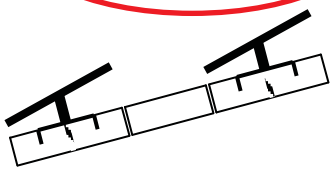
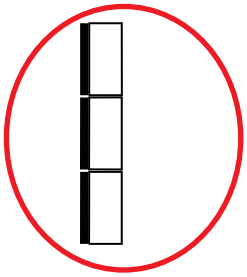
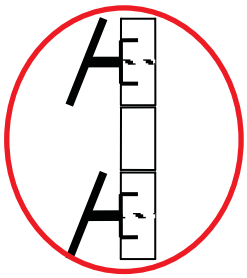
	Integriert (verklebt)	Integriert / geformt (verklebt)	abgesetzt
Flachdach			
Schrägdach			
Fassade			

Tabelle 2: *Fokus der Anwendungen aufgrund der Marktpreise*

Neben dem relativ teuren Baustoff Foamglas stellte sich das Abdichten von Spezialformen auf Flachdächern als zu teuer heraus. Im Integrierten Schrägdach sind Tiefpreis-Lösungen z.B. durch Sandwichpanele auf dem Markt. Diese sind schwer zu unterbieten.

Fassade Integriert (verklebt)

Fassadenelemente welche Solarstrom Produzieren und gleichzeitig Dämmen sind absolut neuartig. Der Aufbau von PV Modulen mit Foamglasdämmung und deren Testauswertungen werden in diesem Kapitel beschrieben.

Konstruktion

Standard PV Module werden mit dem Dämmstoff Foamglas in der Werkstatt verklebt. Die Elemente aus PV-Foamglas haben dadurch die Grösse von Standard Modulen, welche in der Regel 1,6 x 1 m oder 1,3 x 1,1 m aufweisen.

Bild 1: *PV Modul Mit Foamglas*
(Quelle: Basler & Hofmann AG)

Neben dem bituminösen Kleber werden die PV-Foamglaselemente mit Z-Winkel sicherheitshalber zusätzlich im Mauerwerk verankert. Dabei stellen die Z-Winkel keine Kältebrücken dar, da sie in der Mitte der Dämmung ansetzen.

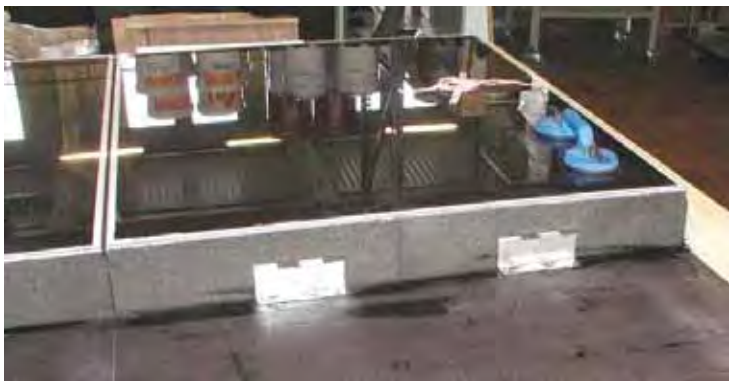


Bild 2: *PV Modul mit Foamglas und Sicherheitsverankerung mittels Z-Winkel*
(Quelle: Pittsburgh Corning AG)

Versuche mit unterschiedlichen Klebern

Es wurden Klebetests durchgeführt, um die Haftung zum Foamglas zu prüfen sowie verschiedene Optionen für die diskutierten Anwendungen zu haben. Es hat sich dabei herausgestellt, dass sowohl elastische Produkte auf Basis SMP (=Terostat MS-Produkte) als auch harte bzw. hart-elastische Produkte auf Basis Polyurethan (=Macroplast UK bzw. CR) eine gute Haftung zum Foamglas aufbauen können.

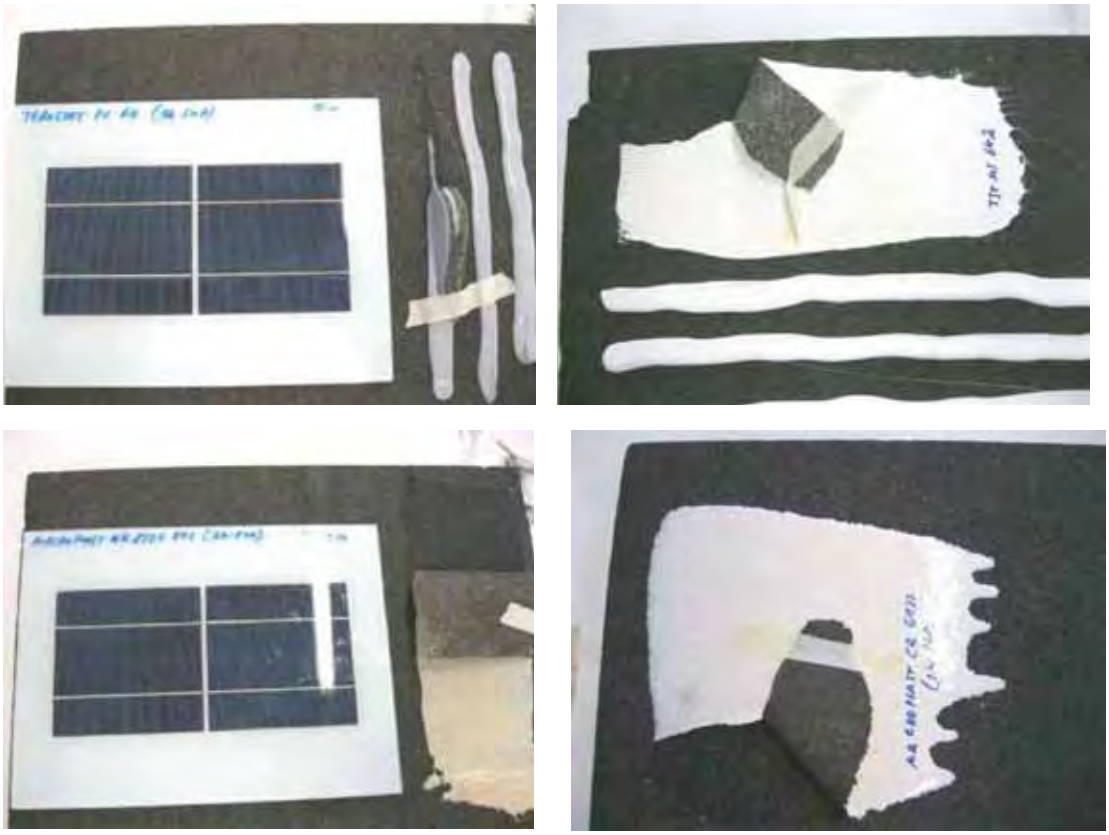


Bild 3: *Versuche mit verschiedenen Klebern (Quelle: Henkel AG)*

Klebeversuche

Die Klebeverbindung wurde mit 3 Modultypen durchgeführt:

Glas-Glas Modul

- 1,3 x 1,1 m
- Typ a-Si Dünnschichtmodul
- Hersteller Pramac (Oerlikon Solar)

Glas-Tedlar Modul

- 1,6 x 1 m
- Typ Gerahmt Black Design 4 mm Glas und Tedlar
- Hersteller 3S

Hybrid Modul

- 1,6 x 1 m
- Typ Hybridkollektor
- Hersteller 3S

Glas-Glas Modul

Der Kleber Terostat MS 642 1 resp. 2 Komponenten von Henkel wurde für die Glas - Foamglas Verbindung verwendet. Für das 1,3 x 1,1 m grosse Modul von Pramac wurden 1,8 Liter oder 2,7 kg verwendet. Diese Menge könnte in einem industriellen Klebeprozess noch um einiges reduziert werden.

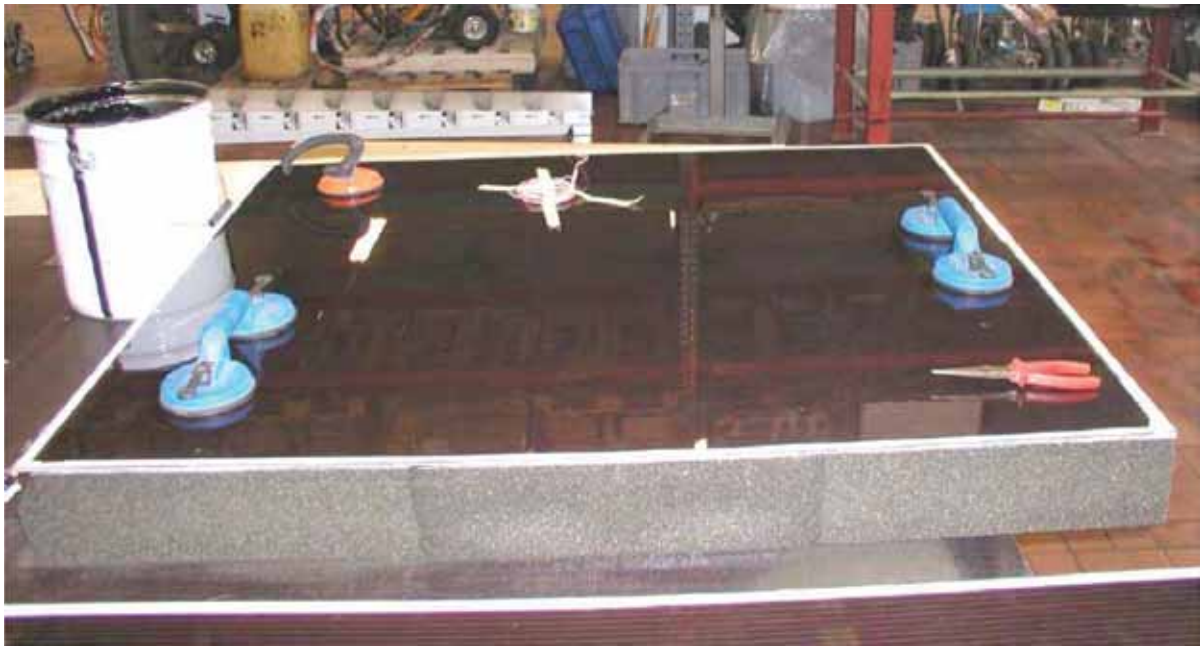


Bild 4: *Glas-Glas Modul mit Foamglas verklebt* *(Quelle: Pittsburgh Corning AG)*

Glas-Tedlar Modul

Der Kleber Terostat MS 642 1 resp. 2 Komponenten von Henkel wurde für die Tedlar - Foamglas Verbindung verwendet. Für das 1,6 x 1 m grosse Modul von 3 S wurden 2,2 Liter oder 3,3 kg verwendet.

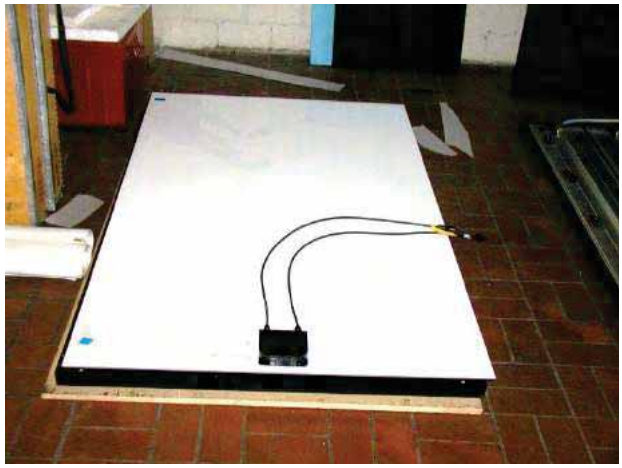


Bild 5: *Gerahmtes Modul mit Tedlar Rückwand in Vorbereitung für die Verklebung mit Foamglas*
(Quelle: Pittsburgh Corning AG)

Hybrid Modul

Der Kleber Terostat MS 930 von Henkel wurde für die Aluminium - Foamglas Verbindung verwendet. Für das 1,6 x 1 m grosse Modul von 3 S wurden 1.8 Liter oder 2.7 kg verwendet.

Bild 6: *Links: Hybridmodul der Firma 3s, rechts: Fomaglas mit Ausspaarungen für dieVerklebung*
(Quelle: Pittsburgh Corning AG)

Kabelführung

Da zurzeit mit Standardmodulen gearbeitet wird, ist eine Schlaufung der Kabel notwendig. Als Alternative dazu können die Kabel abgelängt und gerade geführt werden. Wichtig ist, dass keine Hohlräume zwischen Modul und Dämmung entstehen. Deshalb sollten die Kabelvertiefungen genau so tief sein wie die Kabeldurchmesser. Ein vollautomatisches Fräsen der Kabelaussparung und der Aussparung der Auschlussbox ist gut denkbar. Bei grossen Serien würden die Kabel und Anschlussbox komplett in den Rand gelegt, so wie es bei semitransparenten Fassadenmodulen heute bereits gemacht wird.

Bild 7: *Kabelführung - Links oben: Vorbereitung einer Schablone für die Aussparungen. Rechts oben: eingefräste Aussparungen. Links unten: Variante 1 Steckeraustritt an der Seite. Rechts unten: Variante 2 Stecker in Aussparung in oberer Ecke (Quelle: Pittsburgh Corning AG)*

Abdichtung Fugen

Die Dichtung der horizontalen und vertikalen Stösse erfolgt durch im Foamglas ausgefräste Fugen. Diese werden zuerst mit zellig geschlossenem PE Schaum halb gefüllt und dann mit einkomponentigem Kleber versiegelt.

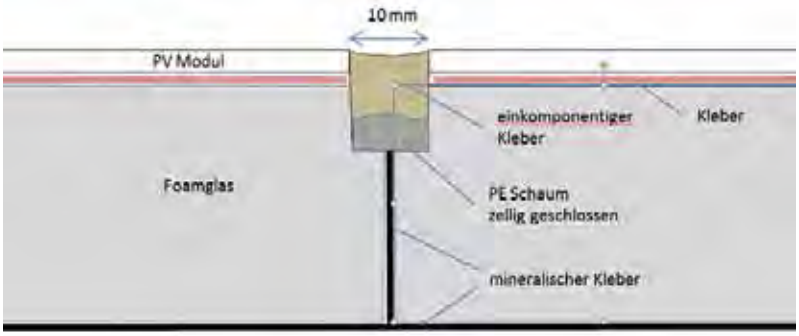


Bild 8: *Schematische Darstellung der Fugen (Quelle: Basler & Hofmann AG)*

Beim Auswechseln eines Modules wird die Fuge zerstört und das Modul kann mit seiner Dämmung ausgebaut werden. Nach entfernen der Dämmreste kann ein neues Element eingeklebt werden und die Fugen können wieder verschlossen werden.

Bild 9: *Bild der vorbereiteten PV-Foamglas Elemente vor der Fugendichtung*
(Quelle: Pittsburgh Corning AG)

Klimalabor Test

Die Module Glas-Glas und Hybrid wurden im SUPSI einem Klimatest mit 200 Zyklen (TC200) unterzogen. Die Visuelle Inspektion (VI) sowie der Elektrolumineszenztest (EL) wurden bei allen 3 Prüflingen bestanden:

- bestanden TC200 Thermal Cycling
- bestanden VI Visual Inspection
- bestanden EL Electroluminescence

Zugversuche

Nach dem Klimakammertest (TC200) wurden die Elemente auf Zugbeanspruchung geprüft.

Glas-Glas Modul, 1. Versuch

Die Belastung erfolge zuerst über 30 Minuten mit 3000 pa. Bei 5000 pa hat sich nach 5 min das Modul abgelöst.

Bild 10: *Zugmaschine für Belastungstest, eingespanntes Glas-Glas Modul nach Versagen (Quelle: SUPSI)*

Resultat: Die sichtbare Modulrückseite zeigt, dass in der grossen Modulmitte eine Verbindung zwischen Kleber und Modul nicht stattgefunden hat. Dies ist darauf zurückzuführen, dass die Foamglasblöcke im Format des Moduls vorgängig zusammengeklebt wurden. Dadurch war die Andruckfläche für eine komplette Verbindung zu groß.

Bild 11: *Zusammengeklebte Foamglasblöcke im Modulformat (Quelle: Pittsburgh Corning AG)*

Glas-Glas Modul, 2. Versuch

Die Produktion wurde umgestellt. Jetzt werden in einer Schablone einzelne Foamglasplatten auf die Modulrückseite geklebt, was eine vollflächige Verklebung und eine innige Verbindung zulässt, welche während der Produktion kontrollierbar ist.

Bild 12: *Bild neuen Arbeitsreihenfolge einzelverkleben der Fomaglasblöcke auf Glas-Glas Modul (Quelle: Pittsburgh Corning AG)*

Resultat: In einem weiteren Versuch hat das Glas - Glas Modul den Zugversuch mit 10.000 pa bestanden. Das zeigt, dass bei vollflächiger Verklebung diese Zyklen problemlos aufgenommen werden können.

Bild 13: *Erfolgreicher Zugtest, eingespanntes Glas-Glas Modul im Test (Quelle: SUPSI)*

Hybridmodul

Das Element mit dem Hybridmodul zerbrach sofort durch eine ungenügende Verklebung zwischen Dämmstoff und dem Holzaufbau. Die Verbindung zwischen Modul und Foamglas war gut. Der Test wurde nicht wiederholt.

Fassade abgesetzt (vorgehängt)

Als Alternative zur verklebten PV-Fassade wurde ein Konzept für eine vorgehängte Fassade erarbeitet.

Konstruktion

Haken, welche bezüglich Höhe und Wandabstand verstellbar sind, wurden in den verklebten Krallenplatten und zusätzlich in die Wand durchgeschraubt. An den Haken wurde mittels Nutsteinen das Befestigungsprofil angeschraubt.

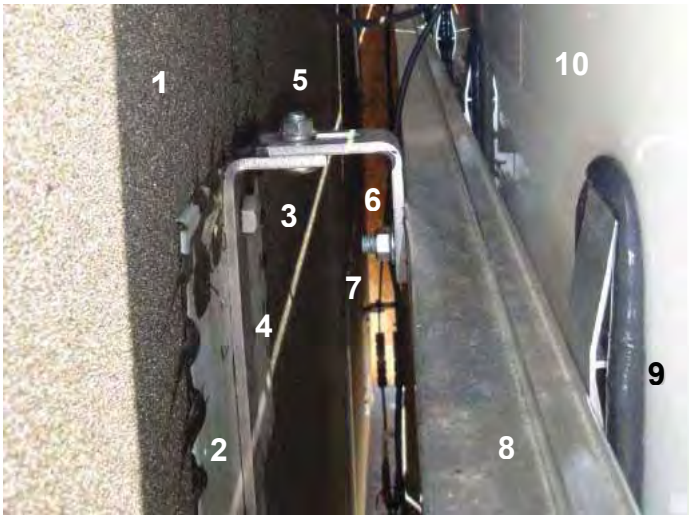
Bild 14: *Vorbereitete Foamglasfassade für vorgehängte Module (Quelle: SUPSI)*

Die Module der Firma Pramac mit Produktionsprozessen der Oerlikon Solar werden standardmässig an 4 an der Rückseite angeklebten Adaptern ausgeliefert. Diese Adapter lassen sich in extrudal gepresste Aluprofilschienen "Optibond" einklicken.

Bild 15: *Moduladapter (ohne Modul) und Querprofil Opbibond*
(Quelle: Schletter AG)

Befestigung

Eine ins Foamglas eingeklebte Krallenplatte trägt das Drehmoment der Wandschraube ab.



1. *Foamglas*
2. *Krallenplatte*
3. *Wandschraube*
4. *Hacken*
5. *Langloch für Wandabstand*
6. *Langloch für Höhe*
7. *Nutstein*
8. *Optibondschiene*
9. *Optibondadapter angeklebt*
10. *Glas-Glasmodul*

Bild 16: *Detailansicht vorgehängete PV Foamglas Fassde(Quelle: Basler & Hofmann AG)*

Eine zusätzliche Abrutschsicherung des Modules in Form eines gummierten Blechbandes wird zur Absicherung der Optibond Klebestellen bei Fassadenapplikationen empfohlen.

Feldtest Aufbau Fassade und Wirkungsgrade

In einem Deskresearch wurde der direkte Verbund von Photovoltaikmodulen und FOAMGLAS Dämmung mit der verschlechterten Wärmeableitung im Vergleich zu hinterlüfteten Installationen untersucht. Die resultierenden hohen Temperaturen führen bei den meisten Solarzellen zu einem Leistungsverlust, der je nach Zellentyp verschieden hoch ist (2-8%). Bei den amorphen Zellen konnte gemäss konsultieren Studien dieser Verlust durch den Annealingeffekt teilweise oder ganz kompensiert werden.

Im Feldtest mit amorphen Siliziummodulen aus der Produktionslinie der Oerlikon Solar konnte der sich positiv auswirkende Annealingeffekt bestätigt werden.

Bild 17: *Feldtest bei SUPSI links: vorgehängte PV Testfassade, rechst: geklebte PV Testfassade*
(Quelle: SUPSI)

Bild 18: *Vorbereitung der Temperatursensoren für den Feldtest vor der Verklebung mit Foamglas*
(Quelle: Pittsburgh Corning AG)

Erster Zwischenbericht der Energieertragsmessungen

Es kann gesagt werden, dass die hinterlüfteten Module fast die gleiche Energie produzieren wie die verklebten. Es fehlen leider noch die Temperaturangaben eines Moduls, die aus technischen Gründen manuell aus der Datenbank extrahiert werden müssen.

27. November 2012, Dr. Thomas Friesen, SUPSI

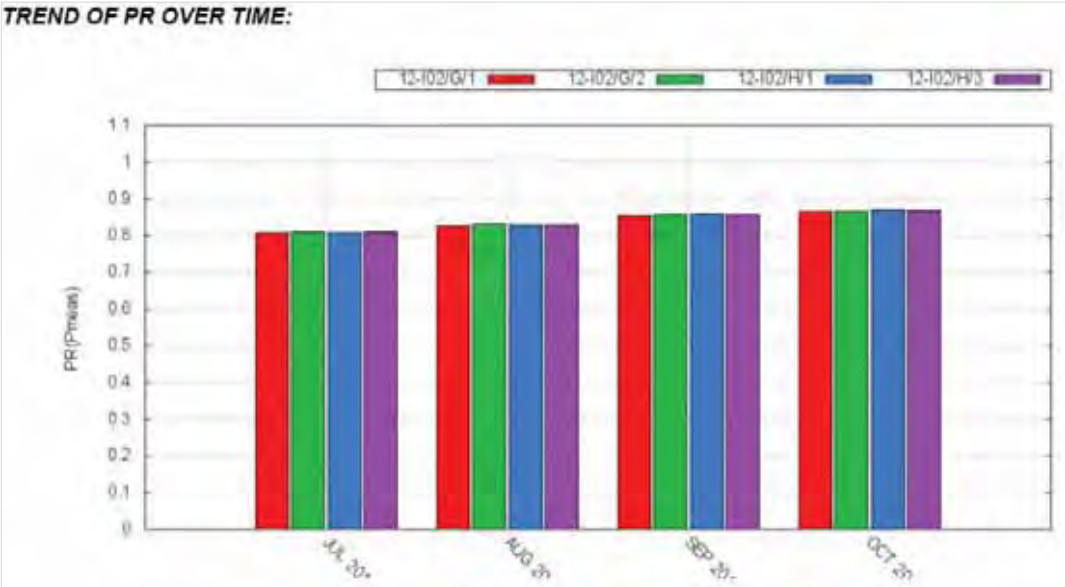


Bild 19: *Leistungsauswertung von Jul-Okt 2011 je 2 Module vorgehängt (h) und verklebt (g)* *(Quelle: SUPSI)*

Reference Pm used to calculate PR: Average indoor Pm measurement

MONTH	METEO		12-I02/G/1	12-I02/G/2	12-I02/H/1
	H [kWh/m²]	Ta [°C]	Δ PR(Pmeas)%	Δ PR(Pmeas)%	Δ PR(Pmeas)%
JUL 2012	79.4	29.9	-0.5	-0.2	-0.6
AUG 2012	88.3	30.5	-0.5	0.3	0.3
SEP 2012	77.9	23.6	-0.3	0.1	0.1
OCT 2012	78.1	18.3	-0.6	-0.6	-0.0
TOTAL	**323.7**	**25.6**	**-0.4**	**-0.0**	**0.0**

DAY TYPE	N° DAYS	METEO		12-I02/G/1	12-I02/G/2	12-I02/H/1
		H [kWh/m²]	Ta [°C]	Δ PR(Pmeas)%	Δ PR(Pmeas)%	Δ PR(Pmeas)%
CLEAR	36	133.6	28.4	-0.5	0.2	1.6
CLOUDY	59	159.3	26.9	-0.4	-0.1	-0.2
OVERCAST	28	30.8	19.2	-0.0	-0.7	-5.2

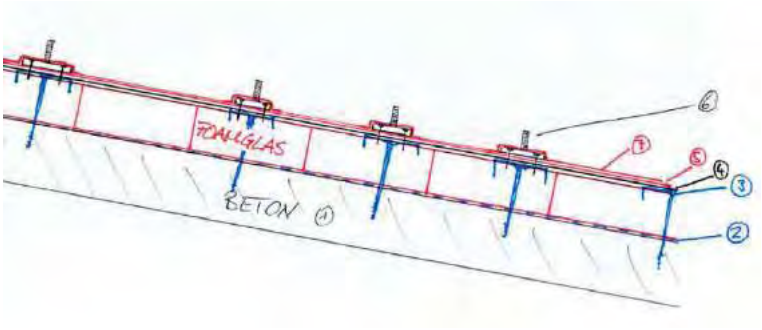
Bild 20: *Leistungsauswertung im Vergleich zu Modul h/2 oben: von Jul-Okt 2011 unten: bei klarem, wolkigem und bewölktem Wetter* *(Quelle: SUPSI)*

Die Module G/1 und G/2 sind die geklebten, H/1 und H/2 die vorgehängten Module. Die angegebenen Werte in der Tabelle oben beziehen sich auf die Unterschiede zum H/2 Modul.

Fazit: Die Unterschiede in der Leistung zwischen den vorgehängten und den geklebten Modulen konnte messtechnisch nicht nachgewiesen werden.

Flachdach abgesetzt

Konstruktion



1. *Beton*
2. *Heissbitumenkleber*
3. *Krallenplatte in Beton befestigt*
4. *Bitumen Abdichtungsbahn*
5. *1. Lage Kunststoffabdichtung*
6. *Montageplatten für UK PV Module in Krallenplatte befestigt*
7. *2. Lage Kunststoffabdichtung (UV beständig)*

Bild 21: *Prinzip Flachdachverankerung* *(Quelle: Pittsburgh Corning AG)*

Bild 22: *Flachdachverankerung : Krallenplatte in Foamglas vor dem setzen der Stockschraube und Abdichten*
(Quelle: Pittsburgh Corning AG)

Bild 23: *Flachdachverankerung fertig abgedichtet* *(Quelle: Pittsburgh Corning AG)*

Befestigung

Die fast wärmebrückenfreie Befestigung zur Aufnahme der Windsogkräfte erfolgt durch die Krallenplatte in die Unterkonstruktion aus Beton. Auf die Krallenplatte werden die Halter für das PV Modul mit einer Ausgleichsmasse aus Silikon versehen und dann verschraubt. Diese Teile werden dann wieder mit Flüssigkunststoff abgedichtet und an die bestehenden Abdichtungen befestigt. Die anderen Teile der Unterkonstruktion sind Standard Dachdeckermaterial.

Flachdach integriert

Konstruktion

Das erarbeitete Konzept mit dem Übernahmen "Wintergarten" hat sich nach der Evaluation von unzähligen Varianten durchgesetzt. Die Meisten Lösungen mussten aufgrund der Kosten für die Abdichtung oder der Materialkosten für Foamglas aufgegeben werden. Zur Favorisierung des Konzeptes "Wintergarten" hat das neu auf dem Markt erschienene Indachsystem "NICER" der Firma Megasol verholfen. Das Indachsystem bleibt bis 3° Neigung dicht. Der Vorteil des Konzeptes besteht darin, dass das Gefälle für die Dachentwässerung nicht mehr durch Masszuschneiden der Dämmung auf verschiedene Dicken und Neigungen erfolgen muss. Weiter braucht die Deckschicht der Dämmung nur noch Unterdachqualität aufzuweisen. Da Foamglas die punktuellen Schnee- und Windlasten aufnehmen kann, erübrigt sich die Dachdurchdringung und Kältebrücken werden vermieden. Eine Verwendung der Warmluft unter dem Dach ist denkbar.

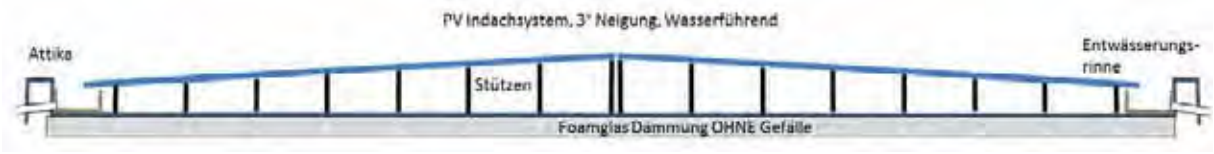


Bild 24: *Prinzip Flachdach mit Attika und integrierter Flachdachlösung "Wintergarten"*
(Quelle: Basler & Hofmann AG)

Als Stützen können z.B. Stützen von Doppelböden eingesetzt werden. Diese gibt es in verschiedenen Längen. Weiter können diese auf dem Dach fein eingestellt werden.

Bild 25: *Links: Standard Stützen für Doppelböden. Mitte: Detail Querstoss Indachsystem vor dem einklappen des Modules. Rechts: Horizontalschnitt Indachsystem mit Module, u-Schiene und Haltefuss mit Holzschrau ben. (Quelle: www.doboplan.de Megasol AG)*

Den Aufbau einer möglichen Pilotanlage für das Konzept "Wintergarten" soll ausserhalb des BFE Projektes erfolgen.

Pilotanlage

Dieser Grossversuch soll die Praxistauglichkeit sowohl in der Serienherstellung der Elemente als auch deren Handhabbarkeit auf der Baustelle unter Beweis stellen.

Gleichzeitig sollen Erfahrungen über die Kosten für solche Fassaden gewonnen werden, da zum heutigen Zeitpunkt noch ein hoher Anteil an Unsicherheitskalkulation der Beteiligten zu vermuten ist. Eine Nachkalkulation nach Vollendung der Baumassnahme bringt dann s chon eher einen verwertbaren Preis pro m^2.

Weiter soll ein Messkonzept erstellt werden, welches die Langzeitauswertung der Technologie zulässt.

Standort

Auf dem Bürogebäude auf einer Südost- und Südwestfassade der Firma Oerlikon Solar in Trübbach soll die Pilotanlage erstell werden.

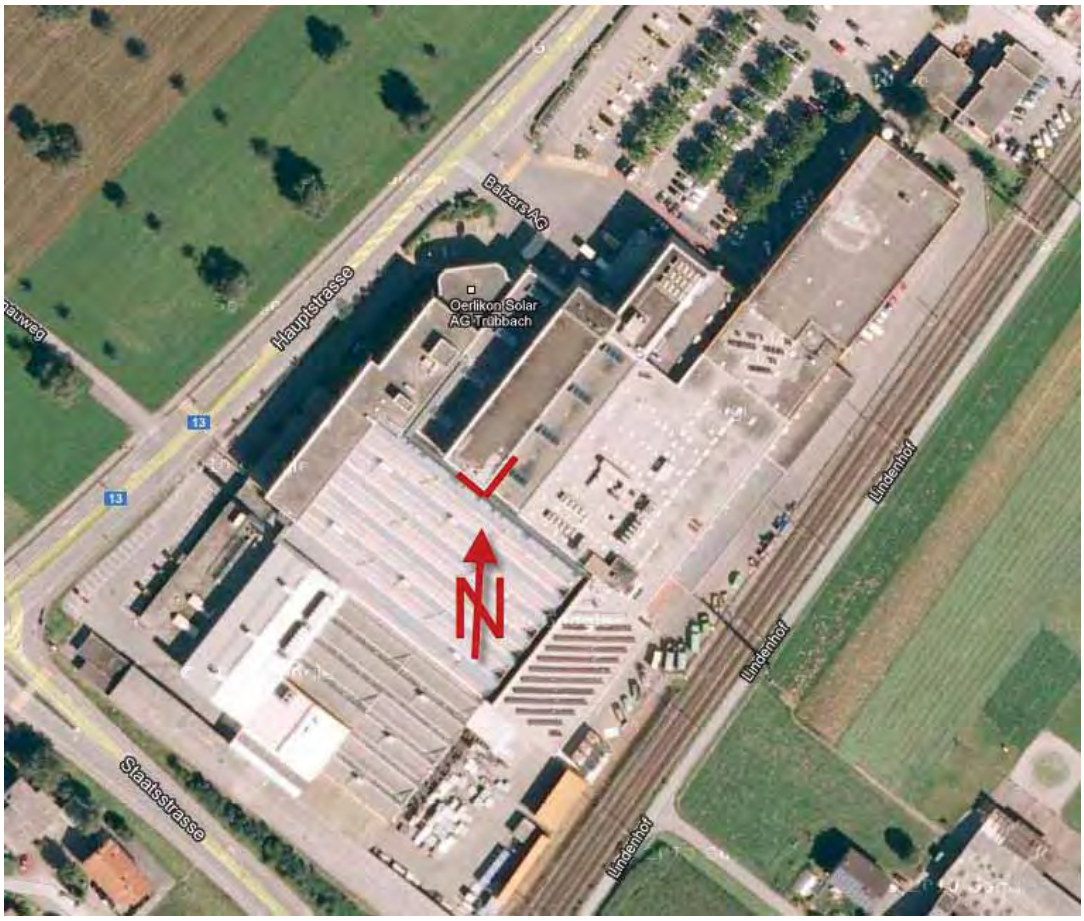


Bild 26: *Luftbild Areal Oerlikon Solar in Trübbach, rot Standort der geplanten Pilotanlage*
(Quelle Basler & Hofmann AG)

Bild 27: *Visualisierung der Südost Fassade mit verklebten Foamglasmodulen*
(Quelle: Pittsburgh Corning AG)

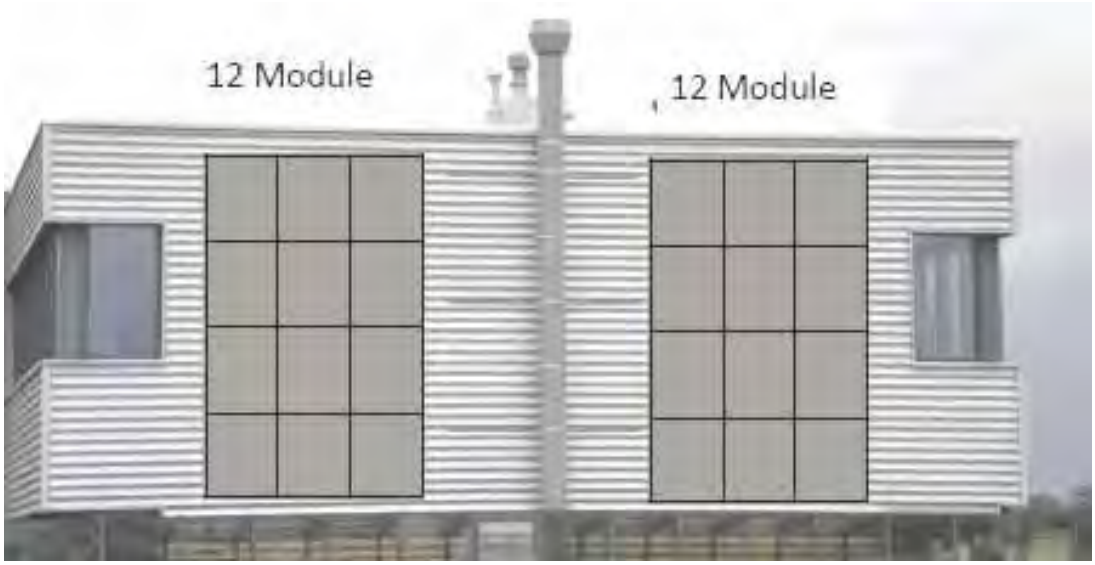


Bild 28: *Visualisierung der Südwest Fassade links mit vorgehängten Modulen rechts mit verklebten Foamglasmodulen (Quelle: Pittsburgh Corning AG)*

Messkonzept

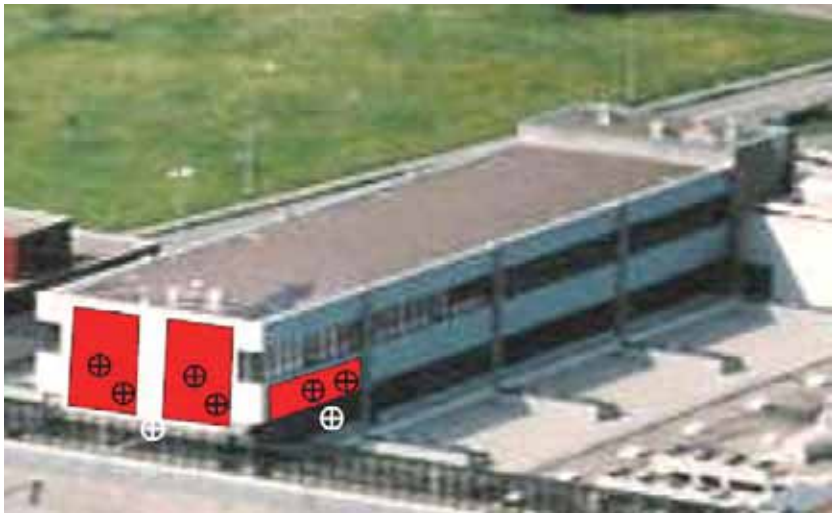


Bild 29: *Platzierung der Temperatur und Einstrahlungssensoren bei der Pilotanlage*
(Quelle: Basler & Hofmann AG)

Schwarze Kreuze: Temperaturmessung Modulhinterseite und Modulverkabelung so geführt, dass saisonal die Kennlinie des Modules aufgenommen werden kann.
Weisse Kreuze: Messung der Umgebungstemperatur und der Einstrahlungswerte

Die Werte sollen in den 15 Minuten-Takt erfasst werden.

Die 3 Felder werden von je einem MPP Tracker geregelt und deren Leistung aufgezeichnet.

Projektstand

Einverständnis GL Oerlikon Solar	Dez 2012
Planung fertig (Elektroplanung)	Jan 2013
Auftrag Fassadenbauer erteilt	Jan 2013
Vorbereitung Module fertig	Feb 2013
Gerüst und Vorbereitung Fassade erfolgt	Feb 2013
Montage Module und Wechselrichter erfolgt	Mar 2013
Elektrische Verkabelung erfolgt	Mar 2013
Inbetriebnahme und Beginn Messaufzeichung	Mar 2013

Nachweise Überkopfverglasungstauglichkeit und Brand

Diese Nachweise werden nicht innerhalb des Vorliegenden Pilot- und Demonstrationsprojektes geführt. Bei einer Weiterentwicklung der Konzepte in Richtung serieller Produkte sollte dies erfolgen. Für das Pilotprojekt kann aufgrund der Gegebenheiten vor Ort darauf verzichtet werden, da die gefährdeten Flächen nicht begehbar und auch keine Fluchtwege kreuzen. Sowohl Foamglas als die PV Module sind schwer brennbar und bilden keine Brandlasten.

Bewertung 2012 und Ausblick 2013

Die Anforderungserfassung und die Konzeptphase sind weitgehend abgeschlossen (siehe grüne Tätigkeiten in der Tabelle unten).

Für das kommende Jahr ist das Vorgehen gemäss dem Meilensteinplan ("Fast Prototyping") vorgesehen:

Deliverables	***2011***				***2012***				***2013***			
	Q1	*Q*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*
Anforderungen												
- Anforderungen an die Lösung	*x*											
Verbindung PV-FOAMGLASS												
- Anforderungen		*x*										
- Konzept - Variantenentscheid		*x*										
- Konstruktion			*x*									
- Labortest			*x*									
- Feldtest				*x*								
Kabelführung u. Steckverbindung												
- Anforderungen			*x*									
- Konzept - Variantenentscheid			*x*									
- Konstruktion				*x*								
- Labortest					*x*							
- Feldtest						*x*						
Eigenschaften (Wirkungsgrad.....)												
- Anforderungen				*x*								
- Konstruktion				*x*								
- Labortest				*x*								
- Feldtest					*x*							
Befestigung der Elemente												
- Anforderungen					*x*							
- Konzept - Variantenentscheid					*x*							
- Konstruktion						*x*						
- Labortest						*x*						
- Feldtest							*x*					
Demo Anlagenbau												
- Anforderungen						*x*						
- Variantenentscheid						*x*						
- Konstruktion / Bau							*x*	*x*	*x*			
- Langzeittest										*x*	*x*	
Wirtschaftlichkeit und Einsatzgebiet												
- Betrachtung Markt												*x*

Tabelle 3: *Zeitplan*

Referenzen

Dieser Jahresbericht referenziert ausschliesslich auf den Projektantrag " Photovoltaik im Verbund mit Dämmstoff FOAMGLAS".

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

Office fédéral de l'énergie OFEN

SOLAR BRICK

INNOVATIVE PHOTOVOLTAIC AND THERMAL INSULATING BUILDING MATERIALS

Annual Report 2012

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Project- / Contract Number	Solar Brick / KTI 13186.1
Duration of the Project (from – to)	01.12.2011 – 31.05.2013
Date	17.12.2012

ABSTRACT

The project is financed by the KTI under the project number: 13186.1 PFFLI-IW.

Goal of the project is to develop a photovoltaic and thermal insulating building material suitable for roof installation. This building material will be tested and demonstrated on a prototype installation including said material. The economic and technical proof will be central and is complemented by many tests, specifically engineered for such a complex system. SUPSI/ISAAC and Designergy SA (which has developed a Patent portfolio of the solar brick concept) are the main partners for the engineering. This team, together with a further research partner, namely Alex Gemperle AG, will provide financing, engineering and the workforce necessary for an upcoming complete installation on a real building.

Aims of the project

The building integration photovoltaic sector becomes more popular and consequently professional interest is increasing. The photovoltaic technology is the only way to achieve integrated delocalized electrical energy production. The cost of the modules is decreasing more quickly than other building elements. At present most roof-top pv systems and the roofs underneath are separate entities. In Building Integrated Photovoltaics (BIPV), the pv modules substitute the most external building layer, as for example the tiles. To our best knowledge, there is no solution for a one-piece photovoltaic roof integrating functions and capable of significantly reducing capex (capital expenditure) by at least 15% and striving to 30%.

The core idea of the SISBE (Structurally Integrated Solar Building Element), patented by Designergy is to integrate different functions of the building envelop (such as thermal insulation and water protection) in one element and system which is able to produce electricity thanks to the integration of photovoltaic modules present on the outer surface. This approach allows therefore also to achieve the highest thermal insulation standards required in modern buildings that are usually not considered while mounting a pv system on a roof.

In regard to the aspect of thermal insulation, the energy policies of industrialized countries, including for instance Switzerland, are strongly pushing towards energy efficiency, which in the building sector translates into new houses with little or zero energy impact. In order to achieve this goal the optimal thermal insulation is a central issue. According to “Bundesamt für Umwelt”, only in Switzerland there are about 1.5 million buildings that need a thermal insulation renovation and on top of that come all new constructions striving, or even subject by law, towards a Minergie standard certification or similar.

The first goal of this project was to **further develop and to optimize the SISBE** construction material that in future will be industrially produced by Designergy and distributed/sold to installers as for instance Alex Gemperle. So far Designergy has developed the patent portfolio regarding the technology of this new kind of material which has been defined as Structurally Integrated Solar Building Element (SISBE). The project will therefore deliver a deeper analysis of this concept by developing it into an up-scalable design that is both economically and technically viable.

One year ago, after the definition of the materials, a **prototype roof installation** featuring nine handcrafted SISBEs was developed and built. This provides the required technologies for a proper installation from the point of view of the other two main technology areas:

- pv technology
- roof construction technology.

Finally, the last step needed towards Designergy’s industrial implementation of SISBEs, namely an industrial production process of the SISBE, needed to be developed while analyzing in-depth the development of the SISBE and the prototype roof. This has been identified as crucial in order to make sure that the highest priority feature needed on large scale, namely economic viability, would not get lost while scaling up.

The main goals of 2012 were the following:

1. Define the material suitable for the SISBE preparation
2. SISBE Prototype production (hand-made)
3. Define and develop a proper fixation system
4. Simulate and test the SISBE (laboratory test) and the installation structure (Roof prototype)
5. Development and implementation of a monitoring system
6. Identify the best PV technologies through outdoor test and measurement
7. Define a roadmap through the SISBE qualification (IEC and CE mainly)
8. Define the industrialization process and a pilot line for SISBE production
9. Plan the Pilot line

Work carried out and results achieved

The project officially started in December 2011.

Because the project is not finished yet and contains ongoing confidential activities the main partner did not give the permission to describe and publish in detail all the activities within the project. Therefore the present Annual report will present shortly the achieved results and the main activities carried out by ISAAC within 2012.

Define the material suitable for the SISBE preparation

A technical team was formed with the target of developing the final idea of SISBE. After several follow up meetings the first prototype and the related installation design was frozen. Main requirement of the SIBSE were:

- Electricity production by means of integration of Photovoltaic technology
- Thermal insulation (U-value of the whole SISBE less than 0.2 W/m2 K)
- Water tightness of the roof system by the use of ad-hoc fastening system
- Mechanical stability
- Reliability of the system
- Architectural integration
- Aesthetical quality
- Standard compliance

The first SISBE prototype was produced with a micromorph photovoltaic module with a panel dimension of about 1300 mm to 1100mm. PRAMAC standard modules were used. In a second step the SISBE was also constructed with common crystalline silicon modules of different design.

SISBE Prototype production (hand made)

Different SISBE prototypes where produced at Swiss PV Module test center (SWPVMTC) in order to be able to perform different tests: mechanical and aging tests mainly.

Define and develop a proper fixation system

In order to guarantee the mechanical stable mounting and the water tightness of the roof system a particular fixation system was developed and patented by Designergy.

Simulate and test the SISBE (laboratory test) and the installation structure (Roof prototype)

Before installing the first nine SISBE elements on a pilot roof, different tests were carried out at the SPVMTC:

- Climatic testing as humidity and freeze test and Damp Heat test
- Mechanical Tests to demonstrate the mechanical resistance of the SISBE sandwich.
- Performance Measurement tests (Indoor) before and after Power Stabilization (Indoor)

All the tests were used to optimize or to define the SISBE materials.

A pilot roof was also installed at ISAAC campus. The inclination of the wooden structure roof is about 6°, which according to Swiss construction regulation SIA is supposed to be the lowest roof inclination possible for the solar tile installation and represents extreme conditions.

Nine SISBE were installed on the roof and the installation procedure was also verified.

The pilot roof was used to test the water tightness of the whole system (SISBE + fastening system) and to monitor the behavior of the roof (temperatures, thermal flows, energy performance, aging, mechanical stability).

For this purpose a special monitoring system was developed.

Figure 1: *In order to test the water tightness of the roof and of the developed fastening system a special outdoor test was installed to simulate rain and wind.*

Development and implementation of a monitoring system

In terms of monitoring tools we installed in the roof thermal, humidity and water sensors and 4 of the 9 SISBEs were connected to MPPT (developed by ISAAC-SUPSI) in order to measure and keep track of the productivity of the PV modules. Special software was developed and installed.

Identify the best PV technologies through outdoor tests and measurements

Different PV Technologies were tested and monitored in order to identify the best solution in term of cost-effectiveness of the SISBE (energy performance, cost,…).

The first monitoring campaign of Micromorph and Crystalline Technology modules gave positive results for the identification of the commercial module to be integrated in the SISBE.

Define a roadmap through the SISBE qualification (IEC and CE mainly)

Since a specific standard on BiPV modules, which could be suitable for the SISBE and its installation is missing, an overview and initial analysis of the exiting PV (in particular IEC) and Construction (in particular SIA and CPD) standard has been done: considering the SISBE system as a multifunctional Building component the outlook seems positive and will be deeper analyzed throughout the rest of the project.

Define the industrialization process and a pilot line for SISBE production

Te layout of the pilot production line exists but not published yet due to patenting constraints: it is basically a twofold purpose lower rate (up to 20/30’000s sqm/yr capacity) industrial line. The twofold purpose is given by the R&D purpose in order to test new materials, technologies and their combinations as well as produce the SISBE output for pilot projects.

Plan the Pilot line

The pilot line was planned to be ready in January 2013 and after a preliminary test it will be installed at DESIGNERGY’s premise in Lugano in order to start the first production for the upcoming roof installation on a building owned by the installing partner GEMPERLE AG.

2012 Evaluation and future prospects

The project is in-line with the time schedule.

Some delay, due to difficulties related to the existing Standards which do not cover the whole SISBE system (as multifunctional Building component and photovoltaic element), has been taken into account at the end of this first year of project. This delay will be absorbed in the next three months thanks to new collaboration with new partners and with a re-orientation of a part of the SISBE requirements.

As said before, in 2013 it is planned to have the first real roof installation in Sins on a building owned by the project partner Gemperle AG; this was already planned at the end of 2012 but the possibility to use the industrially produced SISBEs (pilot line) instead of mostly handcrafted R&D ones strongly contributed to take the decision to postpone the installation (this will be the early proof of a new value chain). The new installation will serve as Pilot and Demonstration roof. A total number of about 48 modules will be installed on an industrial roof of GEMPERLE AG, which faces East and West. The Demonstration roof will be implemented with a monitoring system conceived and controlled by ISAAC.

After this Installation DESIGNERGY and ISAAC will be able to define the final configuration of the SISBE materials together with its installation system and the Industrialization process as well as all other central stakeholders.

Systemtechnik

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Bundesamt für Energie BFE

LANGZEIT-MESSUNG VON PV-ANLAGEN

Annual Report 2012

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Project- / Contract Number	PV-Langzeit-Messung
Duration of the Project (from – to)	01.01.2012 – 31.12.2016
Date	18.11.2012

ABSTRACT

Das PV Labor führt Langzeit-Messungen an unterschiedlichen PV-Anlagen durch und dokumentiert damit das längerfristige Verhalten dieser Anlagen.

Neue Aktivitäten PV-Langzeit-Messung PV Lab 2012 – 2016

Die Aktivitäten des PV-Labors im Bereich der „Langzeit-Messung von PV-Anlagen“ sind wie folgt geplant (Finanzierung vorausgesetzt):

Fortlaufende Aktivitäten:

- Fortführung der Feinmessung von ca. 10 Anlagen im Raume Burgdorf (plus Jungfraujoch/ Birg/ Liestal/ Mont Soleil/ Stade de Suisse).
- Service- und Kontrollgänge an den Anlagen „Dünnschicht-Anlagen Burgdorf“/ Mont Soleil/…
- Fortführung der Grobmessung von ca. 60 Anlagen im Raum Burgdorf (mit Localnet).

Zusätzliche Aktivitäten 2011/ 2012:

- Installation einer Feinmessung auf der PV – Anlage „Emmental Versicherung“ mit 37 kWp Solyndra – Solarmodule mit Sputnik 35S Wechselrichter in Ittigen (BE).
- BSc-Diplomarbeit Marc Hauser: Validierung vom PV-Auslegungsprogramm PVSyst anhand der Messresultate der PV-Feinmessung (Resultat: Abweichungen der gemessenen Werte zu den simulierten Werten bis 20%)!
- BSc-Diplomarbeit Thomas Heiniger: Validierung von 5 PV-Auslegungsprogrammen mit der Referenz PVSyst (Arbeit Hauser).
- Diverse Aktivitäten und Projekte im Bereich der „Verschmutzung von PV-Anlagen“ anhand der Daten des PV-Langzeitmodells.
- Mitarbeit in TÜV-Arbeitsgruppe zu „Brandrisiken in PV-Anlagen und Erstellung von Sicherheitskonzepten zur Risikominimierung“.
- Ausrüsten des Hochhauses „Sihlweidstrasse 1“ (60 m hoch mit 23 Wechselrichtern) mit Fronius Dataloggern zur Ertragsauswertung. Aus Kostengründen wurde keine Feinmessung installiert. Ein Ausbau der Messinfrastruktur (Pyranometer, Referenzzellen etc.) auf allen vier Seiten ist geplant, jedoch aus Kostengründen zurückgestellt. Die Auswertung läuft seit März 2012.
- Bestückung der PV-Anlage „Lawinenverbauung Lehmann“ 10 kWp in Bellwald mit neuer Messinfrastruktur Solarlog (Ende 2012).
- Start internes Projekt neue Hard- und Software für „PV-Langzeitmessung“ für on-line Darstellung.
- Bau der Messinfrastruktur für Erweiterung „APH neu“ mit 6 neuen Anlagen abgeschlossen.
- Projektarbeit Schneider „PV-Anlagen im hochalpinen Gelände“ anhand der Daten der PV-Langzeitmessung und der Anlage Lehmann in Bellwald.
- Projektarbeit Boss „Evaluation einer neuen Grobmessung“ für die Langzeitmessung.
- Projekte und Abklärungen im Bereich „Verschmutzung von PV-Anlagen“.
- Auslegung von PV-Anlagen im In- und Ausland mit Bezug auf die Messdaten der PV-Langzeitmessung.

Geplant:

- Sammeln von Forschungsfragen im Umfeld der PV-Langzeitmessung.
- Projekt: Statistische Auswertung Daten der PV-Langzeitmessung (Beizug von Prof. habil. Dr. Eva Schüpbach und Uni Bern).
- Schneelasten auf PV-Anlagen/ Ertragseinbussen durch Schnee auf PV-Anlagen.

Informationsarbeit

Das PV-Labor erhält viele Anfragen für Präsentationen und Veranstaltungen. Dabei sind die Resultate der PV-Langzeitmessung immer ein Thema. Veranstaltungen 2012 (Auszug):

- Energieapero zum Thema „Photovoltaik“ im PV-Labor der BFH-TI (ca. 140 Teilnehmer) mit Laborführung.
- Inforama Zollikofen: PV und Landwirtschaft (Kurs mit Inforama).

- Einführung in die Photovoltaik für Architekten (2 Kurse AHB BFH).
- Wahlmodul „PV-Systemtechnik BFH-TI“.
- Semester - Kurs für Externe „PV-Systemtechnik“ (über 40 Teilnehmer).
- Vortrag „Beitrag der PV zur Energiewende“ GV SVTI in Luzern Juni 2012.
- Ausstellung Diplomarbeiten mit Beispielen der PV-Langzeit-Messung.
- Kurs mit geografischem Institut Uni Bern (Prof. habil. Dr. Eva Schüpbach) mit Besuch der PV-Anlage Jungfraujoch und der Langzeitmessung.
- Vortrag Brenet-Tagung ETHZ September 2013: Erste Betriebserfahrungen an der grössten umlaufenden PV-Fassade der Welt.
- „Anwendung von PV“ (Schulung des Amtes für Raumplanung des Kantons Bern).
- Seminar Swissolar „PV und Brandrisiko“ an der BFH-TI mit Laborführung.

Weitere 20-30 Vorträge zur Anwendung der PV vor verschiedenen Gremien/ Vereinen etc. durch Prof. Urs Muntwyler im Jahr 2012.

Ausblick 2013

- Beitrag PV-Konferenz Staffelstein 2013: „Langzeit-Messung von PV-Anlagen als Basis für die Evaluation von PV-Simulationsprogrammen„ eingereicht und am 24.10. 2012 akzeptiert!
- Buchprojekt: ein technischer Buchverlag hat Urs Muntwyler für ein anwender-orientiertes Buch angefragt. Es wird abgeklärt, ob die übrigen Projekte finanziert sind und ev. Kapazitäten dafür abgestellt werden können.
- Beitrag EVER 2013 Monaco eingereicht: Has Europe a need for solar plants in Africa?
- PV-Konferenz Basel 2013: Beitrag zur „PV – Langzeitmessung“ wird eingereicht.
- CISBAT – Beiträge für 2013 vorgesehen.

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des transports, de l'énergie et de la communication DETEC

Office fédéral de l'énergie OFEN

PHOTOVOLTAÏQUE ET NEIGE

HORIZON DES SOLUTIONS POUR L'INSTALLATION SUR LES TOITS DANS LES RÉGIONS ENNEIGÉES

Annual Report 2012

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Project- / Contract Number	SI500568 / SI500568-01
Duration of the Project (from – to)	01.02.2011 – 30.07.2014
Date	30.08.2012

ABSTRACT

Measurement campaign conducted during the Winter 2011/2012 highlights the following points on the different studied technologies:

- Automatic snow clearing solution Eulektra:

  The consumption of the automatic snow clearing solution is too large relatively to the gain. Balance (production minus consumption) over the winter period is negative. To be effective, other parameters as snow depth, temperature and weather forecast should regulate the device,

- Manual snow clearing solution Solutronic:

  This is an interesting solution if someone is on site and takes into account the various parameters to have an efficient installation,

- Polymer application Freso:

  The measurement campaign has failed to highlight the effectiveness of this solution. We hope to have better results with a greater inclination,

- Double face modules Sanyo HIT Double:

  A small thickness of snow is more rapidly cleared thanks to the heat of the rear cells. However, the smaller height from the ground of these modules decreased the winter efficiency: due to a specific structure for these double modules, the bottoms of the modules are closer to the ground and the evacuation of the snow was stopped

- Amorphous modules Flexcell:

  The amorphous modules are on the ground and the thick layer of snow during all the winter, no energy was produced during the snow season.

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Description du projet

Le projet, en partenariat avec le canton de Neuchâtel, Viteos SA et Planair SA, se base sur une installation didactique sur les toits du Lycée Blaise Cendrars à La Chaux-de-Fonds.

Il est prévu de comparer la production de différentes technologies photovoltaïques dans les conditions d'enneigement. Les différentes technologies ainsi que les systèmes de déneigement étudiés sont répertoriés dans le paragraphe « technologies installées ».

La conception et l'installation des capteurs et des systèmes de déneigement se sont déroulées durant l'année 2011.

Les mesures de production/consommation des différentes technologies se dérouleront durant les hivers 2012, 2013 et 2014.

Technologies installées

Les technologies suivantes ont été installées sur le toit du Lycée Blaise Cendrars :

Technologie	Fabricant	Puissance de l'installation
Si Amorphe	Flexcell	1.35 kW_p
Si Monocristallin	Bosch	1.41 kW_p (x5)
HIT[1] Double	Sanyo	1.26 kW_p
Si Polycristallin	Trina	1.41 kW_p

Tableau 1: *Type de technologies des panneaux PV*

La technologie amorphe a été choisie pour ses propriétés de sensibilité au rayonnement diffus, qui devrait lui permettre de chauffer même avec une faible épaisseur de neige.

La technologie HIT Double a été choisie pour sa double couche photovoltaïque, qui devrait lui permettre de fonctionner et de monter en température par la réflexion de la lumière sur la neige environnante.

Les modules du fabricant Trina permettront de comparer la production de panneaux chinois et de panneaux allemands de même puissance.

Les solutions de déneigement installées sur les différents champs de capteurs Bosch sont:

Type	Solution de déneigement	Remarques
Si Monocristallin, 1.41 kW_p	Sans déneigement	Installation de référence
Si Monocristallin, 2,82 kW_p	Solutronic (solution 1)	Inversion **manuelle** du courant dans les panneaux
Si Monocristallin, 1.5 kW_p	Eulektra (solution 2)	Inversion **automatique** du courant dans les panneaux
Si Monocristallin, 1.5 kW_p	FRESO (solution 3)	Application de polymère permettant de rendre les surfaces hydrofuge.

Tableau 2: *Type de solution de déneigement (panneaux cristallins uniquement)*

[1] *HIT : Heterojunction with Intrinsic Thin layer*

L'installation complète dispose de 8 champs d'environ 1.4 kW_p chacun, soit une puissance totale d'environ 11 kW_p. La solution de déneigement Solutronic nécessite deux champs de capteurs: il n'y a donc que 7 champs représentés.

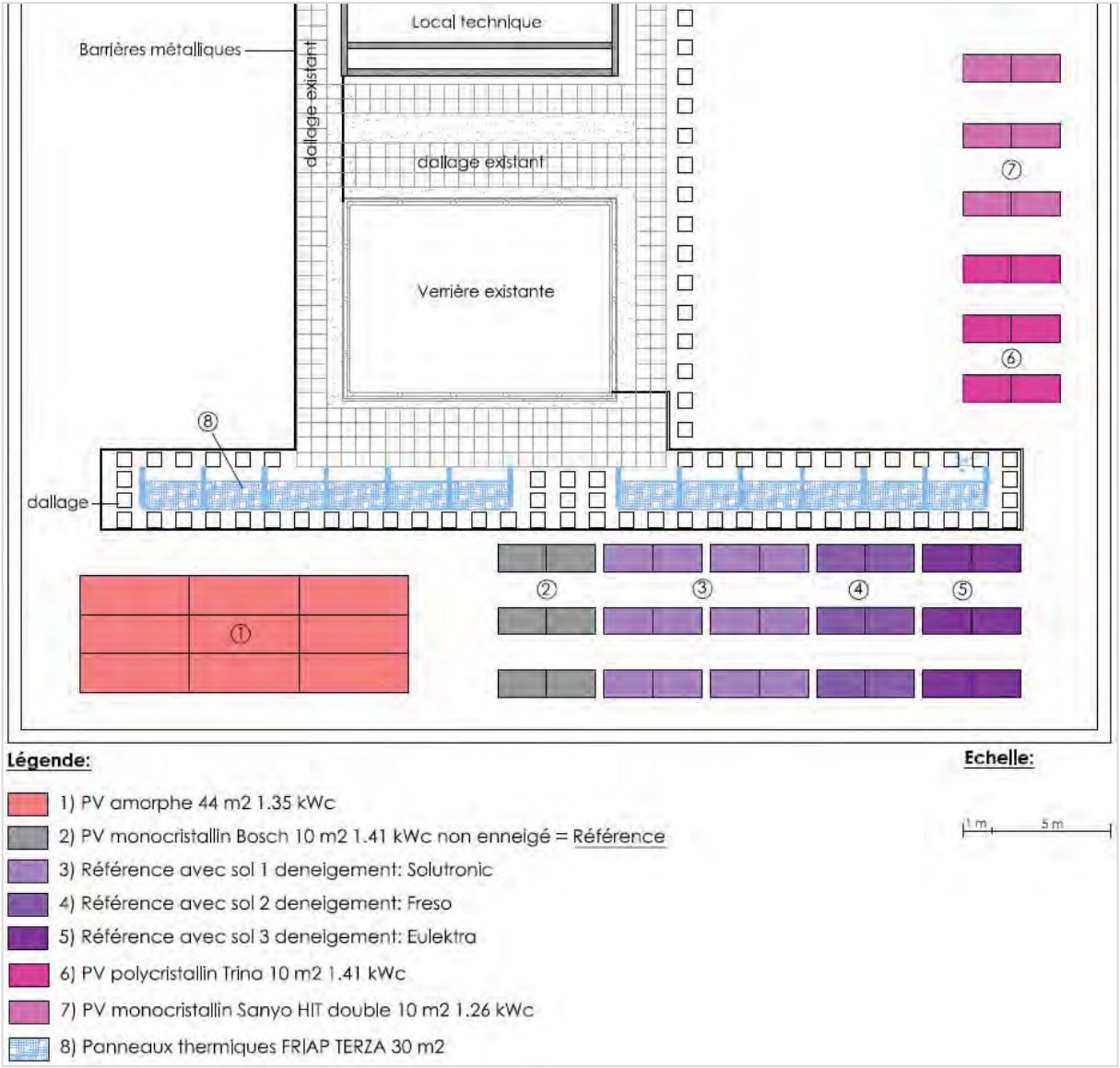


***Figure 1**: Vue d'ensemble de l'installation sur le toit du Lycée*

Les 7 champs PV disposent de leur propre onduleur et d'un équipement de supervision (Solarlog) permettant d'enregistrer les différents paramètres (production d'électricité, T° extérieure, ensoleillement (W/m^2)).

Les deux champs disposant d'un système d'inversion de courant possèdent un équipement de mesure de l'énergie consommée.

Bilan global hiver 2012

Le tableau ci-dessous présente la production des différentes solutions et la consommation des solutions inversant le courant entre le mois de janvier et le mois de mars 2012:

	Janvier *(du 10 au 31)*	**Février** *(du 1er au 29)*	**Mars** *(du 1er au 31)*	**Bilan**
Eulektra				
Consommation [kWh/kWc]	*133*	*295*	*52*	
Production [kWh/kWc]	*9*	*52*	*128*	*-291*
Solutronic				
Consommation [kWh/kWc]	*2*	*6*	*0*	
Production [kWh/kWc]	*21*	*44*	*127*	*185*
Bosch référence				
Production [kWh/kWc]	*6*	*36*	*122*	*164*
Freso				
Production [kWh/kWc]	*6*	*29*	*121*	*156*
Sanyo HIT D				
Production [kWh/kWc]	*9*	*35*	*150*	*193*
Trina				
Production [kWh/kWc]	*7*	*23*	*124*	*154*
Flexcell				
Production [kWh/kWc]	*0*	*0*	*0*	*0*

***Tableau 3**: Production et consommation des différentes solutions avec bilan sur la période janvier-mars 2012*

Remarques:

- La date d'acquisition des données de production avec la solution Solutronic a commencé début janvier 2012.
- La date d'acquisition des données de production avec les autres solutions a débuté le 17 janvier.
- Toutes les données de consommation ont débuté le 10 janvier.

► Le mois de janvier n'est pas représentatif pour une comparaison avec la solution Solutronic. Dans la suite de l'étude nous allons donc **enlever 15kWh/kWc à la solution Solutronic** afin que celle-ci soit comparable aux autres solutions.

La solution **Eulektra** permet une production supérieure sur les périodes hivernales mais la consommation de courant est excessive par rapport au gain de production. Le bilan global est négatif.

La solution **Solutronic** permet une production légèrement supérieure. Cette technologie nécessite une rigueur de la part du maître de l'ouvrage pour atteindre une bonne performance.

Dans notre configuration, la solution **Freso** n'a pas donné de meilleures performances que la solution de référence. La production est même légèrement inférieure. L'explication est donnée dans le chapitre suivant.

Les panneaux **Sanyo** ont été défavorisés par leur plus faible garde au sol au mois de février mais ont un bilan final sur les trois mois bien supérieur à la référence.

Les panneaux **Trina** ont été péjorés au mois de février par les accumulations de neige. Le bilan global est donc légèrement inférieur à la référence.

Les capteurs **Flexcell** étant installés à plat sur le sol, ils ont été recouverts par la neige tout au long de l'hiver.

Une explication plus détaillée du fonctionnement de chaque solution est présentée au chapitre suivant « bilan détaillé ».

Bilan détaillé hiver 2012

L'analyse détaillée du fonctionnement des solutions a été réalisée sur deux périodes représentatives d'un fonctionnement hivernal avec chutes de neige:

Période 1 (du 24 au 26 janvier 2012)

Le mardi 24 janvier, une chute de neige d'environ 10 cm a eu lieu suivie d'une période de deux jours avec des températures positives (5 à 6°C en journée) qui a eu comme conséquence de faire fondre la neige.

Le graphique ci-dessous montre les chutes de neiges journalières (en rouge) et l'épaisseur du manteau neigeux sur une surface plane (en bleu).

Figure 2 : *Chute de neige journalière et cumul sur une surface plane*

Les graphiques ci-dessous montrent l'évolution de la production suivant les technologies.

***Figure 3**: Données de production de la solution Solutronic du 24 au 27 janvier 2012*

***Figure 4**: Données de production des installations du 24 au 27 janvier 2012*

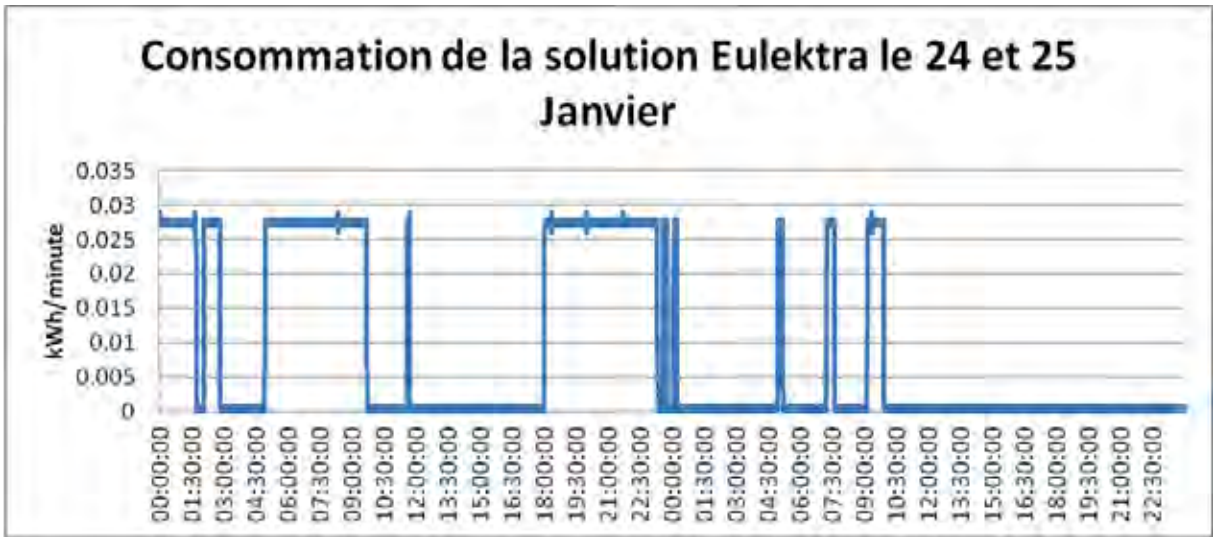


Figure 5**: Consommation de la solution Eulektra les 24 et 25 janvier.* ***0.027 kWh/min = 1.6 kW

De cette période 1, nous pouvons tirer les enseignements suivants:

- L'installation **Eulektra** est productrice dès que les conditions d'ensoleillement le permettent. Pour cela une quantité d'énergie considérable est injectée dans le déneigement. 24 kWh ont été consommés entre le 24 et le 25 janvier pour un gain par rapport à Bosch référence de 3.6 kWh entre le 24 et le 26 janvier.
- Une faible quantité de neige au sol permet à la solution **Sanyo** de produire grâce à la face arrière. De plus, une faible quantité de neige est plus rapidement évacuée que pour les autres solutions.
- Les panneaux **Trina** se sont rapidement dégagés le 26 janvier, suivi par les **Bosch référence** et la solution **Freso**.
- L'inversion de courant pour la solution **Solutronic** n'a pas été mise en marche du fait de la météo. Les panneaux se sont comportés comme les Bosch référence.

Période 2 (du 17 au 24 février 2012)

Le vendredi 17 février, un épisode neigeux se termine et est poursuivi par une nouvelle chute de neige de quelques centimètres la nuit du 19 au 20 février. Les jours suivants sont ensoleillés et nuageux (18,19, 20, 23 février) ou seulement ensoleillés (21, 22, 24 février).

***Figure 6**: Etat des panneaux le 17 février avec dans l'ordre: Eulektra, Freso, Solutronic (x2) et Bosch référence*

***Figure 7**: Etat des panneaux le 17 février (Trina devant et Sanyo à l'arrière plan)*

***Figure 8**: Etat des panneaux le 20 février (Trina à droite et Sanyo à gauche)*

***Figure 9**: Etat des panneaux le 20 février avec dans l'ordre Eulektra, Freso, Solutronic (x2) et Bosch référence*

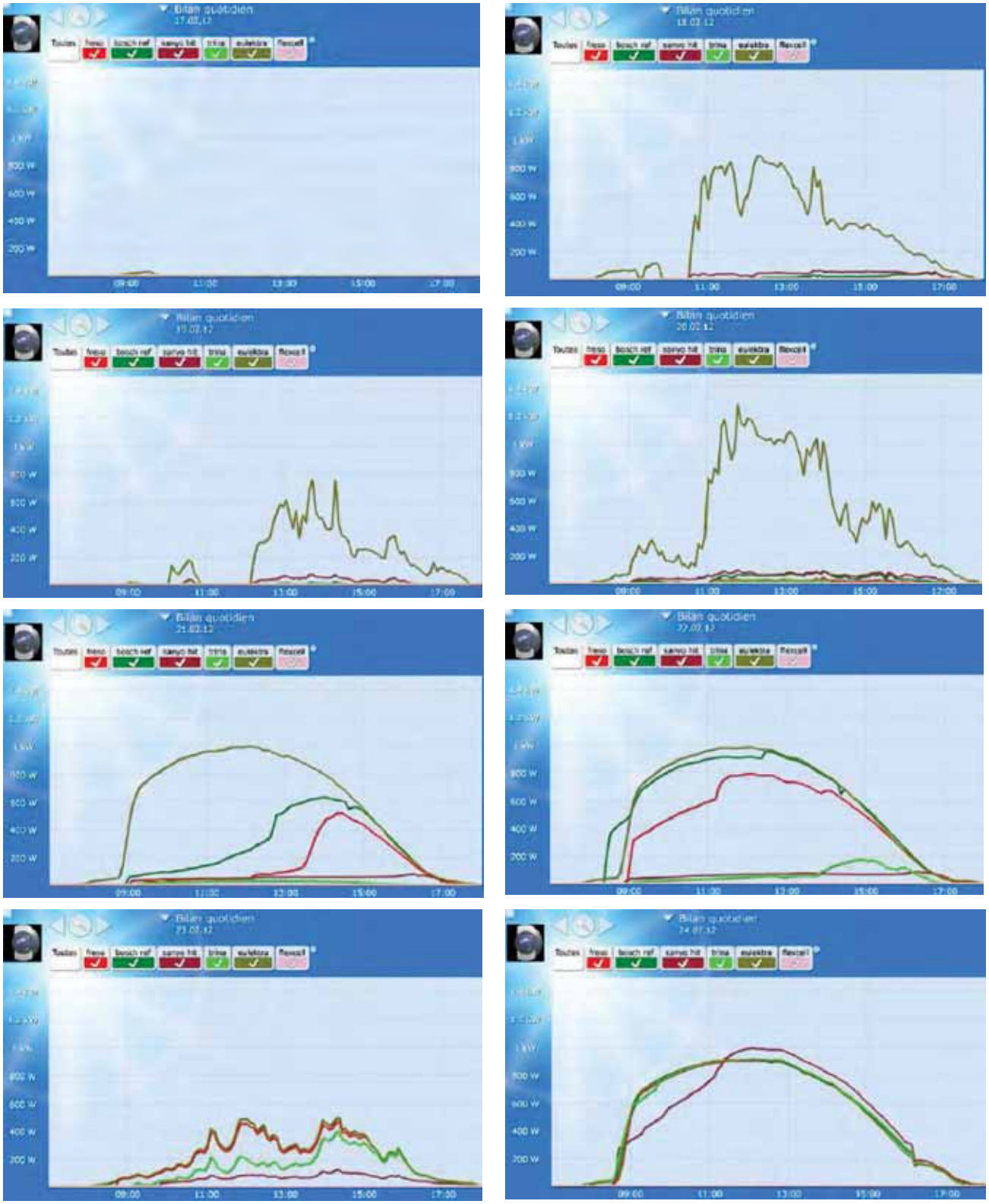


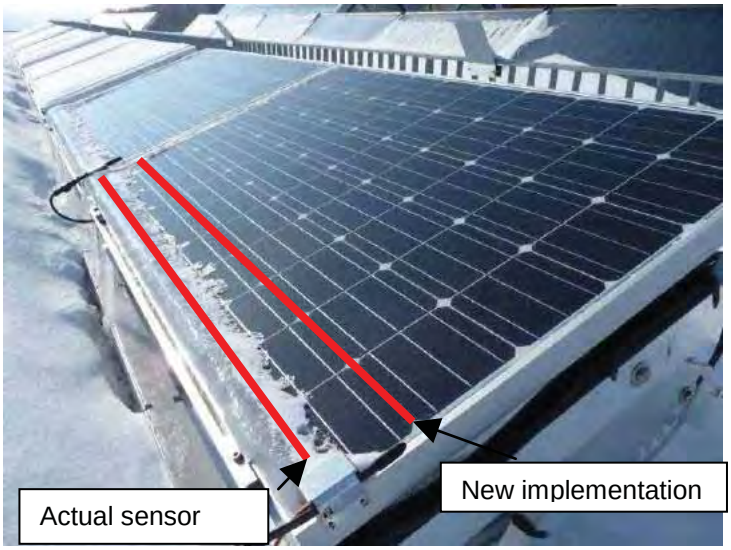
***Figure 10**: Données de production des installations du 17 au 24 février 2012*

Figure 11 *: Données de production de la solution Solutronic du 17 au 24 février 2012*

Remarque : Le 17 et le 20 février, le système de déneigement à été mis en marche durant 2 heures. Cette injection de courant est visible sur les données de production du Solarlog bien qu'il s'agisse en réalité d'une consommation.

De cette période 2, nous pouvons tirer les enseignements suivants:

- Le 17 février, la solution **Eulektra** est en marche alors que seul le bas des panneaux est sous la neige. Le détecteur en bas des panneaux indique la présence de neige. En effet, la neige a fondu et un « bourrelet » de glace s'est formé en bas des panneaux à cause des températures très négatives (-10°C). L'apport d'énergie n'est pas suffisant. Afin de contrer ce problème, nous avons déplacé le détecteur vers le haut comme sur la figure ci-dessous:



- La solution **Solutronic** a été mise en route deux fois (le 17 et le 20 février) sans résultats probants à cause de la température extérieure. Il aurait été intéressant de mettre en marche le déneigement le 21 février entre 8 heures et 10 heures.
- Le 21 février, la solution **Bosch référence** est la première à se dégager de la neige suivi de la solution **Freso** qui ne sera dégagée que complètement à la fin du 22 février.
- Les capteurs **Trina** sont défavorisés par une épaisse couche de neige qui empêche une bonne évacuation de la neige. Une accumulation locale est visible en figure 8. Ils ne seront dégagés qu'à la fin du 23 février.
- Une forte épaisseur de neige a défavorisé également les panneaux **Sanyo** pour les raisons suivantes:
  - La face arrière capte peu de rayonnement du faite que le sol (la neige) est proche des panneaux. L'angle avec lequel la face arrière voit le sol est réduit.
  - Pour des raisons de structure spécifique, les panneaux étant plus bas que les autres, le bas des panneaux s'est trouvé dans la neige empêchant la neige d'être évacuée correctement.
- Une fois dégagés (le 24 février et jour suivants), les capteurs **Sanyo** produisent environ 25% de plus par kWc que la référence.
- Les capteurs **Flexcell** sont sous la couche de neige et ne produisent donc pas.

Conclusion

La solution de déneigement **Eulektra** est une solution automatique de déneigement. Malheureusement, la consommation est bien plus importante que le gain apporté par cette solution. Voici quelques conditions afin que le déneigement soit pertinent :

- Météo de la journée suffisante pour apporter la perte due au déneigement.
- T° ambiante pas trop froide, sinon l'effet du déneigement électrique proposé ici est nul.
- Pas de rechute de neige rapide suite au déneigement.
- Activation du déneigement quand une irradiation est déjà présente : le soleil poursuit l'action enclenchée, l'inversion de courant accélère les choses.
- Irradiation à venir suffisante pour que l'inversion de courant soit pertinente (gains>pertes).

L'expérience du terrain nous a également permis de voir que le détecteur de neige était placé trop bas sur le panneau. Nous l'avons donc remonté.

La solution de déneigement **Solutronic** est une bonne alternative quand une personne, sur place, peut prendre en compte tous les paramètres ci-dessus.

Les solutions avec injection d'énergie n'ont pas démontré leur efficacité pour des conditions très froide, le surplus d'énergie à injecter pour obtenir un effet reste largement supérieur au gain possible dans les jours suivants.

La solution **Freso** n'a pas permis d'obtenir de meilleurs résultats que la solution de référence. Une inclinaison supérieure pourrait peut-être démontrer le contraire, mais aucune différence de glissement n'a été constatée.

Les panneaux **Sanyo** ont été défavorisés par l'épaisse couche de neige que nous avons eu cette année et la garde au sol moins élevée que les autres panneaux. Lors d'une faible couche de neige, nous avons vu que la face arrière permet un dégagement plus rapide des modules. Un rendement supérieur, mesuré à 18%, des panneaux est possible en conditions neigeuses grâce à la face arrière, mais il a ici également été limité par la couche de neige au devant des panneaux.

Les modules **Trina** ont également souffert de l'épaisse couche de neige et d'une accumulation locale légèrement supérieure que pour les autres modules. Le dégagement de la neige a été plus difficile. Aucune technologie particulière n'a été mise en œuvre sur ces panneaux cette année.

Les modules **Flexcell** ont été complètement recouverts par la neige et n'ont donc pas produit durant cette période hivernale.

L'irradiation hivernale étant limitée, il est important de maîtriser la dépense énergétique pour en bénéficier.

Les perspectives d'études pour l'année prochaine sont, en coordination avec les partenaires:

- Mesures sur l'ensemble de la saison hivernale et analyse du gain au niveau annuel.
- Déterminer, en fonction de différents paramètres (neige récente, température, météo prévue avec, entre autres, l'irradiation), la pertinence de mettre en route le déneigement.
- Déblayement de la neige directement en-dessous des panneaux afin d'observer d'une manière plus identique la faculté des technologies à évacuer la neige (analyse des effets pour la sécurité des personnes).

Comme pour l'optimisation du photovoltaïque dans les réseaux électriques, l'optimisation du fonctionnement d'une installation photovoltaïque en condition neigeuse requerra d'excellentes prévisions météorologiques afin de gérer son enclenchement raisonné aux moments opportuns.

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Bundesamt für Energie BFE

POTENTIAL VON PHOTOVOLTAIK AN SCHALLSCHUTZWÄNDEN ENTLANG VON NATIONALSTRASSEN

Annual Report 2012

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Date	10.12.2012

ABSTRACT

Photovoltaic (PV) power plants can be realized in a rather large amount without the need to use up additional free space if the PV installations are combined with existing infrastructure. The combination of PV and noise barriers on highways is especially suitable herefore, due to the modular construction of the noise barriers, which favour a fast and also modular installation of PV modules, which can be prepared before installation. PV is one of the few possible double uses for noise barriers.

Four different possible PV plant designs have been developed for this study.

The existing ASTRA database called MISTRA LBK from the FEDRO contains datasets for various noise barrier constructions on highways. These datasets have been examined concerning the most significant parameters for the use of PV.

For the different potentials such as theoretical and technical potential, corresponding parameter sets have been evaluated and described. The study shows, that for almost all possible orientations of noise barriers on highways there is a technical solution to install PV power plants. For each noise barrer in the database, the PV construction type with the highest resulting PV module area has been assigned. This results in potentials in terms of PV module area, nominal power and expected annual energy production.

With these assumptions a theoretical potential of about 2.2 Mio m^2 has been calculated, corresponding to a nominal power of about 440 MW_p and an annual energy production of approximately 410 GWh. For the technical potential, limitations by existing products such as dimensions of a module have been taken into account, leading to a technical potential of 1.3-1.5 Mio m^2 or 210-240 MW_p. The annual energy production is estimated at 200-230 GWh. With the non-technical limitations taken into account, the usable potential leads to 0.7-1.0 Mio m^2 module area corresponding to 110-165 MW_p or an annual energy production of 100-160 GWh.

The evaluated usable potential of around 150 GWh annual energy production for PV installations in combination with noise barriers on the national highways could balance the energy consumption needed for the operation of the national highways. 2010, the energy consumption for the operation of the national highways including illumination and ventilation of tunnels, was at 150 GWh. The nominal power of around 165 MW_p of PV on noise barriers evaluated as usable potential is a similar amount of PV as cumulative installed PV power in Switzerland overall end of 2011.

Einleitung / Projektziele

Entlang von Schweizer Nationalstrassen (Autobahnen) befinden sich zahlreiche Lärmschutzwände (LSW) zum Schutz gegen den Strassenlärm. An einer LSW besteht grundsätzlich die Möglichkeit, eine Photovoltaik-Anlage zu errichten um damit elektrischen Strom zu erzeugen ohne zusätzliche, freie Fläche zu beanspruchen. Um das Photovoltaik (PV) Potential auf den bestehenden und geplanten LSW zu ermitteln, werden die LSW auf ihre Eignung für mögliche PV-Anlagetypen anhand eines Beurteilungsschemas überprüft.

Anhand einer Bestandsaufnahme der aktuellen und geplanten Schallschutzprojekte im Schweizerischen Autobahnnetz soll das technische und realisierbare Potential der Kombination von PV und Schallschutz in Kombination an Nationalstrassen ermittelt werden. Dazu wird ein entsprechender Eignungskatalog für PV-Schallschutzanlagen erarbeitet, welcher sich am Prozess der Planung und Realisierung von Schallschutzanlagen orientiert.

Die sinnvolle Kombination von PV und Schallschutz kann als Kommunikationsbotschaft und als Vorbild für andere Länder dienen. In der Realisierung wird innovativen Unternehmen die Möglichkeit geboten, sich im Bereich PV und Schallschutz zu etablieren. Damit werden neue, hoch qualifizierte Arbeitsplätze geschaffen und erhalten.

Kurzbeschrieb des Projekts

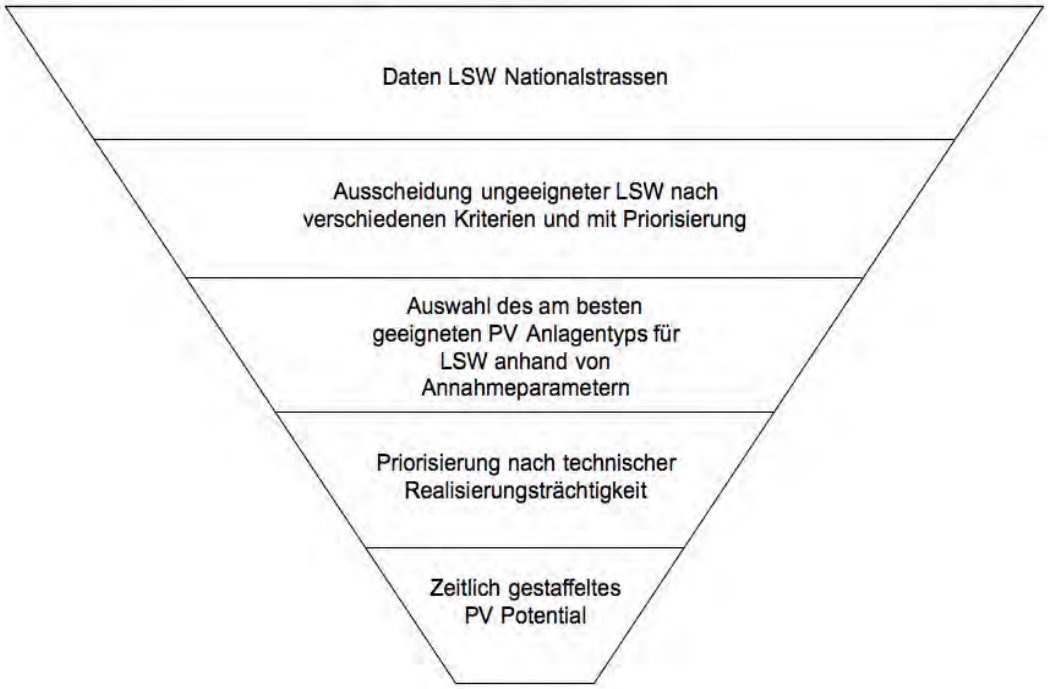
Das Flächenangebot des Strassenareals ist mit 100 m^2/Kopf fast doppelt so gross wie bei den Gebäudeflächen. Hier gilt es, dass grosse Flächenangebot bei den Strassen für die sinnvolle Kombination mit PV zu nutzen. Um die technisch und ökonomisch sinnvollen Schallschutzprojekte für eine Kombination mit PV ermitteln zu können, wird ein Kriterienkatalog erstellt. Dieser soll neben den photovoltaischen Kriterien auch praktische Hinweise auf mögliche Realisierungsformen enthalten. Um eine effiziente Realisierung von Photovoltaik und Schallschutz zu ermöglichen, soll die Planung und der Bau der PV Anlage sich so weit möglich und sinnvoll an den Prozessen der Planung des Baus von Lärmschutzmassnahmen orientieren, damit insbesondere eine zeitgerechte Realisierung gewährleistet wird. Das Vorgehen und die Anwendung des Kriterienkatalogs sollen anhand von Fallbeispielen erfolgen.

Für die Finanzierung und den Betrieb der PV-Schallschutzanlagen werden verschiedene Betreibermodelle auf ihre Eignung untersucht und beschrieben. Neben den technischen Möglichkeiten wurden auch vor allem Private Public Partnership „PPP“ und langfristige Mietverträge für die Flächen etc. untersucht.

Durchgeführte Arbeiten und erreichte Ergebnisse

Um eine bestehende LSW auf die Eignung der PV-Nutzung zu überprüfen, wird die LSW nach verschiedenen Kriterien bewertet bzw. ausgewählt. Dazu gehören neben allgemeinen physikalischen Eigenschaften auch standortspezifische Eigenschaften und Einschränkungen, welche durch verschiedene PV Anlagetypen entstehen.

Als Eingabe werden Daten zu den Lärmschutzwänden des Bundesamtes für Strassen (ASTRA) eingesetzt. Für eine Anwendung mit Photovoltaik ungeeignete LSW werden basierend auf verschiedenen Kriterien ausgefiltert. Anschliessend wird anhand von technisch relevanten Parametern der geeignetste Anlagentyp für einen Lärmschutzwandabschnitt ermittelt. Mit der Annahme von unterschiedlichen Parametern können die unterschiedlichen Potentiale ermittelt werden. Durch Festlegung von Toleranzbändern für die Parameter kann auch eine Priorisierung der potentiellen PV Anlagen erreicht werden und damit auch eine zeitliche Staffelung einer Umsetzung (Fig. 1).



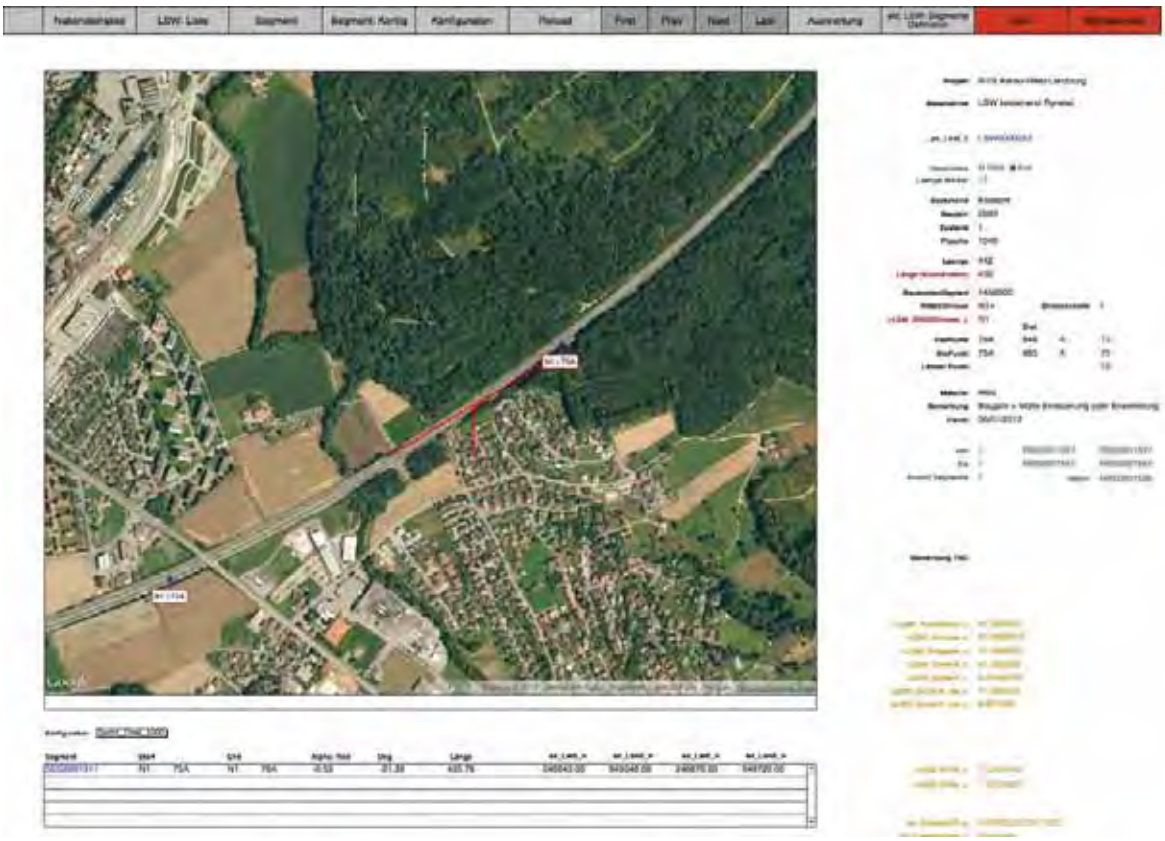
Figur 1: *Schematischer Ablauf LSW Analyse zur Ermittlung des Potentials von PV an Lärmschutzwänden.*

Grundlage für die PV Potential Analyse an den Lärmschutzwänden sind die Daten über die Lärmschutzwände. Die minimal notwendigen Parameter sind für eine Beurteilung mit der entwickelten Methode zwingend notwendig. Die Vollständigkeit der Daten der Lärmschutzwände ist für die Vollständigkeit der PV Potential Analyse entscheidend. Die erweiterten Kriterien können für eine Präzisierung der PV Potential Analyse genutzt werden.

Für die Berechnung des Photovoltaik-Potentials auf Lärmschutzanlagen wurde eine Datenbank erstellt und verwendet. Mit dieser ist es möglich, die Projektdaten aus der MISTRA-LBK Datenbank einzulesen und weiter zu verarbeiten. So ist es möglich, mit den verschiedenen Konfigurationen an Parameter-Sets die Abschätzungen durchzuführen. Für die Potentialermittlung erfolgt eine Berechnung für jedes einzelne Segment der LSW. Die Ergebnisse der Berechnungen können in detaillierter Form von Listen oder zusammengefasst in Form einer Übersicht nach frei definierbaren Kriterien dargestellt werden. Weiter besteht die Möglichkeit Informationen zu einzelnen LSW in einer Übersicht inklusive einer Kartendarstellung zu erhalten (Fig. 2).

Für eine noch flexiblere Datenanalyse können definierbare Teilmengen der Datenbank exportiert und in weitere Programme (bspw. MS EXCEL) eingelesen werden.

Für die Umsetzung der geografischen Informationen wurden verschiedene Hilfsmittel aus dem Bereich der Geoinformationssysteme genutzt. Für die Visualisierung wurde das frei zugängliche Google Earth verwendet.



Figur 2: *Screenshot TNC Projekt-Datenbank mit eingebundenem Geo-Informationssystem.*

Projekt-Meilensteine:

Meilenstein 1: Datenerfassung ist abgeschlossen und ein Modell für Kategorisierung erstellt.

Meilenstein 2: Technisches Potential der Lärmschutzmassnahmen an Nationalstrassen ist ermittelt.

Meilenstein 3: Betreibermodelle aus Sicht des ASTRA sind verglichen und anhand von Fallbeispielen erläutert.

Meilenstein 4: Abschluss des Projektes mit Abgabe des Schlussberichtes und Präsentation am 29. November 2012 beim Auftragsgeber ASTRA.

Ergebnisse:

Basierend auf den 236 v ollständigen und repräsentativen Datensätzen der MISTRA LBK wurde gemäss der vorgestellten Methode das theoretische Potential und ein kurz- und mittelfristiges technisches Potential berechnet. Diese wurden dann mit den entsprechenden Annahmen auf schweizweite Werte hochgerechnet. Für das erschliessbare Potential sind anschliessend noch die nicht-technischen Parameter mit berücksichtigt worden.

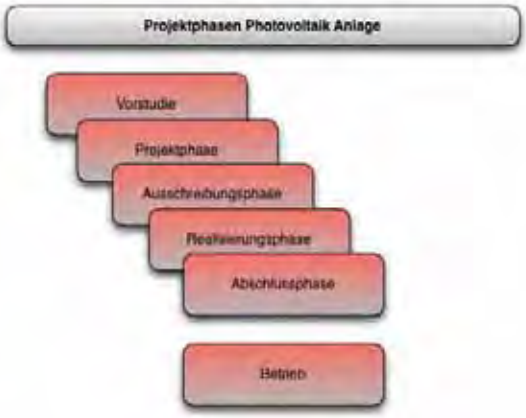
Für das theoretische Potential beträgt die so ermittelte PV-Fläche ca. 2.2 Mio m^2 mit einer Nennleistung von 440 MW und e inem erwarteten jährlichen Stromertrag von ca. 410 GWh. Mit Berücksichtigung der nicht-technischen Parameter besteht ein realisierbares Potential von 0.7 - 1.0 Mio m^2 oder 110 – 165 MWp Nennleistung, was zu einem elektrischen Jahresertrag von 100 – 160 GWh führt (Fig. 3). Somit ist das ermittelte realisierbare Potential von Photovoltaik an Lärmschutzwänden entlang der Nationalstrassen des Bundes ausreichend, um den Jahresbedarf an elektrischer Energie für den Betrieb der Nationalstrassen in der Jahresbilanz decken zu können. (145 GWh im 2010, inklusive Tunnel und Beleuchtung). Zum Vergleich, die Nennleistung von 165 MWp entspricht etwa der bis Ende 2011 total in der Schweiz installierten PV Leistung (190 MWp gem. BfE Umfrage 2011).

	Fläche (m^2)		Leistung (MW_p)		Stromertrag (GWh)	
	pessimis-tisch	*optimis-tisch*	*pessimis-tisch*	*optimis-tisch*	*pessimis-tisch*	*optimis-tisch*
Zugewandt	208'081	401'300	33	64	32	61
Abgewandt	456'121	608'161	73	97	69	92
Bifacial	12'662	20'036	2	3	2	3
Gesamt	**676'864**	**1'029'497**	**108**	**165**	**103**	**156**

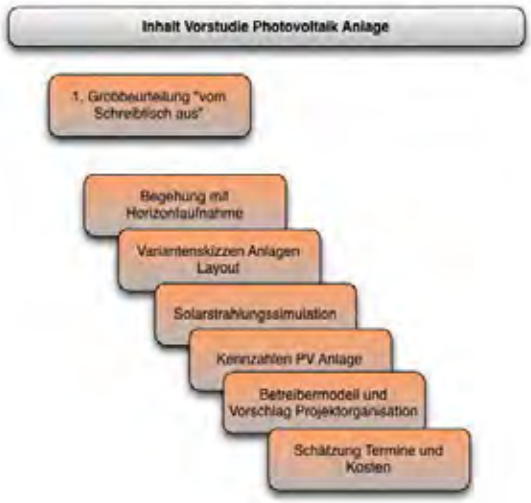
Figur 3: *Realisierbares Potential von Photovoltaik an Lärmschutzmassnahmen. Abhängig vom gewählten Szenario ergeben sich auf 0.67 bis 1 Mio m2 eine mögliche Anlagennennleistung von 110 bis 165 MW und ein erwarteter jährlicher Stromertrag von 100 bis knapp 160 GWh.*

Für eine erfolgreiche Realisierung einer LSW mit PV gilt es, die unterschiedlichen Abläufe und Prozesse von Schallschutzvorhaben und Photovoltaik-Anlagen so zu kombinieren, dass die Kombination optimal genutzt werden können (Fig. 4).

Grundsätzlich muss beachtet werden, dass die Gesamtdauer eines Photovoltaik-Projektes üblicherweise weit kürzer ist, verglichen mit einem Strassenbau- bzw. Schallschutzvorhaben. So braucht eine PV Anlage von der Planung bis zur Inbetriebnahme typischerweise etwa ein Jahr, während der Prozess in einem Tiefbau Vorhaben mehrere Jahre dauern kann bis zur Inbetriebnahme des Werkes. Eine möglichst frühe Zusammenarbeit im Prozess ist empfehlenswert.



Figur 4*: Phasen eines Photovoltaik-Projekts*



Figur 5*: Elemente einer Vorstudie zur Beurteilung der Eignung von Photovoltaik in Kombination mit Lärmschutzbauwerken*

Die Refinanzierung der Photovoltaikanlage ist entweder über die kostendeckende Einspeisevergütung KEV oder durch Vermarktung des ökologischen Mehrwertes z.B. Solarstrombörsen möglich.

Es gibt unterschiedlichste Betreibermodelle, welche auch schon erfolgreich für PV Schallschutzprojekte angewendet wurden. Für die erfolgreiche Realisierung und Betrieb einer PV Schallschutzanlage sind Sicherheiten bei der Refinanzierungsmodellen für den Betreiber notwendig. Die planerische Sicherheit im Ablauf einer Bewilligung einer PV Schallschutz Anlage ist für einen potentiellen Investor ebenfalls wichtig. Die stark gesunkenen und weiterhin sinkenden Systempreise in der Photovoltaik erlauben es, Investoren für die Realisierung und den Betrieb von PV Anlagen zu finden.

Alle Ergebnisse der Studie sowie Beschreibung der angewendeten Methodik und Empfehlungen liegen in Form eines Schlussberichtes vor.

Nationale / internationale Zusammenarbeit

Für das Projekt wurde eine begleitende Kommission unter der Leitung von Herrn Cédric Joseph, ASTRA gebildet. Die Begleitgruppe bestand aus den Fachexperten Prof. Dr. Heinrich Häberlin der FH Burgdorf, Dr. Kurt Heutschi, Empa und Dr. Stefan Kunz, Meteotest. Anlässlich einer Schlusspräsentation wurden die Ergebnisse der Studie weiteren Vertretern des ASTRA, sowie Vertretern des Bundesamtes für Energie, dem UVEK, den Kantonen sowie der SBB vorgestellt.

Bewertung 2012 und Ausblick 2013

Basierend auf den Erkenntnissen aus dem Forschungsprojekt Potential Photovoltaik an Lärmschutzwänden entlang der Nationalstrassen und den Erfahrungswerten von bereits realisierten PV Schallschutz Projekten werden folgende **Empfehlungen** durch die Verfasser der Studie ausgesprochen:

1. Die Kombination von PV und Lärmschutzwänden kann damit einen wichtigen Beitrag zur vermehrten Nutzung von Photovoltaik zur Stromgewinnung auf bestehender Infrastruktur in der Schweiz leisten.
2. In der Kombination von konventionellen PV Anlagen und bifacialen PV Anlagen kann auf beinahe allen Ausrichtungen von Lärmschutzwänden eine PV Anlage installiert werden.
3. Es wird empfohlen, eine einheitliche Handhabung der Abläufe, Prozesse, Kriterien und Bewilligungen für spätere PV Anlagen Contractoren anzustreben.
4. Die Prüfung von Lärmschutzwänden auf eine Eignung für die Kombination mit PV im Planungsprozess des ASTRA im Rahmen einer Sanierung oder eines Neubaus einer Lärmschutzwand sollte fest etabliert werden.
5. Mit der in der Studie entwickelten Methode und dem erstellten Datenbankmodell kann eine schweizweite Positiv- Liste der besonders geeigneten Lärmschutzwände erstellt werden. Dies kann periodisch mit dem jeweils aktuellen Datenstand zu den Lärmschutzwänden erfolgen, sollte aber spätestens bei Erreichen eines hohen Grades an Vollständigkeit der Datensätze betreffend Lärmschutzwänden erneut durchgeführt werden um die in der Studie ermittelten Potentiale flächendeckend auf Projekte anzuwenden.
6. Wir empfehlen unabhängige Vorstudien für PV Anlagen an als geeignet eingestuften Lärmschutzwänden erstellen zu lassen. Damit sind belastbare Grundlagen vorhanden, welche für eine Ausschreibung der PV Schallschutzanlage oder eine weiterführende Projektplanung verwendet werden können.
7. Um schnell praktische Erfahrungen mit den Prozessabläufen zu sammeln, sollte anhand von einigen ausgesuchten Beispielprojekten für unterschiedliche Anlagetypen eine Vorstudie erstellt und eine Ausschreibung der Anlagen zu Handen späterer PV Anlage Contractoren durchgeführt werden.

Als weiteres Vorgehen prüft das ASTRA, eine Richtlinie ausarbeiten zu lassen, die eine erste Einschätzung einer Photovoltaikanlage im Planungsprozess vom Neubau oder Sanierung von Lärmschutzwänden im Bauvorhaben obligatorisch vorsieht.

Referenzen

[1] Forschungsauftrag 59/96 ASTRA, „Erprobung von drei integrierten Photovoltaik-Schallschutz-Versuchsanlagen; TNC Consulting AG.

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[3] „European Potentiall of PV-Noise Barriers“, EU Thermie B Project, 1999; TNC Consulting AG.

[4] „PV on noise barriers, Progress in Photovoltaics; Research and Applications“; TNC Consulting AG.

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PV-TRACKING-SYSTEM AUF DEM SKILIFT IN TENNA

EINE ERSTE AUSWERTUNG

Annual Report 2012

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Project- / Contract Number	Solarskilift Tenna
Duration of the Project (from – to)	01.08.2011 – 30.06.2012
Date	13.03.2013

ABSTRACT

The world's first solar ski lift has a 60 kW PV system that is tracked in one axis. The robust design of the mechanical system requires less material than usual: less than 100kg of steel per kW nominal PV module. To achieve this goal the steel cables function as the support structure for the PV modules.

Generally, it is assumed that the electricity production of solar tracking systems increases by about 30% compared to non-tracked installations. The yield achieved by the solar ski lift is 78% higher than the yield of a fixed plant in the same region for an average January. This is attributed to the fact that the panels are not covered by snow and to the high reflectance values of the snow cover of the surroundings, especially in the morning and evening. In the following months this high value decreases and, as the snow melts, it reaches around 34%. It is possible to obtain high yields PV even in the winter in the Alps. Commonly obtaining high PV-yields in a region like the Alps, is known to be a systemic problem of PV in snowy region, but can be overcome by a tracking-system.

Einleitung / Projektziele

Etwa ein Viertel aller grossen PV-Anlagen ist heute mit Trackern ausgerüstet. Dies entspricht weltweit über 250 MW PV-Modulen, welche auf Trackern betrieben werden [1]. Aufgrund der Tatsache, dass der Marktanteil von grossen Systemen steigt, ist zu erwarten, dass auch der PV-Tracker-Markt in einem rasanten Tempo wächst.

Theoretisch stehen im Vergleich zu festen Installationen ca. 41% mehr Sonnenlicht zur Verfügung, wenn PV-Module dem täglichen Lauf der Sonne nachgeführt werden [2]. Für die Mittelmeer-Region werden Gewinne zwischen 31% und 36% bei Zwei-Achsen-Systemen gegenüber festen Installationen berechnet (Tabelle 1).

Huld zeigte [3], dass in Nordwest-und Mitteleuropa der relative Gewinn (Verstärkung) der zweiachsige nachgeführten Systeme höher ist als im Süden. Der absolute Gewinn von Tracking-Systemen ist jedoch mit 250 kWh pro kWp im Norden (Flachland) eher gering im Vergleich zu den typischen jährlichen Gewinnen in Portugal und im Mittelmeerraum, wo sie im Bereich von 400-600 kWh pro kWp liegen.

Tabelle 1: *Berechnete Solar Eingangsverstärkung zweiachsig-nachgeführter Systeme relativ zu einer festen Installation Bei 35° Neigung in mehreren Südeuropäischen Standorten berechnet mit dem PVGIS Online-Tool [3] [4]*

Lokalität	Geografische Breite	Gewinn [%]
Zürich, CH	47°22'	24%
Genova, It	44°24'	31%
Barcelona, Sp	41°23'	33%
Valencia, Sp	39°27'	31%
Malaga, Sp	36°43'	36%
Tunis, Tu	36°49'	33%
Nadur, Malta	36°20'	36%

Aufgrund der Tatsache, dass die grösste Verstärkung am Morgen und am Abend erreicht wird, sollten Tracker nicht zu nahe beieinander platziert werden, um eine gegenseitige Verschattung zu verhindern.

Solar Skilift Tenna

Schema und Messkonzept am Solarskilift in Tenna

Der weltweit erste Solarskilift wurde am 17.12.2011 in Tenna (GR) in Betrieb genommen Er ist mit einer 60kW Anlage ausgerüstet und wird durch ein einachsiges SolarWingsTrackersystem angetrieben. Dieser Skilift ersetzt einen alten Skilift, welcher am gleichen Standort demontiert wurde.

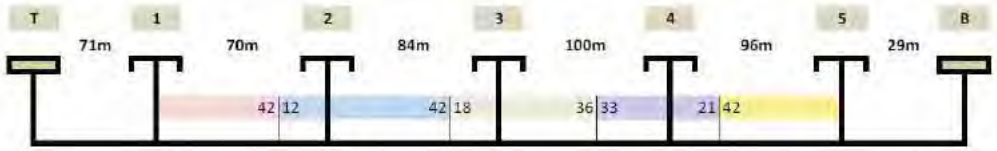
Die Messeinrichtung misst den Ertrag des Wechselrichters, welcher den String um den Mast 2 bewirtschaftet. Gleichzeitig wird der Gesamtverbrauch gemessen, welcher für diese Auswertung allerdings keine Relevanz hat. Eine technische Übersicht der PV-Anlage ist der Abbildung 1 zu entnehmen.

Übersicht

Anzahl Wings:	82		Masse Wing:	
Module pro Wing:	3		Masse Modul:	99.2 x 1640 x 50 mm
Anzahl Module:	246		Gewicht Modul:	21 kg
Modultyp:	HBS-245-60-6-012	**245** W		
DC-Nennleistung:	60.3 kW			

Modulaufteilung pro Abschnitt

Abschnitt	A	B	C	D	E	F
Anzahl Wings	0	18	20	23	21	0
Anzahl Module	0	54	60	69	63	0
Leistung [kW]	0	13.2	14.7	16.9	15.4	0



	Mast	Typ	Anz. Module	P-DC$_n$ [W]	P-Ac$_n$ [W]	Anzahl Strings	Module / String	
Wechselrichter 1	1	Siemens PVM10	42	10'290	10'000	3	14	WR Talstation
Wechselrichter 2	2	Siemens PVM13	54	13'230	12'400	3	18	WR Talstation
Wechselrichter 3	3	Siemens PVM13	54	13'230	12'400	3	18	WR Talstation
Wechselrichter 4	4	Siemens PVM13	54	13'230	12'400	3	18	WR Bergstation
Wechselrichter 5	5	Siemens PVM10	42	10'290	10'000	3	14	WR Bergstation
Total			**246**	**60'270**	**57'200**			

***Abbildung 1**: Technische Übersicht der PV-Anlage Quelle: Hassler Energia Alternativa AG*

Design und Funktionen: Ein-Achsiges-Tracking

***Abbildung 2**: Solarskilift Tenna. Quelle: Genossenschaft Skilift Tenna*

Aktuelle PV-Tracking-Systeme erfordern üblicherweise 200kg schwere Tragpfeiler aus Metall (Stahl oder Aluminium), um die Windlast-Anforderungen zu erfüllen [4]. Der Solar Wings-Ansatz nutzt dagegen Kabel, um die Module zu befestigen und erfüllt damit die Windlast Anforderungen mit weit weniger Stahl.

Wie in Baumgartner et. al [4] erläutert, profitieren Solar Wings-Tracking-Systeme davon, dass Kabel von mehreren 100 Metern Länge montiert werden können. Die Solarmodule hängen mehrere Meter über dem Boden. In Standard-Anwendungen wie Skilifts und Seilbahnen, werden die Kabel als kostensparende Lösung verwendet, wobei dem Kunden trotzdem höchste Zuverlässigkeit und Sicherheit garantiert werden können. Wie in Abbildung 2 dargestellt ist, werden die PV-Module tragenden Elemente auf Tragseilen montiert. Somit ist es nicht notwendig, im Abstand von einigen Metern, Pfeiler in den Boden zu treiben, wie es oft für PV Trackern der Fall ist.

Die Fundamente der Stützen müssen allerdings wegen der Windlast deutlich massiver ausfallen als bei einem Skilift ohne Photovoltaikmodule der gleichen Grössenordnung.

Eigenschaften von Solar Wings [4]:

- Weniger als 100 kg Stahl, um 1 KW-PV-Leistung in ein-oder zweiachsiger-Konfiguration nachzuführen.
- Vorhandene Trag-Kabel tragen die elektrische DC-Verkabelung, es braucht also keine Kabelschächte für die DC-Leitungen bis zu den Zwischenstützen.
- An den Zwischenstützen werden die DC-Leitungen im Boden der Berg oder Talstation zugeführt.
- PV-Modul-Höhe über dem Boden ist wählbar, typisch sind 4m, und bietet somit eine inhärente Sicherheit, Diebstahlschutz.
- Duale Nutzung der Fläche unterhalb der PV-Anlage für Skibetrieb oder landwirtschaftliche Verwendung möglich.

Abbildung 3: *Detail Zwischenstütze Solarskilift Tenna. Quelle: Genossenschaft Skilift Tenna*

Technische Merkmale des Tracking-Systems aus [4]:

- Möglicher Drehwinkel: +/-60 °
- Ein Drei-Phasen-Wechselstrom-Motor um die 60kW Module nachzuführen
- SPS übernimmt die zeitgesteuerte Nachführung
- Sensoren: Wind, Temperatur, Schnee, Kraft
- Automatische Anpassung der Panelausrichtung bei hohen Windlasten
- Automatische Anpassung der Panelausrichtung bei Schneefall

Kosten

Die Investitionskosten einer Photovoltaik-Anlage liegen im Vergleich mit einer Aufdachanlage höher, da die Fundamente für die Stützen des Skilifts aufgrund der Wind und Schneelast der Module deutlich massiver sein müssen. Dies widerspiegelt sich vor allem in den Kosten für die Fundamente (Tabelle 2). Bei einer Wirtschaftlichkeitsberechnung der Anlage müssten diese zusätzlichen Kosten ebenso wie der höhere Ertrag in Betracht gezogen werden.

***Tabelle 2**: Mehrkosten Solar-Skilift Tenna gegenüber zu einem herkömmlichen Skilift*

Bauteil	Solarskilift	Regulärer Skilift
Fundamente	CHF 250‘000.-	CHF 90‘000.-
Stützen, Seile	CHF 40‘000.-	CHF 30‘000.-
PV-Module	CHF 260‘000.-	

Resultate nach einem Jahr Betrieb (Dezember 2011 –Dezember 2012)

In der Theorie geht man davon aus, dass einachsig nachgeführte System einen Ertragsvorteil von bis zu 30% haben können [5]. In Tenna wurde im ersten Jahr ein Mehrertrag von 48% gegenüber einer Anlage ohne Nachführung gemessen [6].

Dies ist einerseits damit zu erklären, dass die Anlage weitestgehend von Schnee freigehalten (etwa 13% des Mehrertrags) werden kann und andererseits die Anlage aufgrund der Nachführung stärker vom Albedo-Effekt der Schneedecke profitieren kann (etwa 5% des Mehrertrags). Es ist anzumerken, dass die Referenzanlage über die Möglichkeit verfügt, den Schnee elektrisch zu entfernen (Module werden während etwa 6 Stunden beheizt) wovon in der Messperiode regelmässig Gebrauch gemacht wurde.

Es ist daher davon auszugehen, dass eine Anlage in der gleichen Region, die nicht mit dieser Möglichkeit ausgestattet wurde, deutlich kleinere Erträge erwirtschaften würde als die Referenzanlage.

Tabelle 3: *Vergleich zwischen nachgeführter und nicht nachgeführter Anlage am gleichen Standort bezogen auf 1 kWp normiert*

Vergleich Solarskilift - nicht nachgeführte Anlage am gleichen Standort bezogen auf 1KWp (normiert)													
	Dez 11	Jan 12	Feb 12	Mrz 12	Apr 12	Mai 12	Jun 12	Jul 12	Aug 12	Sep 12	Okt 12	Nov 12	Dez 12
Solar-Skilift	165%	178%	170%	161%	141%	132%	131%	129%	128%	136%	147%	158%	160%
Referenzanlage	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Mehrertrag	65%	78%	70%	61%	41%	32%	31%	29%	28%	36%	47%	58%	60%

Die nachgeführte PV-Module des Solarskilifts erhöhen den Ertrag im Vergleich zu einer festinstallierten Anlage, je nach Jahreszeit, bis zu 78% (vgl. Tabelle 3). Dies wird auf die fehlende Schneebedeckung, die hohen Reflexionswerte der Schneedecke vor allem am Morgen und am Abend zurückgeführt. Nach dem Monat Januar nimmt dieser hohe Wert ab und geht nach der Schneeschmelze auf etwa 34% zurück. So ist es möglich auch im Winter in den Alpen hohe PV-Erträge zu generieren was üblicherweise als ein systemisches Problem der PV in schneebedeckten Regionen gilt.

Der durchschnittliche Mehrertrag für das gesamte Jahr 2012 liegt bei über 48%. Es werden weiterhin Messungen durchgeführt.

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DISTRIBUTION GRID ANALYSIS AND SIMULATION WITH PHOTOVOLTAICS (DIGASP)

SIMULATION APPROACH TO INVESTIGATE THE IMPACT OF DISTRIBUTED POWER PRODUCTION WITH PV ON A POWER GRID

Annual Report 2012

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Project- / Contract Number	SI/500549 / SI/500549-01
Duration of the Project (from – to)	01.09.2010 – 31.12.2012 (request for extension until December 2013)
Date	14.12.2012

ABSTRACT

The project “Distribution Grid Analysis and Simulation with Photovoltaics (DiGASP)” (former name “distributed PV generation") investigates the technical impact of distributed PV power production on low- and medium voltage grids. The main questions to be answered in this task are the following:

- How much PV can be fed in the power grid at a certain point?
- What are the restrictions for feeding in PV power, and how can they be mitigated?
- What effects can be expected, if certain modifications are applied to the distribution power grid (such as active / reactive power control, energy storage, tap changing transformers, active load control, …)

By modelling the grid with adequate algorithms for PV, these questions shall be answered, and in a second step, be adapted to the distribution grid of ewz Zürich.

Given the results of this project, a distribution system operator (DSO) should know the possibilities and limits of its grid concerning distributed feed-in of PV, and have a guideline / method where to place future investments in order to strengthen its grid for PV.

In 2012, the project made relevant progress in the following fields:

- First simulation results and conclusions
- Publication of load profile generator and Simulation Framework
- Start of measurement project in Zurich

Einleitung

Dieses Projekt wird im Rahmen des PV$^+$ Grid Calls des PV ERA NET mit den Projektpartnern *Austrian Institute of Technology* und der *Universität Oldenburg* durchgeführt. Ein besonderes Gewicht hat deshalb der Wissenstransfer zwischen den beteiligten Institutionen: Dank der internationalen Kooperation wird ein Mehrwert für das Projekt angestrebt, der bei der rein nationalen Projektbearbeitung nicht erreicht werden könnte.

Das Projekt bildet zudem den Beginn und einen integralen Bestandteil der Dissertation des Projektleiters. Die enge Zusammenarbeit mit dem Institut für *Elektrische Energieübertragung und Hochspannungstechnik (EEH)* der Abteilung für *Informationstechnologie und Elektrotechnik (D-ITET)* der *ETH* ist somit ein weiterer Pfeiler für das Projekt.

Projektziele

Die wesentlichen Ziele des Projekts sind die detaillierten und fundierten Antworten auf folgende Fragen:

- Wie gross ist die PV-Leistung, die in ein bestimmtes Verteilnetz eingespeist werden kann?
- Welches sind die Limitierungen für die Einspeisung von PV in ein Verteilnetz, und wie können diese beeinflusst werden?

Die Beeinflussung der physischen Einspeisebegrenzungen ist dabei ein wichtiges Thema. Es soll untersucht werden, mit welchen Massnahmen welche Effekte erzielt werden können. Folgende Massnahmen stehen heute zur Diskussion:

- Berücksichtigung von Korrelation zwischen Last und Einspeisung
- Blindleistungsregelung am PV-Wechselrichter
- Wirkleistungsregelung am PV-Wechselrichter (Abregelung der Wirkleistung)
- Verwenden eines Stelltransformators als Ortsnetztransformator
- Ausrichtung der PV-Analgen variieren
- Dezentrale Speicher
- Demand Side Management (Algorithmus von vorangehender Dissertation ETH)

Die Roadmap beschreibt das geplante weitere Vorgehen im Projekt.

Termin	Arbeitsschritt	Verantwortlich	Dokumentation
Dez 12 / Jan 13	Jahresberichte BFE / PV ERA NET	B & H	Bericht
Feb 13	Analysis Temp. Resolution	B & H	Paper
Mai 13	Simulationsresultate Modellnetz	B & H	Bericht
2013	Paper P(U) Q(U)-Regelung	AIT	Paper
2013	Paper Meteodatengenerator	Uni Oldenb.	Paper
Okt 13	Case Studies	B & H	Kurzbericht
Sep 13	Publikation Resultate PVSEC	B & H	Paper
...	Publikation Teilergebnisse an Konferenzen / in Journals		Paper
2013	Workshop / Meeting mit weiterem Netzbetreiber	B & H	Protokoll / Bericht
Dez 13	Bericht Messprojekt ewz	B & H	Bericht
Dez 13	Schlussbericht DiGASP	B & H	Bericht

Durchgeführte Arbeiten und erreichte Ergebnisse

Die hier vorgestellten bisher durchgeführten Arbeiten konzentrieren sich auf die Arbeiten von Basler & Hofmann. Die folgende Liste stellt die Meilensteine der durchgeführten Arbeiten vor:

Lastprofilgenerator

Der Lastprofilgenerator wurde im Jahresbericht 2011 vorgestellt und im Sommer 2012 publiziert [1].

Simulation Framework

Das Simulation Framework wurde im Jahresbericht 2011 kurz vorgestellt und im Herbst 2012 publiziert [2]. Abb. 1 zeigt ein Flussdiagramm des Frameworks.

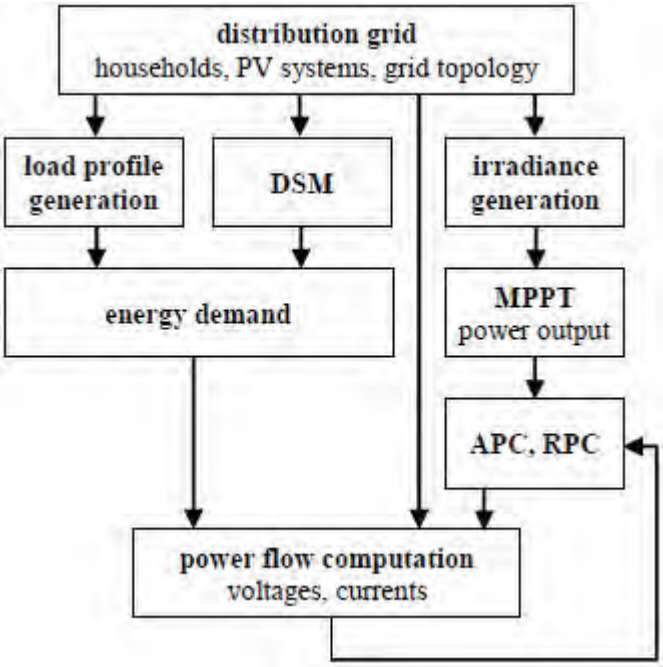

Abb. 1: *Flussdiagramm des Simulation Frameworks.*

Granularität Lastprofile

Mangels guter Referenzen in der Literatur wurde anhand öffentlich zugänglicher Lastmessungen mit Sekundenauflösung die Effekte der Granularität (Sampling Rate) von Lastmessungen untersucht. Die Inhalte wurden im Jahresbericht 2011 kurz vorgestellt und werden voraussichtlich an der Power Tech 2013 in Grenoble publiziert.

Simulationsresultate

Eine Reihe von Simulationsresultaten konnte im Jahr 2012 erarbeitet werden. Diese werden im kommenden Jahr verifiziert und breiter abgestützt. Die Abbildungen Abb 2. bis Abb. 4 zeigen eine kleine Auswahl der Ergebnisse.

Für die Ergebnisse wurden meist 1-Jahressimulationen mit Minutendaten gemacht, Abb. 4 basiert auf Stundenmittelwerten.

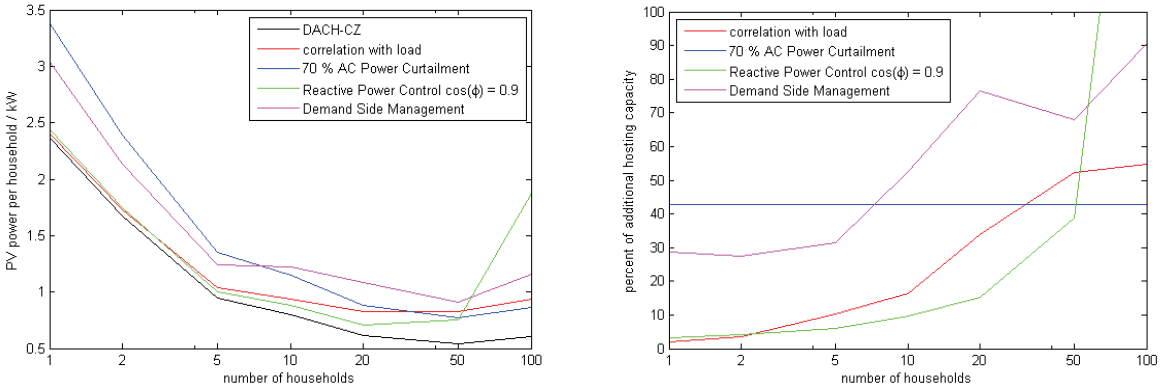

Abb. 2: *PV Hosting Capacity (Fassungsvermögen für PV) einer Stichleitung mit fünf Knoten. An jedem Knoten sind n Haushalte angeschlossen, wobei n in der x-Achse abgebildet ist. Die Stichleitung ist so dimensioniert, dass Sie die Haushaltslasten gerade noch versorgen kann.*

Links: Absolute PV Hosting Capacity für verschiedene Annahmen / Szenarien.

Rechts: Zusätzliche PV Hosting Capacity in Prozent, Referenz sind die DACHCZ-Richtlinien [3].

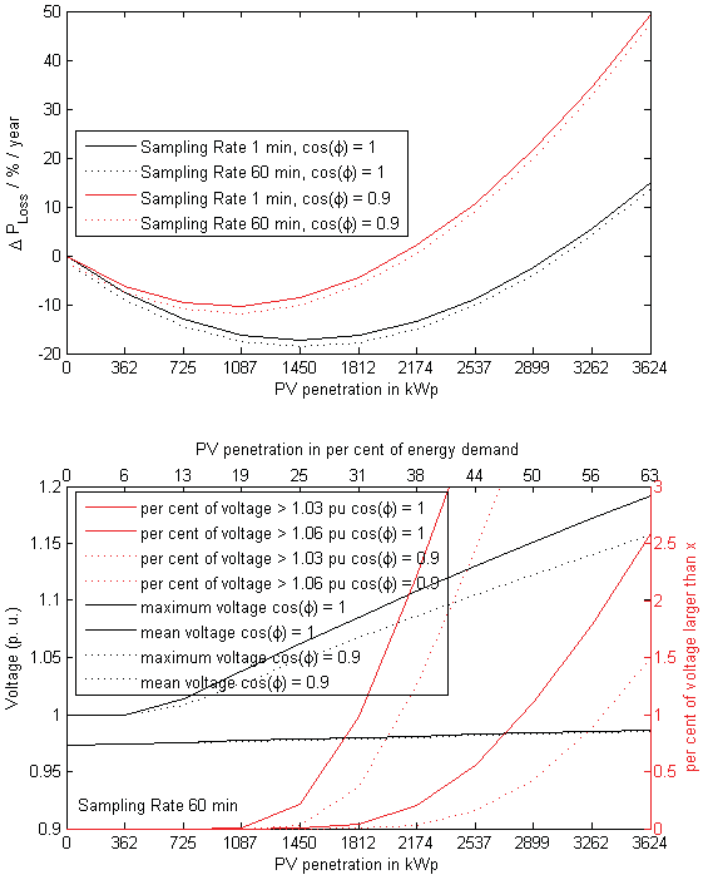

Abb. 3: *Resultate aus einer Fallstudie in Zürich (NS-Netz an 2x1000 kVA Transformator).*

Oben: Netzverluste sinken bei zunehmender PV-Einspeisung, steigen bei weiter erhöhter Einspeisung aber wieder an.

Unten: Spannungserhöhung bei zunehmender PV-Einspeisung

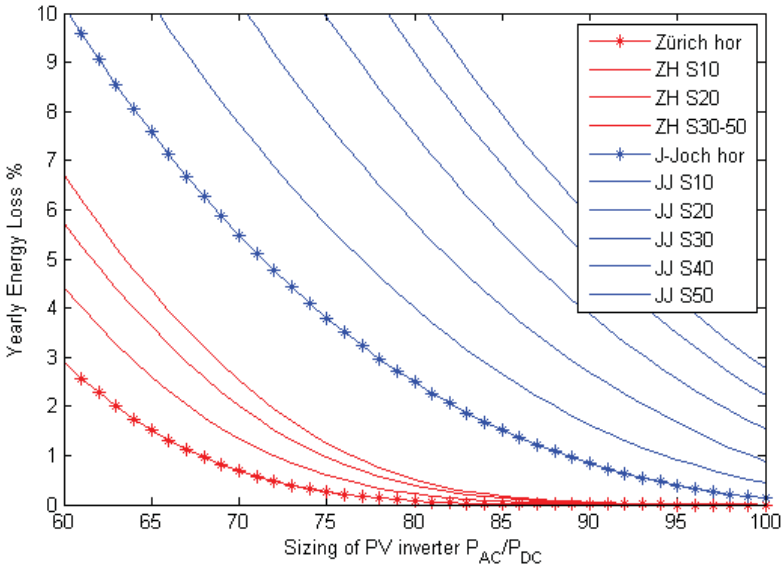

Abb. 4: *Energieverlust durch Unterdimensionieren des Wechselrichters für die Standorte Zürich und Jungfraujoch bei verschiedenen Modulneigungswinkeln. Beträgt für eine Beispielanlage in Zürich (Südausrichtung, Neigungswinkel 10°) die Wechselrichterleistung nur 75% der Modulleistung, ist der Energieertragsverlust wegen dem zu kleinen Wechselrichter immer noch kleiner 1%.*

Präsentationen

An verschiedenen Stellen wurden Teilresultate dieses Projekts vorgestellt:

- Nationale PV-Tagung 2012 in Baden (www.swissolar.ch)
- Drei Energieaperos 2012 des Kantons Aargau (Baden, Lenzburg und Aarau) (www.energieaperos-ag.ch)
- IEEE PES-Workshop in Bern (www.ieee.ch/chapters/pes)

Nationale Zusammenarbeit

Nationaler Austausch und nationale Zusammenarbeit hat insbesondere mit der ETH Zürich und dem ewz stattgefunden.

ETH Zürich

Die ETH übt mit Professor Andersson (Institut EEH - Power Systems Laboratory) die wissenschaftliche Betreuung der Arbeit aus. Intensiver Austausch besteht mit den Doktoranden des Instituts.

EWZ (Elektrizitätswerk der Stadt Zürich)

Nebst der kontinuierlichen Unterstützung im Rahmen von Korreferaten und Rückmeldungen zu aktuellen Projektresultaten hat das ewz einer Messkampagne zur Charakterisierung von Haushaltslastdaten zugestimmt. Das angekündigte Messprojekt konnte im November 2012 gestartet werden. Die Verbrauchsdaten von 55 Haushalten werden in 1-Minuten-Schritten ausgelesen und künftig für die Netzsimulationen verwendet.

Internationale Zusammenarbeit

Internationale Zusammenarbeit besteht mit den Projektpartnern (Universität Oldenburg und Austrian Institut of Technology) sowie mit dem Konsortium des IEA PVPS Task 14.

Universität Oldenburg (Projektpartner PV-ERA.NET)

Die Universität Oldenburg hat im Jahr 2012 einen Generator für stochastische Einstrahlungsdaten programmiert. Die Arbeiten sind weitgehend abgeschlossen und sollen im kommenden Jahr publiziert werden. Die generierten Einstrahlungsprofile werden in den Simulationen dieses Projekts verwendet.

Austrian Institute of Technology Ait (Projektpartner PV-ERA.NET)

Aufgrund von administrativen Verzögerungen konnte das AIT erst gegen Ende 2012 mit den Projektarbeiten beginnen. Vorgesehen sind folgende Beiträge:

- P(U) und Q(U)-Regelung: Stabilitätsbetrachtungen
- Verifizierung einer Case Study mit DigSilent

Bewertung 2012 und Ausblick 2013

Rund 2/3 der Projektarbeiten sind abgeschlossen. Während der meteorologische Teil weitgehend erfüllt ist, sind im Bereich Regelung noch einige Punkte offen.

Grundsätzlich wurde im Jahr 2012 die Basis für die Netzsimulationen gelegt, so dass im 2013 der Fokus auf der Erzeugung von Simulationsresultaten liegt.

Für das Jahr 2013 ist insbesondere Folgendes zu erreichen:

- Präsentieren eines Lösungsansatzes für die Q(U) und P(U)-Regelung
- Präsentieren des Meteodatengenerators
- Präsentieren diverser Simulationsresultate
- Durchführen zweier Case-Studies

Insgesamt liegt das Projekt wegen administrativen Verzögerungen rund anderthalb Jahre hinter dem Zeitplan. Ein Gesuch um Verlängerung wurde gestellt, der Projektabschluss ist neu für 2013 geplant.

Referenzen

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[2] Christof Bucher et al., **Simulation of Distribution Grids with Photovoltaics by Means of Stochastic Load Profiles and Irradiance Data,** Frankfurt, PVSEC 2012

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Internationale Koordination

P. Hüsser
Schweizer Beitrag zum IEA PVPS Programm, Task 1 – SI/400735 / SI/400735-01 **265**

R. Frischknecht, R. Itten, K. Flury
Schweizer Beitrag zum IEA PVPS Programm, Task 12 – SI/500738 / SI/500738-01 **270**

T. Nordmann, L. Clavadetscher
Schweizer Beitrag zum IEA PVPS Programm, Task 13 – IEA PVPS Pool 2012.01 **276**

P. Renaud, L. Perret, J. Fahrni
Swiss contribution to IEA PVPS, Task 14 – **High penetration of PV systems in electricity grids** – IEA PVPS Pool II 2011.01 **282**

J. Remund
Swiss contribution to IEA SHC, Task 46 – Solar resource assessment and forecasting – SI/500184 / SI/500184-05 **289**

P. Toggweiler, T. Hostettler
Normierung für PV-Systeme – SWISSOLAR 17967 **296**

S. Nowak, M. Gutschner
PV ERA NET: Networking and integration of national and regional programmes in the field of photovoltaic (PV) Solar energy research and technological development (RTD) in the European research area (ERA) – PV ERA NET / CA-011814 **304**

S. Nowak, M. Gutschner
SOLAR-ERA.NET: ERA-NET on solar electricity for the implementation of the solar Europe industry initiative – SOLAR-ERA.NET / EC FP7 321571 **308**

S. Nowak, A. Mastronardi, S. Gnos, N. Guthapfel
REPIC: Swiss Interdepartmental Platform for Renewable Energy and Energy Efficiency Promotion in International Cooperation – SECO UR-00123.03.01 **312**

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SCHWEIZER BEITRAG ZUM IEA PVPS PROGRAMM, TASK 1

Annual Report 2012

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Project- / Contract Number	SI/400735 / SI/400735-01
Duration of the Project	01.01.2012 – 31.12.2012
Date	28.04.2013

ABSTRACT

The Swiss contribution to the PVPS Programme includes:

- National Survey Report, a summary of developments in the market and political areas. The report's data is integrated into the IEA's Trends in Photovoltaic Application Report
- Targeted search for new contacts in the PV area, maintain a network of contacts.
- Contributions/organizations to/of national and international workshops
- PR-work in Switzerland. Reference to the programme's international publications.
- Providing information for government, industry and media about the global development of PV

The results of these activities include:

- National Survey Report (NSR) based on the statistics provided by the Swiss Association of Solar Professionals.
- 2 Task 1 meetings in Stockholm (S) and Aarhus (DK)
- 3 Workshops in Stockholm, Frankfurt and Hangzhou (China)
- Webmastering support for www.iea-pvps.org

Ongoing work:

- Workshop organization for the PV conferences in Paris (Okt. 2013) and Taiwan (Nov. 2013)
- Participation at Task 1 Meetings in Vienna (February) and Korea (November)
- Input for the new "Snapshot"-Trends Report
- National survey report 2012

Kurzbeschrieb des Projekts

Task 1 unterstützt die generelle Strategie des PVPS Programmes (Kostenreduktion, Potenzial erfassen, Barrieren beseitigen, Kooperation mit Nicht-IEA-Ländern) mit folgenden Produkten:

- PV POWER Update, seit April 2009 erscheinender E-Newsletter. 2 Ausgaben in 2012
- Trends Report (Trends in Photovoltaic Applications, Survey report of selected IEA countries Between 1992 and 2011), ein Jahresbericht zur Markt- und Technologie-Entwicklung der dem Programm angeschlossenen Länder
- Reports und Workshops zu spezifischen Themen der Photovoltaik
- Eigene Programm-Homepage unter www.iea-pvps.org

Ziel ist es, die identifizierten Zielgruppen (Regierungen, EW's, Industrie, Forschung usw.) mittels qualitativ hochstehenden Produkten zu informieren.

Der Schweizer Beitrag innerhalb des PVPS Programms (Task 1) konzentriert sich auf folgende Schwerpunkte:

- National Survey Report [1], eine Zusammenstellung der Marktentwicklung und des politischen Umfeldes in der Schweiz. Diese Daten werden im Trends Report [2] zusammengefasst und publiziert.
- Organisieren von Schweizer Beiträgen in PV Power sowie Mitarbeit im Editorial Board.
- Bewerbung der Anmeldemöglichkeit für den E-Newsletter (als Ersatz für die gedruckte Version)
- Gezielte Suche nach weiteren Kontakten innerhalb der Zielgruppe
- Beiträge an Workshops und Konferenzen auf nationaler und internationaler Ebene
- Organisation von Workshops
- Medienarbeit in der Schweiz: Hinweise auf internationale Publikationen des Programms, Publizieren von Marktstatistiken
- Unterstützung des ExCo beim Internetauftritt

National Survey Report NSR

Der NSR bildet die Grundlage für den jedes Jahr erscheinenden "Trends Report". Als Basis für die Statistiken dienen die jährlichen Erhebungen des Sonnenenergie Fachverbandes Swissolar, ergänzt mit Daten der VSE-Statistik zu den netzgekoppelten PV-Anlagen. Die nachfolgende Tabelle gibt einen Überblick über die erhobenen Marktzahlen.

Auszug aus dem “National Survey Report”:
The cumulative installed PV power in 4 sub-markets

	Cumulative installed capacity as of 31 December 2011 (kW)																			
Sub-market	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Stand-alone domestic	1 540	1 675	1 780	1 940	2 030	2 140	2 210	2 300	2 390	2 480	2 570	2 740	2 810	2 930	3 050	3 200	3 800	4 000	4 200	4 400
Stand-alone non-domestic	70	100	112	143	162	184	190	200	210	220	230	260	290	320	350	400				
Grid-connected distributed	2 200	2 900	3 600	4 050	4 850	5 950	7 630	9 420	11 220	13 340	15 140	16 440	18 440	21 240	23 740	30 040	41 540	67 040	104 140	206 700
Grid-connected centralised	900	1 100	1 200	1 350	1 350	1 450	1 470	1 480	1 480	1 560	1 560	1 560	1 560	2 560	2 560	2 560	2 560	2 560	2 560	
TOTAL (kW)	4 710	5 775	6 692	7 483	8 392	9 724	11 500	13 400	15 300	17 600	19 500	21 000	23 100	27 050	29 700	36 200	47 900	73 600	110 900	211 100

PV Power

PV Power update wurde im Berichtsjahr 2 Mal als elektronische Version versandt. Zusätzlich wurden 200 Exemplare für die EUPVSEC-Konferenz gedruckt und in Frankfurt verteilt.

Die Schweiz ist zuständig für den Versand des Newsletters an etwa 2500 Adressaten weltweit sowie an die nationalen Experten im Netzwerk.

Trends Report 1992-2011

Basierend auf den Daten des "National Survey Reports" wurde Ende Oktober 2012 der Trends Report publiziert. Zeitgerecht konnten die wesentlichen Tabellen zu Beginn der Europäischen PV-Konferenz in Hamburg auf dem Internet aufgeschalten werden. Die gedruckte Ausgabe wurde Anfang November ausgeliefert.

Die wichtigsten Daten aus dem Report sind im Internet unter www.iea-pvps.org [3] einsehbar. Der ganze Report wie auch einzelne Tabellen können als PDF-Dokumente heruntergeladen werden.

Workshops

Task 1 war insgesamt an 3 Workshops beteiligt. 2 davon wurden in Eigenregie organisiert. Wie in den Vorjahren war die Schweiz hauptverantwortlich für den EUPVSEC-Workshop, Japan organsierte den asiatischen Workshop, dieses Mal in China.

Utility Activities within Photovoltaics, April 19th, 2012, Stockholm, Sweden

Die Kombination von Task 1 Meetings mit einem nationalen Workshop war wiederum sehr erfolgreich. Der Schwedische Task1-Vertreter organisierte diesen Workshop mit sehr guter Beteiligung schwedischer Energieversorgungsunternehmen und Installateuren.

Assigning a fair price to photovoltaic electricity, Frankfurt Germany, Sept. 27th 2012

Interessierte Workshopbesucher bekamen einen Überblick über die laufenden Diskussionen zu den Themen Netmetering, Netzbelastung und Wandel in der Art der Stromversorgung. Der Wert der Photovoltaik in diesem Umfeld wurde rege diskutiert.

IEA PVPS Workshop at PVSEC 22, Hangzhou, China, Nov. 6th, 2012

In Kombination mit der asiatischen PV-Konferenz und unter Ausnutzung des gleichzeitig stattfindenden ExCo-Meetings konnte ein attraktiver Workshop – Programm zusammengestellt werden. Ziel war es, vor allem chinesische Akteure mit den Dienstleistungen und Publikationen von IEA-PVPS bekannt zu machen und neue Kontakte zu knüpfen.

Konferenzen

EUPVSEC Frankfurt: Posterpräsentation der Resulate des Trends Reports 2011. Zusätzlich wurden für den PVPS-Stand (innerhalb des EPIA-Standes) Flyer mit den neusten Resultaten des Trends Reports aufgelegt. Der PVPS-NL wurde in einer gedruckten Version (200 Exemplare) ebenfalls abgegeben.

PVSEC22 in Hangzhou, China: Orale Präsentation [5] zum Trends Report 1992 – 2011. Zusätzlich Workshop (siehe oben).

PR und Networking

Mit-Organisation der Schweiz. Photovoltaik-Tagung 2012 von Swissolar in Baden. Mitglied des Programm-Komitees.

Leitung der Kommission Photovoltaik des Branchenverbandes Swissolar.

Der direkte Draht zu den Swissolar-Mitgliedern ermöglicht auch das direkte Abrufen von spezifischen Informationen zum PV-Markt in der Schweiz.

Bewertung 2012 und Ausblick 2013

Task 1 war 2012 stark involviert in die Diskussion zur strategischen Ausrichtung von PVPS. Für das ExCo ist Task 1 wichtig für die Definition der Strategie und Taktgeber für neue Impulse.

Diese Diskussionen haben die interne Task1-Diskussion stark geprägt aber auch wertvolle neue Ideen für die zukünftige Stossrichtung des Programmes gebracht.

Vertiefte Diskussionen fanden zum Thema Netmetering als mögliche Ablösung für die Kosten deckende Einspeisevergütung (Feed in Tariff) statt. Diese Diskussionen werden in 2013 innerhalb einer neuen Subtask weiter geführt.

Im Herbst 2012 wurde beschlossen, bereits im März 2013 eine erste Veröffentlichung zu der Marktzahlen 2012 zu machen (Baby Trends).

Ziel ist auch, den Trends Report etwas früher als bisher zu publizieren.

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IEA-PVPS TASK 12: SWISS ACTIVITIES IN 2012

ÖKOBILANZEN VON SOLARSTROM

Annual Report 2012

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Project- / Contract Number	SI/500738 / SI/500738-01
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Date	11.12.2012

ABSTRACT

Life cycle assessment (LCA) is an environmental management tool for analysing, comparing and improving the environmental impacts of products or technologies. The ecoinvent database provides life cycle inventory data for currently more than 4000 unit processes. Amongst other datasets, photovoltaic life cycle inventory data are provided.

Within the Swiss contribution to the *IEA PVPS Task 12, subtask 2*, the dataset of ethylene-tetrafluoroethylene (ETFE) was updated. The consideration of latest emission figures of the concerned industry results in a significant reduction of the environmental impacts in the ETFE production.

Furthermore, an LCA of Flexcells a-Si-laminates produced by the Swiss manufacturer VHF-Technologies SA was established and published. It is shown, that, from an environmental point of view, these laminates are among the most favourable photovoltaic technologies. This is due to the small amount of materials needed and the non-use of a mounting system, since the modules are integrated in roof systems and facades.

The work on the LCA on µc-Si modules of a TEL Solar AG was completed and the publication of the inventories and results was approved.

The investigation of PV recycling started in 2011. However, due to delays in the supply of information from one manufacturer and due to the stop of the recycling activities of the other manufacturer, the LCI of PV recycling could not be completed yet.

Within another BFE commissioned project, LCI data on important PV technologies were updated in view of the new national energy strategy 2050. This covers the production of crystalline modules and their feedstock with Chinese electricity and new developments with regard to material efficiency, material origin, and electric module efficiency.

Einleitung / Projektziele

Ökobilanzen sind ein Umweltmanagement-Werkzeug, um die Umweltauswirkungen von Produkten und Technologien zu analysieren, zu vergleichen und zu verbessern. Eine wesentliche Grundlage für Ökobilanzen sind Sachbilanzdaten, welche die Energie- und Massenflüsse über die verschiedenen Lebensphasen des zu untersuchenden Objektes beschreiben. Die ecoinvent Datenbank stellt zurzeit solche Sachbilanzdaten für mehr als 4'000 Einheitsprozesse bereit [1]. Diese Daten werden in allen bedeutenden Ökobilanz-Softwareprodukten angeboten und von über 4'500 Nutzern in über 40 Ländern weltweit verwendet.

Die letzte Aktualisierung der Photovoltaik(PV)-Sachbilanzdaten im Rahmen der ecoinvent Projekte wurde im Frühjahr 2009 durchgeführt [2-4]. Die Sachbilanzdaten im ecoinvent Datenbestand v2.2 beschreiben die Situation der amerikanischen und europäischen PV-Industrie sowie die Anwendung von 3 kWp PV-Anlagen auf Gebäuden in der Schweiz und in Europa im Jahr 2005.

Da sich der PV-Sektor rasch weiterentwickelt und signifikante Verbesserungen verschiedener PV-Systeme erreicht wurden, ist es von Interesse, diese Änderungen auch in den Sachbilanzdaten abzubilden.

Im Rahmen der *IEA PVPS Task 12, Subtask 2* werden verschiedene PV-Ökobilanz-Projekte durchgeführt. Die Schweizer Projektpartner aktualisierten im Jahr 2008 die Sachbilanzdaten zu Cadmiumtellurid-Modulen [5]. Sie stellten im Jahr 2009 neue Datensätze zu Freiflächen- und Photovoltaik-Grossanlagen für eine Implementierung in der ecoinvent Datenbank bereit [6]. 2010 wurden die Solarstrommixe in 26 Ländern aktualisiert sowie verschiedene Chemikalien und Materialien, die in der PV-Industrie verwendet werden, bilanziert [7]. 2011 wurde der Methodik-Leitfaden der Task 12 zu Ökobilanzen von Solarstrom überarbeitet, die Sachbilanzdaten für Ethylen-Tetrafluor-Ethylen (ETFE) erstmals aktualisiert und Sachbilanzdaten der Herstellung von a-Si-Laminaten einer Schweizer Firma erarbeitet [8].

Um die Wahrnehmung der Photovoltaik als umweltfreundliche Technologie aufrecht zu erhalten, sind seit zwei Jahren Bestrebungen im Gange ein Sammelsystem von Modulen nach dem Anlagerückbau zu etablieren und ein Recyclingsystem für die Photovoltaik-Module aufzubauen. Mit den von den Schweizer Projektpartnern der IEA-PVPS-Task 12 geplanten Arbeiten wird beabsichtigt, diese Entwicklung in den Ökobilanzdaten zu berücksichtigen.

Für das Jahr 2012 plante der Schweizer Projektpartner folgende Arbeiten durchzuführen:

- Erarbeitung von Sachbilanzdatensätzen zu Modul-Take-Back-Systemen und Modul-Recycling
- Erarbeitung von Sachbilanzdaten eines a-Si-Laminats eines Schweizer Herstellers und eines µC-Si-Moduls eines zweiten Schweizer Herstellers.
- Diskussion der Sachbilanzdaten mit IEA-PVSP Task 12 Projektpartnern.
- Planung und Vorbereitung der nächsten 4-Jahresperiode der IEA-PVSP Task 12

Die Verantwortung über die Inhalte und Publikation der Sachbilanzdaten liegt bei *treeze GmbH.* Es ist geplant, dass die Daten im Rahmen einer Aktualisierung des ecoinvent Datenbestands publiziert werden (verantwortlich: *ecoinvent Centre*). Das Review der 2009, 2010, 2011 und 2012 neu erstellten und überarbeiteten Datensätze durch das ecoinvent Zentrum ist hängig.

Kurzbeschrieb des Projekts / der Anlage

Das Ziel des Gesamtvorhabens, Subtask 2 innerhalb des Task 12, LCA, ist das Erarbeiten von aktuellen Sachbilanzdaten zur Stromerzeugung mit Photovoltaikanlagen. In Tabelle 1 sind die einzelnen Bereiche im Subtask 2 aufgelistet. Wesentliche Aktivitäten finden in den USA, der Schweiz und voraussichtlich China und Japan statt. Die Deutschen Institute äusserten sich vorsichtig oder waren am Task 12 Treffen nicht anwesend.

Tabelle 1: Neue Struktur der Aktivitäten im Subtask 2 des IEA-PVPS Task 12

	Subtask 2. LCA
2.1	LCA Methodology and Methodology Guidelines
2.2	LCAs of cristalline Silicon PV
2.3	LCA of thin film PV
2.4	LCAs of other PV systems
2.5	LCA of Materials, BOS, and Operation
2.6	LCA of Supply Chains
2.7	Data Management
2.8	Overall assessment of PV

Durchgeführte Arbeiten und erreichte Ergebnisse

Im Rahmen des Schweizer Beitrags zur IEA PVPS Task 12 wurden folgende Arbeiten im Jahr 2012 durchgeführt:

- Erneute Aufdatierung und Veröffentlichung des Sachbilanzdatensatzes für Ethylen-Tetrafluor-Ethylen (ETFE)
- Aktualisierung und Veröffentlichung von Sachbilanzdaten und Ökobilanzergebnissen von a-Si-Laminaten vom Typ Flexcell des Schweizer Herstellers VHF-Technologies SA.
- Erstellung und Aktualisierung von Sachbilanzdaten und Ökobilanzergebnissen von µc-Si Modulen eines Schweizer Herstellers. Die Daten wurden für einen Chinesischen Produktionsstandort modelliert.
- Präsentation der neusten Ökobilanzergebnissen zu einer chinesischen Produktionslinie an der 27. Europäischen Konferenz und Ausstellung zu Solarenergie (EU PVSEC) in Frankfurt (siehe Erarbeitung der Sachbilanzdaten unter Kapitel0) [9].

Sämtliche in den Jahren 2009, 2010, 2011 und 2012 erarbeiteten Sachbilanzdaten stehen Interessierten unter www.lc-inventories.ch kostenlos zum Download zur Verfügung. Die Daten werden in einem Datenformat zur Verfügung gestellt, welches den Import in alle gängigen Ökobilanz-Softwareprogramme erlaubt.

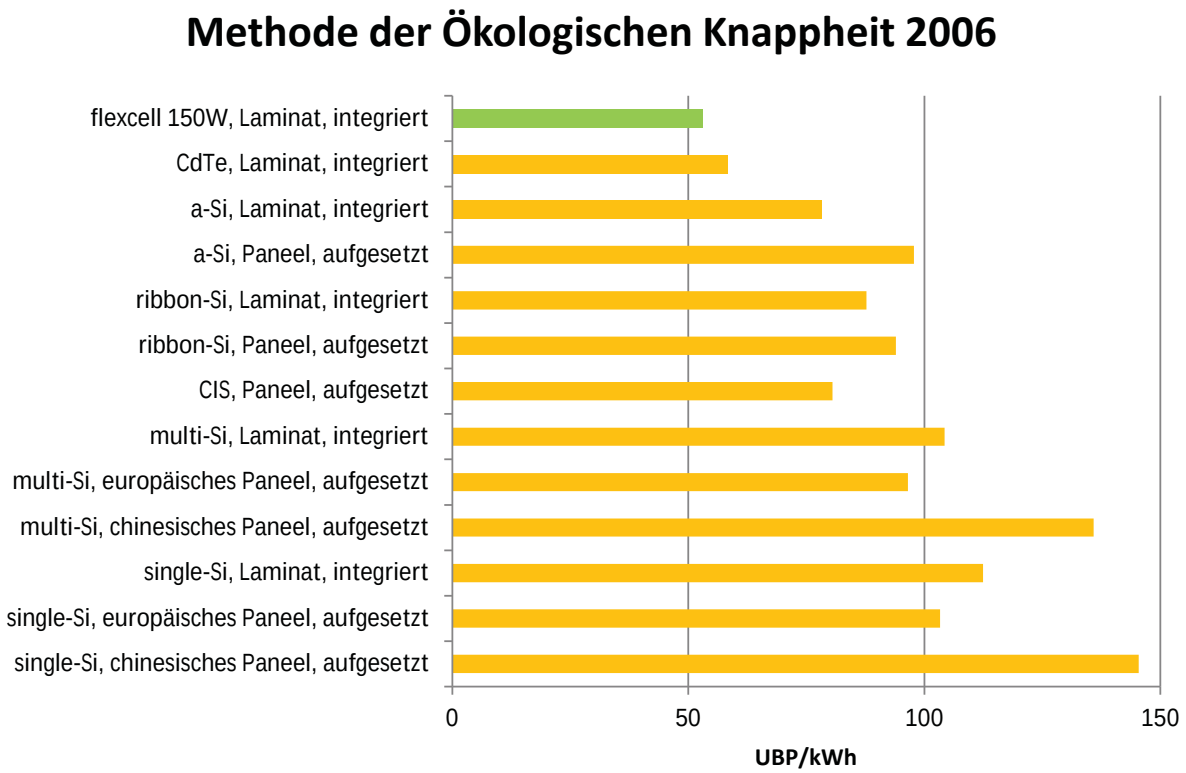
Aufgrund von Verzögerungen bei der Bereitstellung der nötigen Informationen, war es nicht möglich, die geplanten Arbeiten zur Erstellung von Sachbilanzdaten des Modulrecyclings durchzuführen. Die Datenbeschaffung ist nachwievor im Gange und erfolgt in einer Zusammenarbeit mit Parikhit Sinha (First Solar). Die Zusammenarbeit mit Sylke Schlenker (Sunicon) kann leider nicht fortgesetzt werden, da die Recyclingaktivitäten bei Sunicon gestoppt wurden. Die geplante Recycling-Pilotanlage wird nicht gebaut werden.

Sachbilanzinventar Ethylen-Tetrafluorethylen (ETFE)

Zu ETFE, welches in der Produktion der PV-Anlagen benötigt wird, wurde die Sachbilanz weiter aktualisiert. Der Treibhausgasausstoss in der Herstellung beträgt 87 kg CO_2-äq/kg ETFE. Der Carbon Footprint wird somit um gut zwei Drittel reduziert. Der nach wie vor hohe CO_2 Fussabdruck von ETFE steht im Zusammenhang mit fluorierten Kohlenwasserstoffen, welche bei der Herstellung der Rohmaterialien (Teflon) emittiert werden. Bei diesen Stoffen handelt es sich um hochwirksame Treibhausgase.

Sachbilanzinventar Flexcell A-Si Laminat

Die im Jahr 2011 erhobenen Sachbilanzdaten der Produktion von a-Si-Laminaten vom Typ Flexcell wurden 2012 aktualisiert, verfeinert und veröffentlicht [10]. Die Auswertung der Daten in Figur 1 zeigt, dass diese Technologie bezüglich der Umweltbelastungen im Vergleich mit anderen Technologien sehr gut abschneidet. Dies ist auf den geringen Materialverbrauch in der Produktion und in der Installation zurückzuführen. Die Treibhausgasemissionen betragen 27 gCO_2-äq./kWh.



Figur 1: *Umweltbelastungen von Solarstrom produziert mit einer Fotovoltaik-Flachdachanlage mit Flexcell-Modulen (grüner Balken), respektive Schrägdachanlagen mit verschiedenen Modulen (orange Balken). Bewertung mit der Methode der Ökologischen Knappheit 2006 [11]. 1'050 kWh/kW$_P$ Jahresertrag der Flexcell-Anlage und 922 kWh/kW$_P$ Jahresertrag der Anlagen mit anderen Technologien.*

Nationale / Internationale Zusammenarbeit

Auf nationaler Ebene erfolgt die Zusammenarbeit primär mit dem ecoinvent Zentrum, welches die Validierung der aktualisierten Datensätze übernehmen soll. Aufgrund der umfangreichen Anpassungsarbeiten an der ecoinvent Datenbank (inhaltlich und strukturell), war das ecoinvent Zentrum auch dieses Jahr nicht in der Lage, die bereitgestellten Daten zu validieren.

Der Sachbilanzdatensatz der flexiblen a-Si-Laminaten wurde in Zusammenarbeit mit dem Schweizer Hersteller VHF-Technologies SA bereitgestellt.

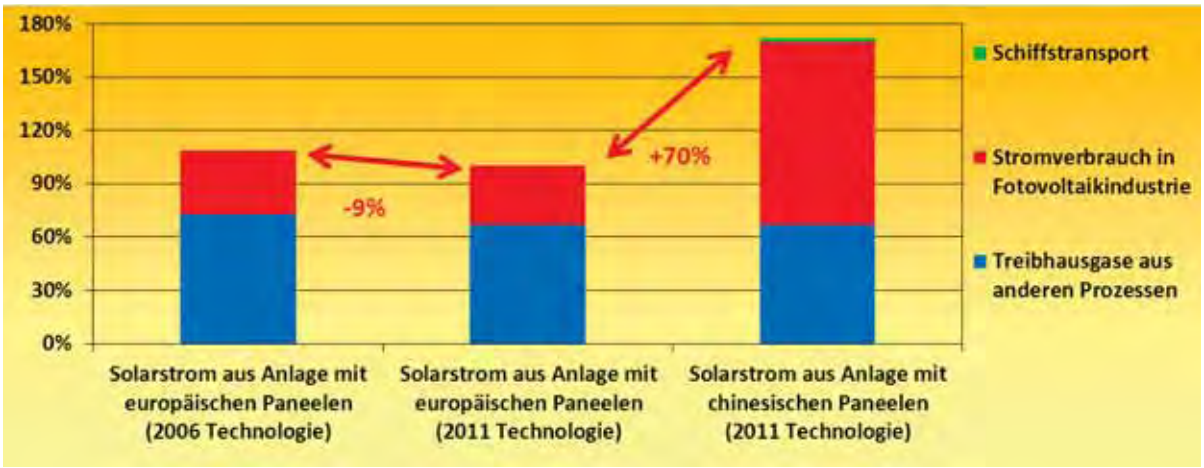
Die Erstellung von Sachbilanzdatensätzen zu mikromorphen Silizium PV-Modulen in Zusammenarbeit mit TEL Solar AG ist abgeschlossen.

In einem BFE Projekt im Zusammenhang mit der neuen Energiestrategie 2050 des Bundesrates wurden die Wertschöpfungsketten der wichtigsten PV Technologien aktualisiert [12, 13]. Dies umfasst insbesondere:

- Die Herstellung von kristallinen Modulen und deren Vorkette mit chinesischem Strommix
- Die Materialeffizienz und Materialherkunft von siliziumbasierten Modulen
- Der Wirkungsgrad verschiedener Photovoltaik-Modultechnologien
- Die Sachbilanzdaten der Herstellung von Cadmiumtellurid-Modulen der Firma First Solar in Deutschland, Malaysia und den USA

Auf internationaler Ebene fanden insbesondere Diskussionen zu den zukünftigen Arbeiten der *IEA PVPS Task 12* statt. Es wurde versucht, innerhalb von Subtask 2 die Ökobilanz-Aktivitäten besser zu strukturieren und zu bündeln. Erste Kontakte mit Vertretern Chinas konnten geknüpft werden. Wichtige Partner im Zusammenhang mit den geplanten Arbeiten zu Modul-Recycling sind Sylke Schlenker, Sunicon, Deutschland und Parikhit Sinha, First Solar, USA. Da die Recycling-Aktivitäten bei Sunicon verkauft wurden, können von dort keine Informationen mehr erwartet werden. Auch First Solar ist im Zusammenhang mit Recycling-Daten sehr zurückhaltend.

Am 27. Symposium Photovoltaische Energie in Bad Staffelstein, an der 10. nationalen Photovoltaik-Konferenz in Baden sowie an der Europäischen Photovoltaik Konferenz (27th EU PVSEC) in Frankfurt wurden von den Schweizer Projektpartner Ergebnisse zum Einfluss von Marktverschiebungen und Technologieentwicklungen auf die Ökobilanzresultate von Solarstrom präsentiert [9, 14, 15]. Diese zeigen, dass der in der Fotovoltaikindustrie verwendete Strommix einen grossen Einfluss auf die Umweltbelastung von Solarstrom hat und dass es grosse Unterschiede zwischen europäischen und chinesischen Modulen gibt (siehe Figur 2). Die Reduktion der Umweltbelastung und der Treibhausgas-Emissionen durch Effizienzgewinne aufgrund von technischen Fortschritten werden durch den vermehrten Import von Solarzellen und Modulen aus China deutlich überkompensiert.



***Figur 2**: Treibhausgasemissionen von Solarstrom, produziert mit einer 3KWp-Schrägfachanlage mit Modulen aus Europa (2006 versus 2011 Technologie) und China. Moduleffizienz: 2006: 13.2 %; 2011: 13.6 %. Jahresertrag: 809 kWh/kWp. Anlag-Lebensdauer: 30 Jahre.*

Weiter nahm Rolf Frischknecht an einer Sitzung der IEA PVPS Task 12 teil. Dabei ging es im Wesentlichen um den Informationsaustausch und die Koordination zukünftiger Aktivitäten.

Bewertung 2012 und Ausblick 2013

Die Sachbilanzdaten von amorphem Silicon auf flexiblen Substraten des Hersteller VHF-Technologies SA sind erstellt und zusammen mit den Ökobilanzergebnissen veröffentlicht.

Die Sachbilanzdaten von mikromorphen Silizium PV-Modulen in Zusammenarbeit mit TEL Solar AG (früher Oerlikon Solar AG) sind erstellt. Die Freigabe zur Publikation der Resultate und Sachbilanzen wurde erteilt.

Die Durchführung der geplanten Modellierung der Modul-Take-Back-Systeme und des Modul-Recyclings war aufgrund der fehlenden Daten von Sunicon und First Solar nicht möglich. Für die Datenbeschaffung besteht weiterhin Kontakt zu Parikhit Sinha (First Solar). Wir werden weiter versuchen diese Arbeiten zu Ende zu führen.

Für 2013 sind folgende Arbeiten geplant:

- Erstellung von Sachbilanzdatensätzen zu Modul-Take-Back-Systemen und Modul-Recycling
- Überarbeitung der Daten zum Wasserverbrauch während des Betriebs (Reinigung) von Photovoltaik-Anlagen.
- Aktualisierung und Erweiterung der Sachbilanzdaten von Photovoltaik-Strom in der Schweiz, erzeugt mit Modulen aus chinesischer Produktion.

Falls von Mitgliedern der IEA PVPS Task 12 weitere Sachbilanzdaten zu Photovoltaik-Technologien zur Verfügung gestellt werden, wird angestrebt, diese für eine Implementierung in den ecoinvent Datenbestand (weiterhin v2.2) aufzubereiten.

Das Projekt wird seit dem 1.11.2012 durch die von Rolf Frischknecht neu gegründete Firma treeze Ltd. betreut.

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SCHWEIZER BEITRAG ZUM IEA PVPS PROGRAMM, IEA PVPS TASK 13

Annual Report 2012

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Project- / Contract Number	IEA PVPS Pool 2012.01
Duration of the Project (from – to)	2010 – 2013
Date	17.12.2012

ABSTRACT

Switzerland takes part in the Photovoltaic Power Systems (PVPS) program of the International Energy Agency (IEA), Task 13: Performance and Reliability of Photovoltaic Systems, 2010 - 2014

The overall objective of Task 13 is to improve the operation, reliability and, thus, electrical and economic output of photovoltaic power systems and subsystems

- providing a common platform where quality aspects are elaborated and exchanged among the stakeholders
- disseminating this knowledge to different market actors.

Task 13 is focusing on:

- Providing reliable statistical data for any kind of decision makers for different PV applications and system locations (e.g. different countries, regions, climates).
- Technical issues such as adapting test methods and reliability assessments of PV modules, comparing the long-term behavior of systems and components, as well as performance analysis and optimization of PV systems

Subtask 1: Statistical System Performance Analysis

Subtask 2: Analytical PV System Assessment

Subtask 3: PV Module Characterisation and Life Time Assessment

Subtask 4: Dissemination

TNC Consulting AG is the responsible Subtask 1 leader and also the activity leader 1.1 Database and Analysis of PV Systems.

In the Year 2012 the 'Input Tool' as well as the web-database was functional for the experts of Task 13. By the end of 2012 datasets of 56 PV systems and a total of 205 years of operational data was collected.

Einleitung / Projektziele

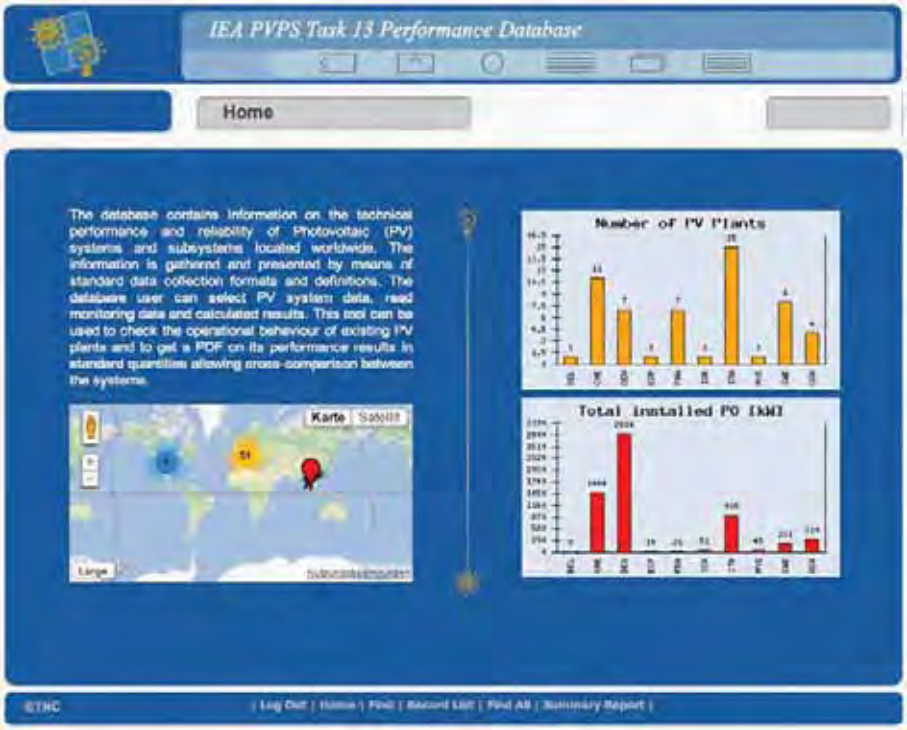
Die Schweiz ist durch TNC Consulting AG im IEA Task 13 vertreten und leitet Subtask 1, 'Statistical PV System Performance Analysis'. Der Beitrag ist im Wesentlichen die Aktivität 1.1, 'Database and Evaluation of PV Systems' und besteht im Einsammeln, der Bereitstellung und der Darstellung von Anlagen- und Betriebsdaten von PV Netzverbundanlagen der Task 13 Mitgliedländern sowie von anderen Datenquellen. Das gewählte Datenformat entspricht weitgehend dem Format der der 'IEA PVPS Task 2 Performance Database' und die Auswertung der Betriebsdaten ist vom IEC Standard 61724,1998 übernommen. Das ermöglicht eine normierte Auswertung und Darstellung von Betriebsdaten von unterschiedlichen PV Netzverbundanlagen in verschiedenen geografischen Regionen.

Kurzbeschrieb des Projekts

Allen Beteiligten wurde ein Werkzeug zur Verfügung gestellt, das ermöglicht die Daten im vorgeschriebenen Format einzugeben und zu prüfen (Input Tool). Durch eine Export-Funktion können die gesammelten Daten an die Subtask 1 Verantwortlichen weitergegeben werden. Die gesammelten Daten werden von TNC geprüft und in die Hauptdatenbank eingefügt. Diese Projekt- und Mess-Daten werden über das Internet öffentlich zugänglich gemacht. Dies ermöglicht dem interessierten Benutzer interaktiv zusammenfassende normierte Auswertungen von ausgesuchten PV-Netzverbundanlagen aufzurufen. 2012 standen die beiden Werkzeuge noch ausschliesslich für die Mitglieder des Tasks/ Experten zur Verfügung.

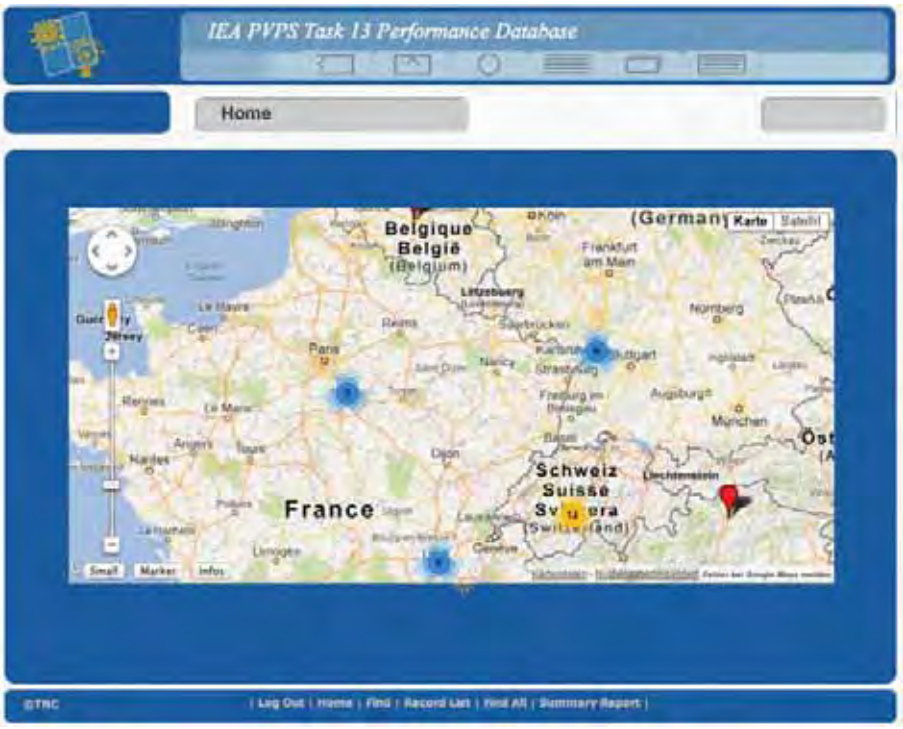
Durchgeführte Arbeiten und erreichte Ergebnisse

5. Task 13 Meeting in Brüssel, 19.-21. März 2012
6. Task 13 Meeting in Golden, Colorado (USA), 23.-25. Oktober 2012

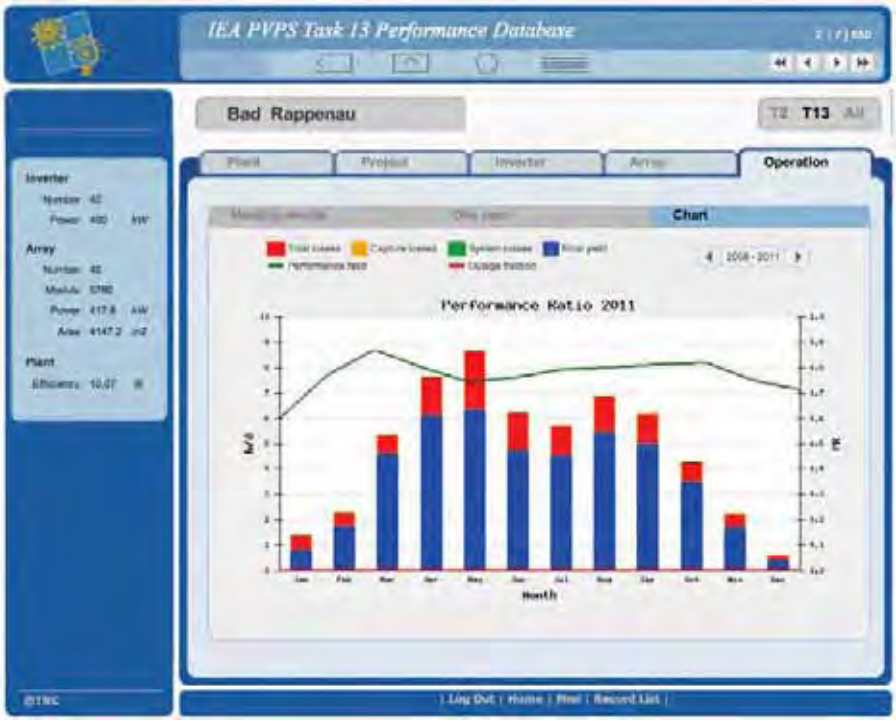


Figur 1: *Startbild für die webbasierte Projekt-Datenbank. Die geografische, numerische und leistungsbezogene Aufteilung der aktuellen Datenbank wird auf der Startseite vorgehalten.*

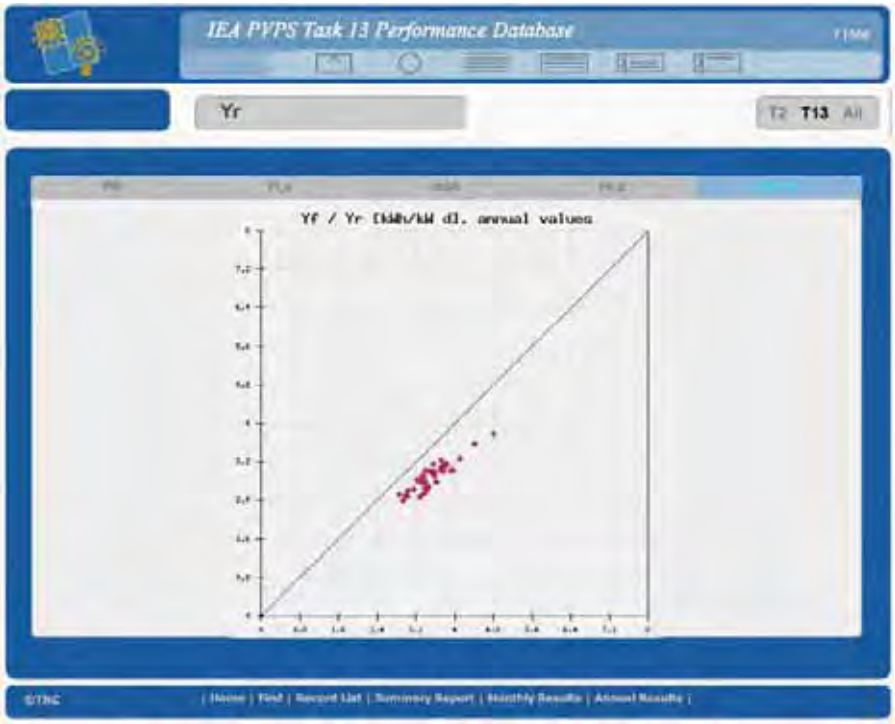
Figur 2: *Die Webdatenbank ist elektronisch gekoppelt mit einer Google-Earth basierten Standortidentifikation.*



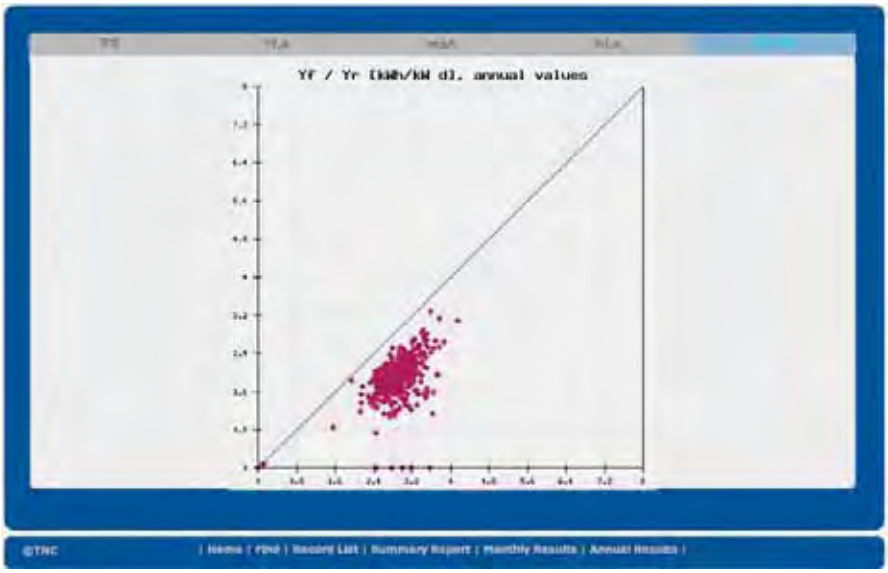
Figur 3*: Die Projektdaten können geografisch im Massstab angepasst am Standort aufgerufen werden.*



***Figur 4**: Beispiel einer Betriebsauswertung, deutsche Anlage Bad Rappenau in Monatsschritten. Die Projektdaten werden in mehreren normierten Auswertungen dargestellt.*



***Figur 5:** Landesauswertung in der neuen Projektdatenbank. Aus Deutschland rapportierte Projekte, Jahresmittelwerte, Final Yield im Vergleich zur Einstrahlung.*



***Figur 6**: Zum Vergleich die Projektdaten in der ebenfalls übernommenen alten Datenbank des Task 2 für Deutschland. In der Datenbank können über das Internet die verschiedenen Projektbeschreibungen (Plants, Projects, Inverter, Array and Operation) individuell aufgerufen werden.*

Bis Ende 2012 sind Datensätze von insgesamt 56 Anlagen mit einem Total von 205 Jahren Betriebsdaten eingegangen (siehe Figur 7).

NEW IEA PVPS Performance Database

	Original data for old/new database	Stand, Oct. 2012 confirmed	datasets delivered	monitoring data years	total P0 or range	your name
Australia (*						
Austria	new	5			10 kW ... 1MW	Karl Berger
Belgium		1	1	0.5		Achim Woyte
Canada (*	old/new	10 tbc			?	Sophie Pelland
China	new	3			?	Liu Haitao
Denmark (*						
France EDF R&D	new	7	5	5	100 kW	Mike van Iseghem
France INES	new	2	2	2		Lionel Sicot
Germany	new	15	7	40	50 kW...5 MW	Christian Reise
Germany	old/new	2			50 kW	Ulrike Jahn
Germany	new	1			50 kW	Stefan Mau
Israel	new	53	1		50 kW...20 MW	M. Green & A. Kafri
Italy (RSE)	new	30	14	27	> 1 MW	Mattia Giussani
Italy (EURAC)	new	3	1	1.5	662 kW	Giorgio Belluardo
Japan	x	24			x	Kazuhiko Kato
Malaysia	new	4	1	1	5 ... 10 kW	Dr. Salam
Netherlands		12			35kW	Wilfried Van Sark
Norway	new	1			45 kW	Anne Gerd Imenes
Spain	old/new	60 tbc			?	Vincente Salas
Spain	new	1	1	5	13.3 kW	A. Lagunas
Sweden	new	10	8		?	Johan Ärlebäck
Switzerland	old (**	11	11	122	3 kW...10 kW	L. Clavadetscher
Switzerland SUPSI	new	20			3 kW	Gabi Friesen
Turkey	new				25 kW...1.3 MW	Harun Girgin
United States	new	20	4	1	?	Sarah Kurtz
Total		225	56	205	(* not a member (** old systems	no info

plus 70 (to be confirmed)

19.10.2012 295

***Figur 7**: In der Projektdatenbank per Oktober 2012 vorhandene Einzelprojekte und rapportierte Betriebsjahre.*

2012 konnten wichtige Fortschritte bei der Rapportierung und Erfassung von Projektdaten verschiedener Länder, insbesondere Deutschland gemacht werden.

Internationale Zusammenarbeit

Durch die Unterzeichnung des 'IEA PVPS Implementing Agreement' hat sich die Schweiz verpflichtet einen internationalen Beitrag zu leisten. Die 'IEA PVPS Task 13 Performance Database' ist ein Werkzeug zur Analyse der Betriebsdaten von PV-Netzverbundanlagen von internationaler Bedeutung und die Mitglieder des Task 13 leisten hiermit einen wertvollen Beitrag. Der Task 13 hat anlässlich der EU PV SEC 2012 in Frankfurt ein erstes Seminar für interessierte Spezialisten durchgeführt.

Bewertung 2012 und Ausblick 2013

Für die Mitglieder/Experten von Task 13 Stand 2012 sowohl das Import-Tool wie auch die WWW-Datenbank zur Verfügung. Die Datensätze der angekündigten Projekte sind noch nicht vollständig und sollen möglichst in 2013 von den Mitglidern des Task 13 noch ergänzt werden.

Referenzen

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[2] Cost and performance trends in grid-connected photovoltaic systems and case studies, Report IEA-PVPS T2-06:2007 December 2007.

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Task 2 Datenbank

[4] **Performance Database**, Version 1.19, Edition: Sept 2006, auf CD-ROM für EUR 20.- erhältlich bei der Taskleitung: Ulrike Jahn, ZAE Bayern, D-91058 Erlangen, E-Mail: ulrike.jahn@.de.tuv.com, als Download oder interaktiv auf der Task 2 Homepage: http://www.iea-pvps-task2.org

IEA PVPS

[5] Info auf Webseite: http://www.iea-pvps.org/

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Département fédéral de l'environnement,
des transports, de l'énergie et de la communication DETEC

Office fédéral de l'énergie OFEN

IEA PVPS TASK 14 – HIGH PENETRATION OF PV SYSTEMS IN ELECTRICITY GRIDS

SWISS CONTRIBUTION

Annual Report 2012

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Project- / Contract Number	IEA PVPS Pool II No. 2011.01
Duration of the Project (from – to)	01.03.2010 – 31.03.2014
Date	15.12.2012

ABSTRACT

The main purpose of Task 14 is to analyze the role of grid connected PV as an important source in electric power systems on high penetration level where additional efforts may be necessary to integrate the dispersed generation in an optimum manner. The aim of these efforts is to reduce the technical barriers to achieve high penetration levels of distributed renewable systems on the electric power system.

Cross-cutting subtask (Information Gathering, Analysis and Outreach) objective is to review and document worldwide implementations of high penetration PV scenarios into electric power systems and based on subtask work, to generalize and refine them to generate a set of convincing cases of safe and reliable implementation.

Subtask 1 (PV generation in correlation to energy demand) objective is to show and determine how with better prediction tools an optimized local energy management, PV penetration level can be improved in grid.

Subtask 2 (High penetration PV in local distribution grids) objective is to identify and evaluate the role of PV in distribution grids, to analyze the impact of high penetration and to make recommendations (Grid Codes, incentives, regulation).

Subtask 3 (High penetration solutions for central PV generation scenarios) objective is to envision the future power system with the integration of system-wide PV integration through the review of PV generation output variation and its predictability, the power system operation and the power system increase.

Subtask 4 (Smart inverter technology for high penetration of PV) objective is to highlight and define inverter technology requirements for successful smart integration of a high penetration of PV (technology, technical requirement, standards and system integration aspects).

Switzerland is responsible of subtask 1 and contributes to other subtasks. The Swiss representation at the IEA-PVPS Task 14 meetings 2011-2012 was ensured (May 2011: Lisbon, Portugal / October 2011: Beijing, China / May 2012: Kassel, Germany / October 2012: Tokyo, Japan)

Purposes of the project

The project aims to analyze the impact of a high penetration of photovoltaic (PV) especially the integration in electricity grid. The high penetration of renewable energy systems (RES) is a real challenge to maintain reliability and stability in electricity grids. The objective is so to analyze and reduce the technical barriers restricting PV penetration in following fields: local energy management (load profiles and weather's effect) → subtask 1, local distribution grids (optimized load management) → subtask 2, central PV generation → subtask 3, inverter technology → subtask 4.

Short description of the project

The task 14 results from a workshop on the role of photovoltaic in Smart Grids.

What are the opportunities and needs for an electricity grid with a high penetration of PV? In a number of countries the PV has been grown rapidly with some problems and issues associated to a question more and more current.

As the initiative and responsibility of the task were taken over by Austria, the following countries announced their interest to participate to the task: Australia, Canada, Switzerland, Germany, Israel, Italy, Japan, Korea, Portugal, USA, China and Thailand.

The main purpose of this task during four years (March 2010 to March 2014) is to promote the use of grid connected PV as an important source in electric power system on a high penetration level. However, these dispersed generators require additional efforts and a great collaboration to be integrated in an optimum manner. It will only be possible when the technical barriers will be reduced. To achieve this objective the task 14 will focus on working with utilities, industry and other stakeholders to develop the technologies and methods enabling the widespread deployment of distributed PV technologies into electricity grids.

The objective would be to:

1. Develop and verify mainly technical requirements for PV systems and electric power systems to allow high penetrations of PV systems interconnected with the grid.
2. Discuss the active role of PV systems related to energy management and system control of electricity grids.

To achieve these objectives the project was divided into five parts: four subtasks and a cross-cutting subtask (Figure 1).

***Figure 1**: Parts of the IEA-PVPS T14 project*

Subtasks description, work done and results

Cross-cutting subtask (Subtask leader: Canada)
«Information gathering, analysis and outreach»

The objective of this subtask is to collect, standardize and share existing information on high penetration PV into electric power systems, based on other subtasks needs.

Activity CC1 (Canada)

In order to share project information an exchange platform has been set up, as well as a number of model documents.

Swiss team has introduced the objectives and results of his work on this Wiki and updates information about studies and project progress.

Activity CC2 (USA)

Activity objective is the collection of high penetration case study. In Switzerland few systems seem respond to questionnaire's standard of this activity (common questionnaire for both activities CC2 and 2.1) but many projects are starting and could be potentially interesting. In this way questionnaire has been sent to SIG, EWZ and Swissgrid. Answers are expected during 2013.

Activity CC3 (USA)

Simulation tools and settings used in *"Distribution Grid Analysis and Simulation with Photovoltaics (DiGASP)"* [1] are presented and discussed by Basler & Hofmann. The electrical grid simulation tools *"Matlab/Matpower"* and *"Neplan"* have been shared on the wiki.

Activity CC4 (Canada)

The report *"Successful method to reach high PV penetration"* will be developed through a workshop in which Switzerland will take part. These cases/scenarios will be thoroughly documented, modeled and simulated with respect to the parameters of interest such as power quality, system stability and economic impact.

Subtask 1 (Subtask leader: Switzerland)
«PV generation in correlation to energy demand»

The objective of this subtask is to show and determine how with better prediction tools an optimized local energy management, PV penetration level can be improved in grid.

Activity 1.1 (Switzerland)

The analysis of the questionnaire *"Use of solar and PV forecasts for enhanced PV integration"*, which was made in the year 2011, has been integrated in an official IEA report about “Photovoltaic and Solar Forecasting” (IEA PVPS T14-01:2012), which will be published beginning of 2013. The results of the questionnaire have been published at the PVSEC conference [2].

Meteotest was further leading a Swiss project dealing with short term forecast:

Prediction models for solar power have usually a forecast horizon of 12 to 72 hours (for example COSMO-EU model). However for this time scales the spatiotemporal evolution of the cloud is difficult to predict and is uncertain with increasingly longer time scales. A shortened forecast horizon (1 - 6 hours) leads to a significant improvement in prediction accuracy [4].

During partly overcast conditions high and low radiation levels can alternate within a very short time. In our project such short-term fluctuations are predicted with the following approach:

The shortest-term forecast model is based on a combination of satellite images and numerical weather model WRF to determine the motion of the clouds, as well as the clear sky radiation model for calculating the radiation on the surface. From the satellite images (Meteosat Second Generation, 3 km resolution) the current cloud cover index is determined.

With the help of the wind field from the numerical weather model WRF trajectories in the clouds for a determined length of 6 hours with a time resolution of 15 minutes are calculated. The global radiation is forecasted with help of the clear sky model and the calculated future position of the clouds (Fig 2).

The forecast is recalculated every 15 minute (the frequency of the satellite images) for 6 hours. With the multi-channel retrieval system of MeteoSwiss (includes visible and long-wave channels) also

clouds during the night can be determined what allows forecasting the radiation also during early morning hours.

The forecast data are compared with ground measurements from 12 stations of the SwissMetNet network and with data from 3 test sites. The project is supported by the BKW FMB AG and is running on until spring 2014.

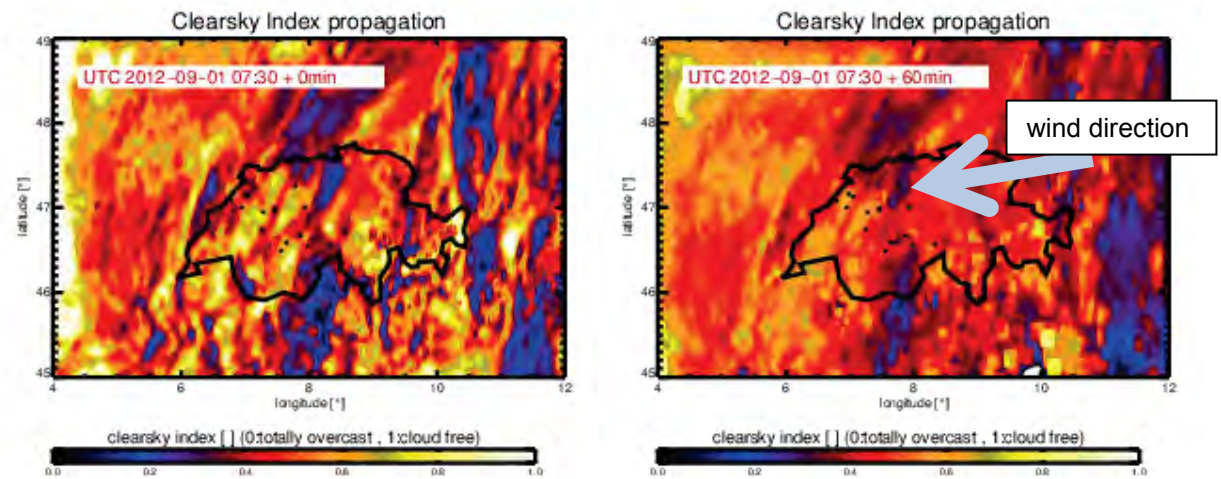

Figure 2: *Situation on September 1st, 2012 with easterly winds. Left: cloud conditions based on satellite image. Right: forecasted cloud conditions one hour later.*

Activity 1.2 (Switzerland)

The basis case study was improved with a typical theoretical solar curve simulated with the Polysun® software (location: Switzerland, Neuchâtel / date: May, 12 (maximal power and generation in the year) / orientation: South (0°) / inclination: 30° / panels: Sovello standard solar panels (power 10 kWp, output ~13.5%)).

Considering that 15% of the household consumption can be shifted at another time, PV generation used on site can be increased of 45%. With a local storage (6kWh batteries), PV generation used on site can be increased of 167%. Finally with both solutions, PV generation used on site can be increased of 187%.

On average Switzerland gets 900-1'000 kWh/kWp a year. Based on an annual private household consumption of 4'000kWh it's possible to produce up to 40% of this consumption with PV without additional penetration to the grid.

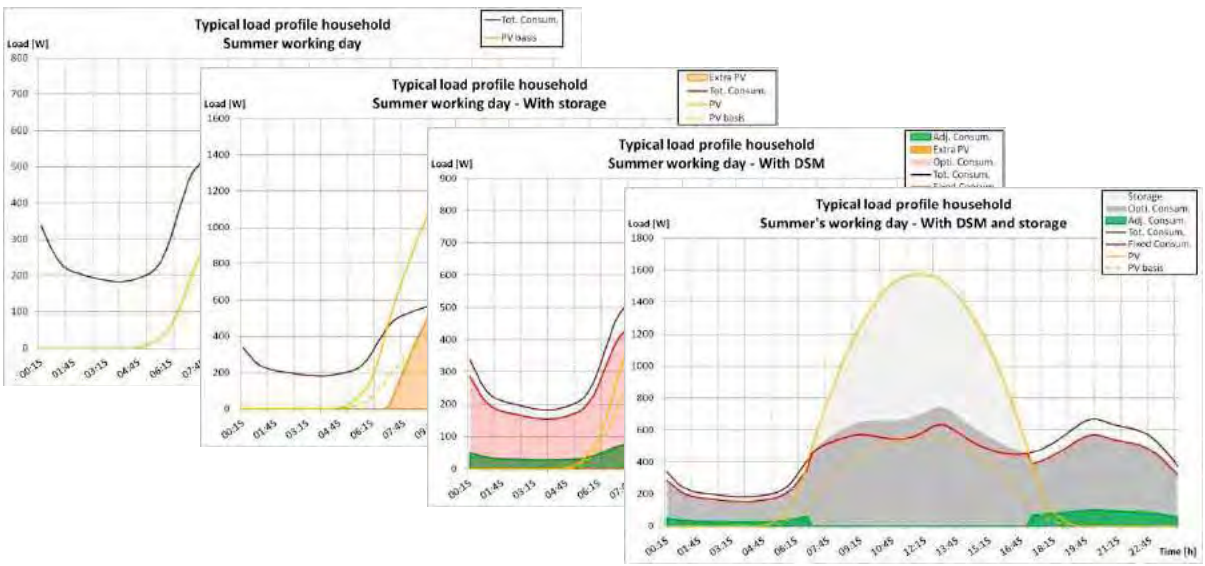

Figure 3*: results of basis case study*

	Power	Generation			of 4'000 kWh yearly consumption
Basis	550 W	495 – 550 kWh			12 – 14 %
DSM	800 W	720 – 800 kWh	(+45%)		18 – 20 %
Storage	1'470 W	1'323 – 1'470 kWh	(+167%)		33 – 37 %
DSM + storage	1'580 W	1'422 – 1'580 kWh	(+187%)		36 – 40 %

***Table 1**: results of basis case study*

The draft report for basis case was sent to task 14 participating countries. They are asked to provide typical data from their areas (typical load profiles and case studies selection).

The test site in Cernier (CHE) (smart meters in households, data transmission and remote consultation) will offer the possibility to study and analyze PV local energy management with storage. But the project should start in 2013.

The IMT, Institute of Microengineering in Neuchâtel (CHE) works on a project for PV local storage. A meeting took place on January to introduce the task 14 to IMT and to discuss a possible collaboration.

Collaboration with IWES has been defined for storage scenario definition and potential of demand side management.

Activity 1.3 (Portugal)

NREL (USA) owns elements regarding procedures to monitor and determine plant variability for the first part of the report on theoretical effects of large PV plant on the grid. They collaborated with EDP (Portugal) and have shared relevant information as inputs to define standards to analyze variability of large PV systems (monitoring standards).

The scope of activity has been redefined in order to make a literature review and analysis about PV variability, with the involvement of international partners. The Portuguese plant will serve as a case study to apply the relevant variability tools identified in existing international studies.

Subtask 2 (Subtask leader: Germany)
«High penetration PV in local distribution grids»

The objective of this subtask is to identify and evaluate the role of PV in distribution grids and to make an analyze cost-benefit for ancillary services. Especially this subtask focuses on the analysis of impact of high PV penetration in distribution grids in order to make recommendations on Grid Codes, incentives and regulation.

Methods and results of the project DiGASP [1] have been discussed on the Task 14 meeting in Kassel (Spring 2012) and will be integrated in the conclusions of Subtask 2.

Activity 2.1 (USA)

The questionnaire *"Survey of high penetration scenarios on distribution feeders"* has been sent to SIG, EWZ and swissgrid (see activity CC2).

A short report addressed to the topic *"review of extension/operation rules of grid operators"* was written by Basler & Hofmann and will be included in Activity 2.1.

Activities 2.2 and 2.3 (Germany) and Activity 2.4 (Canada)

No Swiss contribution in these activities at the moment.

Subtask 3 (Subtask leader: Japan)
«High penetration solutions for central PV generation scenarios»

The subtask will envision the future power system with the integration of system-wide PV integration through the review of PV generation output variation and its predictability including smoothing effect, power system operation planning, and power system augmentation planning.

As for the questionnaire of activities CC2 and 2.1 the questionnaire *"Use of solar and PV forecasts for enhanced PV integration"* has been sent to EWZ and swissgrid.

Activity 3.1 (Canada)

Due to collaboration between activities 1.1 and 3.1 the Swiss group is strong involved in this activity (especially Meteotest, see activity 1.1).

Activities 3.2 and 3.3 (Japan)

No Swiss contribution in this activity at the moment.

Subtask 4 (Subtask leader: Austria)
«Smart inverter technology for high penetration of PV»

This subtask will highlight and define inverter technology requirements for successful smart integration of a high penetration of PV: technology, technical requirements and standards, and system integration aspects.

As funding of Austria has been delayed deliverables of this subtask are not defined yet. At Swiss level, reports will be sent to Sputnik Engineering for validation.

Activity 4.1 (Austria)

No Swiss contribution in this activity at the moment.

Activity 4.2 (Germany)

Generic inverter models are currently collected by the activity leader. Basler & Hofmann takes part in the discussion and contributes its experience with active and reactive power control algorithms in simulations.

Activity 4.3 (China)

Basler & Hofmann prepared a questionnaire that permit to draw up the inventory of current technologies of communication between grid operator and PV systems, and to evaluate inverter communication issues in different utilities. This questionnaire was suggested to Wang Yibo und Yang Zilong (Renewable Energy R&D Center, Institute of Electrical Engineering, Chinese Academy of Science), who also planned to go in this way for development of activity 4.3.The questionnaire is still under development, due to the very different state of the art situations in the affected countries.

Related to activity 4.3 and to interest of some Swiss grid operators Planair SA had established a short inventory of existing monitoring system for PV inverter communication.

National and international collaboration

For Swiss participation to IEA-PVPS task 14 Planair SA allied with Basler & Hofmann AG and Meteotest in order to provide quality services, Swiss developments and knowledge for task 14.

At an international level the collaboration with other participating countries is constructive and efficient as we can see it in various activities.

Planair SA (subtask 1 leader) represented Switzerland during the international meetings in Kassel, Germany (with Basler & Hofmann) and in Tokyo, Japan. After the meeting in Kassel a national meeting was organized to discuss the information received but also to evaluate the situation about Swiss progress and to fix expected objectives and deliverables.

Several presentations to events were given about the Swiss contributions to IEA-Task 14: 10th national PV Symposium in Baden (CHE) on March 22-23, 6th international Smart Grids Week in Bregenz (AUT) on May 21-25, 27th EU PVSEC in Frankfurt (DEU) on September 24-28, IEEE Workshop in Bern (CHE) on October 23rd.

A Swiss meeting with PVPS Pool (Swiss electrical society) took place on October 30th for technical dissemination.

At Swiss level, the collaboration with IMT (see activity 1.2) is an opportunity to disseminate information and results about task 14 but also to give more value to the results by practical examples.

The dissemination of the results of Task 14 to the IEC / CENELEC committees is under discussion. Basler & Hofmann is involved in the IEC TC82 and maintains the communication between Task 14 and IEC. The IEC has though a rather weak position in grid standards and is therefore not a primary dissemination platform for Task 14.

Year 2012 evaluation and outlook for future work in 2013

Swiss team is subtask 1 leader and especially develops activities 1.1 (joined with 3.1) and 1.2. The subtask is well-advanced in its results and deliverables.

Swiss team will ensure the Swiss dissemination of work and results in task 14. A communication plan is planned to organize dissemination.

The spring meeting in 2014 should take place in Switzerland, after a workshop with Swiss utilities. This meeting could be a very good opportunity to disseminate the results of the task in Switzerland.

Activity 1.1

The work is going on but not finished yet. The report about "Photovoltaic and Solar Forecasting: State of the art" (joined with activity 3.1) will be finished and published in 2013.

Activity 1.2

Basis case study was improved and draft report of the study was sent to task 14 participating countries in order to get data from other areas and to conduct additional case studies in 2013. Issues regarding DSM and storage will be included in details.

Activity 1.3

The scope and orientation have to be validated. A literature review is under way. The identify methodology could then be apply to the plant monitored by EDP to determine variability. If interest case studies from other countries could be add.

Switzerland also contributes to other activities:

CC subtask

Normative work, update of wiki, participation to questionnaire, simulation tools and settings of project DiGASP, participation to workshop

Subtask 2

The DiGASP-project and its results will be disseminated in Task 14. Work on active and reactive power control algorithms is continued and will be used to extend the knowledge position of Task 14 in grid control aspects. Specific cases will be simulated with the DiGASP-approach, if required.

Subtask 3

Meteotest will deliver a high penetration case study for Switzerland.

Subtask 4

The focus of the Swiss contribution in Subtask 4 will be to evaluate the state of the art in communication between utilities and PV power plants, as well as to define requirements based on utility demands. This shall mainly be based on the questionnaire for utilities which is under development.

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IEA SHC TASK 46

SOLAR RESOURCE ASSESSMENT AND FORECASTING

Annual Report 2012

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Duration of the Project (from – to)	01.01.2011 – 30.06.2016
Date	17.12.2012

ABSTRACT

IEA SHC Task 46 „Solar Resource Assessment and Forecasting“ is the follow-up of the Task 36, which ended in 2011. From Switzerland University of Geneva and Meteotest are taking part. The goal of IEA Task 46 is to provide the solar energy industry, the electricity sector, governments, and renewable energy organizations and institutions with the means to understand the “bankability” of data sets provided by public and private sectors.

A major component of the task is to provide this sector with information on how accurately solar resources can be forecasted in the near future (sub-hourly, 1-6 hours, and 1-3 days) so that utilities can plan for the operation of large-scale solar systems operating within their systems. Another major component of the task is understanding short-term (1-minute or less) resource variability associated with cloud passages that cause power “ramps”, an important concern of utility operators with large penetrations of solar technologies in their system.

Within this first annual report the goals and the subtasks are defined. Three examples of ongoing work are presented: For activity B1 (“measurement best practices”) a comparison of direct normal irradiance instruments which is going on in Payerne is shortly described. For activity C1 “Short-term forecasting” the current work on the PV power forecast model of University of Oldenburg and the shortest term forecast model developed at Meteotest are shown.

Introduction / project goals

The goal of IEA Task 46 "Solar Resource Assessment and Forecasting" is to provide the solar energy industry, the electricity sector, governments, and renewable energy organizations and institutions with the means to understand the “bankability” of data sets provided by public and private sectors. A major component of the task is to provide this sector with information on how accurately solar resources can be forecasted in the near future (sub-hourly, 1-6 hours, and 1-3 days) so that utilities can plan for the operation of large-scale solar systems operating within their systems. Another major component of the task is understanding short-term (1-minute or less) resource variability associated with cloud passages that cause power “ramps”, an important concern of utility operators with large penetrations of solar technologies in their system.

Based on the outcomes of precedent Task 36, the objectives of Task 46 are to:

- Evaluate solar resource variability that impacts large penetrations of solar technologies
- Develop standardized and integrating procedures for data bankability
- Improve procedures for short-term solar resource forecasting
- Advance solar resource modeling procedures based on physical principles

Achieving these objectives would reduce the cost of planning and deploying solar energy systems, improve efficiency of solar energy systems through more accurate and complete solar resource information, and increase the value of the solar energy produced by solar technologies.

Task 46 focuses on

1) The development, validation, and access to solar resource information derived from surface-based observations, satellite-based platforms, and numerical weather prediction (NWP) models
2) Solar resource variability and forecasting issues pertinent to grid-tied or large-scale penetrations of solar technologies into a national energy system
3) Data bankability issues, especially those related to solar resource measurement practices and merging of measured and modeled data sets
4) Exploring means by which to improve the modeling of the solar resource using satellite-based platforms or other weather observations

As with Task 36 the audience for the results of the Task includes the technical laboratories, research institutions and universities involved in developing solar resource data products. More importantly, data users, such as energy planners, solar project developers, architects, engineers, energy consultants, product manufacturers, and building and system owners and managers, and utility organizations, are the ultimate beneficiaries of the research, and will be informed through targeted reports, presentations, workshops and journal articles. Key results of this task will be posted to the IEA SHC Task 46 Publications web site.

Task definition

Subtask A: Solar resource applications for high penetrations of solar technologies

This Subtask will develop the necessary data sets to allow system planners and utility operators to understand short-term resource variability characteristics, in particular up and down ramp rates, to better manage large penetrations of solar technologies in the grid system. Although this work is primarily focused toward PV systems, which react almost instantaneously to cloud passages over individual panels, the information is also useful for solar thermal and CSP systems where intermittency due to variable solar resources can impact their ability to meet load demands. Subtask A consists of three main activities:

- Activity A1: Short-Term Variability
- Activity A2: Integration of solar with other RE
- Activity A3: Spatial and Temporal Balancing Studies of the Solar and Wind Energy Resource

Subtask B: Standardization and integration procedures for data bankability

This task addresses data quality and bankability issues related to both measurement practices and use of modeled data. Subtask activities are:

- Activity B1: Measurement best practices
- Activity B2: Gap-Filling, QC, Flagging, Data Formatting
- Activity B3: Integration of data sources
- Activity B4: Evaluation of Meteorological Products
- Activity B5: Data Uncertainties over Various Temporal and Spatial Resolutions

Subtask C: Solar irradiance forecasting

Solar irradiance forecasting provides the basis for energy management and operations strategies for many solar energy applications. Depending on the application and its corresponding time scales different forecasting approaches are appropriate. In this subtask forecasting methods covering timescale from several minutes up to seven days ahead will be developed, tested and compared in benchmarking studies. The use of solar irradiance forecasting approaches in different fields will be investigated, including PV and CSP power forecasting for plant operators and utility companies as also irradiance forecasting for heating and cooling of buildings or districts. Subtask activities are:

- Activity C1: Short-term forecasting (up to 7 days ahead)
- Activity C2: Integration of solar forecasts into operations

Subtask D: Advanced resource modeling

Although most of the work in Task 36 involved the testing and evaluation of existing solar resource methodologies, some specific new methodologies have been identified that could be developed within a new task. These methodologies are driven by specific information requests from energy developers and planners. They can include new data sets required for the control and heating and cooling in buildings, solar resource forecasting for CSP plant operations, and the impact of climate change on solar resources, both from an historical perspective as well as estimates of future impacts. Subtask activities are:

- Activity D1: Improvements to existing solar radiation retrieval methods
- Activity D2: Development of global solar resource data sets for integrated assessment of global and regional RE scenarios modeling, with a special focus on CSP and solar heating technologies
- Activity D3: Long term analysis and forecasting of solar resource trends and variability.

The team has started the work in autumn 2011. In 2012 one project meeting was held in Golden CO (USA) at the National Renewable Energy Laboratory (NREL).

The team has been growing since the preceding task (Tab.1).

Table 1: *Active members of the task*

Country	Teams
Australia (new)	Bureau of Meteorology Research Centre, University of South Australia, CSIRO
Austria	Austria Solar Innovation Center, Blue Sky Wetteranalysen
Canada (new)	Green Power Labs
Denmark (new)	Danish Meteorological Institute (DMI), Technical University of Denmark (DTU)
European Commission	JRC
France	ARMINES, Mines ParisTech, Laboratoire PIMENT, Université la Réunion
Germany	DLR, University of Oldenburg, Suntrace GmbH, University of Ulm, CSPS GmbH
Norway	University of Agder
Slovakia	GeoModel Solar s.r.o.
Spain	CIEMAT, CENER, Public University of Navarra, University of Jaen, irSOLaV
Switzerland	Meteotest, UNIGE
USA (partly new)	Department of Energy/National Renewable Energy Laboratory, NASA State University of New York at Albany, University of California San Diego, Irradiance, University of Oregon, Augustyn and Co.

Work done and results

Three examples of ongoing work are described from activity B1 and C1.

Activity B1

DLR and others

Currently MeteoSwiss is performing intercomparisons of three different rotating shadowband radiometers (RSI) and various Delta-T SPN1 in Payerne, Switzerland, in the framework of the COST Action ES1002 WIRE [1]. The investigated RSIs are the RSR2 (Irradiance), the RSP (Solar Millennium/Reichert GmbH) and the Twin RSI (CSP Services) (Figure 1). Final results are expected for 2013. The comparison campaign represents an important step towards the qualification of the performance of RSIs and the Delta-T SPN1. The data from the collocated MeteoSwiss Baseline Surface Radiation Network (BSRN) station are used as reference for the intercomparison.

In the framework of the intercomparisons and the COST Action, a workshop focusing on the first results and the instrumentation was held September 20th - 21st 2012 at Payerne, Switzerland. The participation of the Delta-T instrument and the corresponding presentations will also allow its inclusion in the future versions of the measurement manual. Other presentations at the workshop also addressed important topics for the uncertainty analysis of RSIs. All original presentations are available upon demand on the restricted part of the COST Action website (www.wire1002.ch).

A new measurand for resource assessment that is investigated in B1 is the sunshape and the circumsolar radiation. The replication of a newly developed measurement system is presented in [2].

An extension to meteorological stations with solar trackers called “TraCS” has been tested and validated at PSA in collaboration with the University of Oujda, Morocco. Its purpose is the routine measurement of soiling levels of solar test mirrors additionally to the standard irradiance measurements performed at the stations.

Figure 1: *Test instruments during the measurement campaign in Payerne (Photo: MeteoSwiss).*

Activity C1

University of Oldenburg

University of Oldenburg is investigating an approach based on linear regression to combine forecasts based on cloud motion vectors from satellite images and forecast data of two Numerical Weather Prediction (NWP) models [3]. The used NWP model data are operational forecasts of the integrated forecast system (IFS) run by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the COSMO-EU model, operated by the German Weather Service DWD. There is a strong potential for improving the forecast performance by combining different models. The combined forecasts outperform the single model forecasts for all forecast horizons investigated. For regional day-ahead predictions an improvement of 10% compared to the ECWMF based forecasts is found, when combining the two NWP model forecasts. For intra-day predictions with additional integration of satellite based CMV forecasts, the benefit is even much larger (Fig. 2)

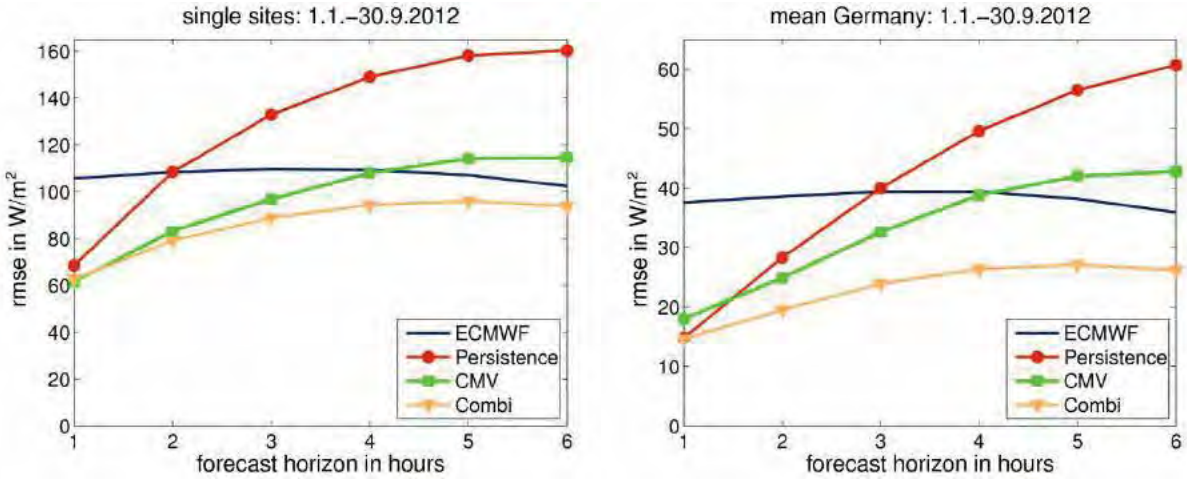

Figure 2: *RMSE of ECMWF based, CMV and combined forecasts in comparison to persistence in dependence on the forecast horizon. For the ECMWF based forecast, the 12:00 UTC run of the previous day is evaluated independent of the forecast horizon and variations of the RMSE with the forecast horizon are due to the horizon dependent data sets Left: single sites, right: German mean.*

Meteotest

Prediction models for solar power have usually a forecast horizon of 12 to 72 hours (for example COSMO-EU model). However for this time scales the spatiotemporal evolution of the cloud is difficult to predict and is uncertain with increasingly longer time scales. A shortened forecast horizon (1 - 6 hours) leads to a significant improvement in prediction accuracy [4].

During partly overcast conditions high and low radiation levels can alternate within a very short time. In our project such short-term fluctuations are predicted with the following approach:

The shortest-term forecast model is based on a combination of satellite images and numerical weather model WRF to determine the motion of the clouds, as well as the clear sky radiation model for calculating the radiation on the surface. From the satellite images (Meteosat Second Generation, 3 km resolution) the current cloud cover index is determined.

With the help of the wind field from the numerical weather model WRF trajectories in the clouds for a determined length of 6 hours with a time resolution of 15 minutes are calculated. The global radiation is forecasted with help of the clear sky model and the calculated future position of the clouds (Fig 3).

The forecast is recalculated every 15 minute (the frequency of the satellite images) for 6 hours. With the multi-channel retrieval system of MeteoSwiss (includes visible and long-wave channels) also clouds during the night can be determined what allows forecasting the radiation also during early morning hours.

The forecast data are compared with ground measurements from 12 stations of the SwissMetNet network and with data from 3 test sites. The project is supported by the BKW FMB AG and is going on until spring 2014.

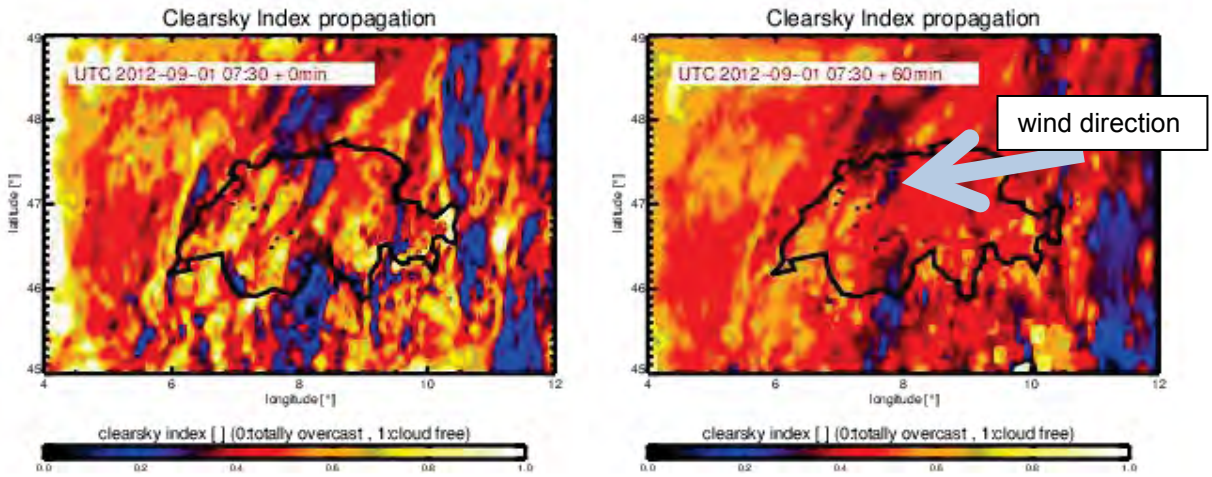

Figure 3: *Situation on September 1st, 2012 with easterly winds. Left: cloud conditions based on satellite image. Right: forecasted cloud conditions one hour later.*

National / international cooperation

The work was done in the framework of IEA Solar Heating and Cooling task 46. From Switzerland there is also University of Geneva part of the task team. The results are exchanged with IEA PVPS Task 14 (high penetration of PV) and the COST action ES1002 (“wire”).

Outlook

The task will go on next year. The team will meet presumably twice with a first meeting in January.

References

[1] Laurent Vuilleumier, Gianluca Paglia, Nicolas Sommer, and Bertrand Calpini; Performance evaluation of radiation sensors for the solar energy sector; 2012; TECO-2012 WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation; Brussels, Belgium, 16-18 October 2012; available online http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-109_TECO-2012/Session1/P1_25_Vuilleumier_performance_eval_radiation_sensors.pdf (visited 16.11.2012)

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Schweizerische Eidgenossenschaft
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Bundesamt für Energie BFE

NORMIERUNG FÜR PV-SYSTEME

IEC-TC 82 UND NATIONALES TK 82 FÜR PV-SYSTEME

Annual Report 2012

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Project- / Contract Number	SWISSOLAR / 17967
Duration of the Project (from – to)	2008 –
Date	Januar 2013

ABSTRACT

The TC 82 of the International Electrotechnical Commission (IEC) is responsible for the development and maintenance of standards for photovoltaic energy conversion systems. It includes all from the solar light, solar cells, solar modules and other Balance of System (BOS) components up to the connection with the private or public electricity grid. In May 2012 several working groups had their meetings in Vancouver and in October 2012 the general TC 82 meeting took place in Oslo. Again high interest with more than 100 participants was recognized. A special welcome to several country delegations from Africa was celebrated. A milestone in Oslo meeting was the achievement in the discussions among TC 82 and TC 64 on the installation standard. The existing TC 82 document will be circulated as a Draft Technical Specification (DTS) in view of its publication as IEC TS 62548. It will have a short lifetime and will be withdrawn with the publication of the future IEC 60364-7-712 edition 2. A Joint Working Group between TC 64 and TC 82, under TC 64 responsibility, shall harmonize the draft 60364-7-712 with the TS 62548 und to publish the new -712 standard.

Within TC 82 (IEC and EN) four standards were published as new or revised documents. More than 30 documents are actually under revision or in preparation as new publication.

On a national level there were the two TK 82-meetings as scheduled with again good participation from the Swiss PV industry. A joint working group with members of TK 64, TK 81 und TK 82 was launched in order to develop a Technical Report (TR) for the lightning protection in PV systems. A publication is scheduled for Spring 2013.

Activities from insurance companies with respect to security and fire safety showed obviously the necessity of reliable standards. Among the ongoing work there are urgent topics such as the new standards for arc detection systems, micro inverters connected to modules und junction boxes with integrated power electronics and updated installation standards.

Einleitung / Projektziele

Normierung für PV-Systeme gilt als übergeordnete Zielsetzung gleich wie jedes Jahr. Das IEC passt dazu regelmässige den strategischen Businessplan an. Die Projektziele aus nationaler Sicht lauten wie folgt:

- PV und Brandschutz: Erarbeiten von Richtlinien für die Praxis
- Blitzschutz, Ausarbeitung von Empfehlungen für PV-Anlagen
- Überarbeitung des Abschnitts 712 in der NIN 2010 (TK 64 Dokument)
- Revision der Norm für die Systemdokumentation und Inbetriebnahme
- Normen für Inselanlagen
- Testverfahren für Lichtbogendetektor
- Test- und Produktenormen für Moduldosen mit integrierter Elektronik
- Informationsveranstaltungen für die Fachleute in der Schweiz

Kurzbeschrieb des Projekts

Normen und technische Regeln für die Photovoltaik sind erforderlich für die Sicherheit von Personen und Material, für die zweckmässige Funktion und für einen fairen und gut funktionierenden internationalen Markt. Das Projekt wird in enger Zusammenarbeit mit Vertretern von Swissolar, der Electrosuisse und den internationalen Normengremien durchgeführt. Der Schwerpunkt liegt in der Betreuung und Leitung des nationalen CES-TK 82 und der schweizerischen Vertretung im IEC-TC 82, welche zuständig sind für die PV-Normen. Die IEC-Normen fokussieren sich auf die Elektrotechnik und zugehörige Themen wie Sicherheit, Brandschutz und generelle Aspekte zur Qualität. Sie decken einen weiten Bereich ab, angefangen vom Sonnenlicht, über Solarzellen, Solarmodule, Systemkomponenten, Installationstechnik, Netzanschluss, Abnahme und den Betrieb von Anlagen.

Seit mehreren Jahren ist die Arbeit des IEC-TC 82 in 5 Arbeitsgruppen (Working Groups, WGs) aufgeteilt plus eine gemeinsame Arbeitsgruppe (Joint Working Group, JWG 1) mit Delegierten aus mehreren IEC-TCs.

WG 1 Glossary
WG 2 Modules, non-concentrating
WG 3 Systems
WG 6 Balance-of-system components
WG 7 Concentrator modules
JWG 1 Decentralized Rural Electrification(JWG TC 82/TC 88/TC 21/SC 21A)

Durchgeführte Arbeiten und erreichte Ergebnisse

Schwerpunkt der Arbeiten bildeten die Überarbeitung und Aktualisierung von bestehenden Normen. Im 2012 sind auf IEC- und EN-Ebene vier neue resp. revidierte Normen in Kraft getreten:

IEC 61730-2	Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing
IEC/TS 62727	Photovoltaic systems - Specification for solar trackers
EN 61701:2012	Salt mist corrosion testing of photovoltaic (PV) modules
EN 0521:2008/A1	Connectors for photovoltaic systems - Safety requirements and tests

Dazu kommen etwa 30 Dokumente gemäss Anhang 1, welche aktuell in Arbeit sind.

Meetings

Die üblichen zwei internationalen WG 3 & WG 6-Meetings fanden in Vancouver und Oslo statt. Ergänzend gab es wie üblich zwei nationale TK 82-Sitzungen und weitere Meetings im In- und Ausland. An den WG 3 & 6-Meetings wurden die diversen Normenentwürfe diskutiert und verabschiedet. Im Weiteren werden jeweils Arbeitsteams gebildet, welche die Normenentwürfe bearbeiten und verfassen. Ergänzend zu Meetings finden vermehrt auch Telefonkonferenzen statt. Da werden Inhalte zu Normenentwürfen diskutiert, aktuell gab es mehrere Konferenzgespräche zum Dokument "Design guidelines and recommendations for photovoltaic power plants". Für die Schweizer Industrie ist das wichtig in Bezug auf die Anforderungen an die Komponenten wie Wechselrichter, Kabel, Schutz und Verbindungselemente.

Das nationale TK 82 hatte zwei Sitzungen mit jeweils etwa 12 Teilnehmern. Das TK 82 besteht gegenwärtig aus 20 Mitgliedern. Ein Meeting fand auf Einladung von Oerlikon Solar in Trübbach satt. Das Sekretariat führt Thomas Plattner von Electrosuisse.

Brandschutz und Prävention

Das Thema Brandschutz bei PV-Anlagen und Vorkehrungen für allfällige Lösch- und Rettungseinsätze wurde auch im Berichtsjahr intensiv verfolgt. Insbesondere in der Schweiz haben neue Publikationen einzelner Gebäudeversicherungen schwerwiegende Markthindernisse aufgebaut. Mit technisch und rechtlich gut fundierten Rekursen konnte Swissolar den Schaden für die Branche in Grenzen halten. Es zeigt sich erneut mit aller Deutlichkeit, wie wichtig zuverlässige und breit abgestützte Normen sind. Insbesondere die NIN und darin der Teil 712 lieferten wichtige Argumente für einheitliche Anforderungen in der Schweiz. Im Herbst 2012 publizierte die Vereinigung Kantonaler Feuerversicherungen(VKF) das Brandschutzmerkblatt für Solaranlagen (Lit. 1). Als ergänzender Bestandteil dieses Brandschutzmerkblattes hat Swissolar ein Stand-der-Technik-Papier verfasst (Lit. 2). Diese beiden Dokumente bilden die Basis für einheitliche Regelungen in der Schweiz.

Weiter werden die Ergebnisse aus dem Projekt PV-Brandsicherheit in Deutschland verfolgt. Unter anderem werden dabei die Hauptgefahren für mögliche Brandursachen aufgezeigt:

- Die Krimpung des Steckers war ungenügend, es entstand ein Lichtbogen.
- Unterbrüche in den Modul und Zellverbindungen
- Schlechte Kontakte im Generatoranschlusskasten können das Abbrennen/Abschmelzen bewirken
- Schadhafte Stecker können heiss werden und Unterbrüche oder Kurzschlüsse erzeugen
- Vorsicht bei der Verwendung von Aluminiumkabeln, die Auswahl der Klemmen ist besonders wichtig.
- Schäden durch Nagetiere

Bei den in jeder Anlage vielfach vorkommenden Steckkontakten und elektrischen Verbindungen besteht das Risiko zur Überhitzung. Insbesondere dürfen bei den Steckern nur 100% kompatible Bauelemente verbunden werden. Eine scheinbare Kompatibilität aufgrund "passender" Steckerkontakte reicht nicht aus! Laboruntersuchungen zeigten, dass wegen verschiedener Materialzusammensetzungen keine Langzeitfunktionalität gesichert ist. Eine mögliche massive Widerstandserhöhung mit entsprechender Erhitzung führt nicht nur zu geringerem Ertrag, sondern kann im Extremfall einen Komponentenbrand auslösen. Es dürfen daher nur Komponenten eines Herstellers und einer Serie miteinander verbunden werden.

Industrie und die Normenorganisationen arbeiten an weiteren Verbesserungen für die Sicherheit und Zuverlässigkeit von PV-Anlagen.

PV in Buildings (BIPV)

Der CENELEC-BIPV-Normenentwurf lang im 2012 erneut zur Stellungnahme auf. Am Entwurf haben drei Vertreter aus der Schweiz mitgearbeitet. Die Erarbeitung des IEC-eigenen Dokuments hat sich verzögert. Der IEC-Entwurf soll stärker auf die Systemaspekte eingehen. Der CENELEC-BIPV-Vorschlag bezieht sich mehr auf Module für Fassaden und Dächer. Das in diesem Zusammenhang ebenfalls relevante Dokument IEC 62548 (Design Requirements for Photovoltaic Arrays) ist seit Ende Jahr zur Abstimmung als TS in Zirkulation und sollte in der ersten Hälfte 2013 in Kraft treten.

Blitzschutz

Blitz- und Überspannungsschutz ist in der Schweiz einerseits in der NIN aber vor allem in den Leitsätzen 4022 geregelt. Für PV-Anlagen wurden von einer Arbeitsgruppe bestehend aus Mitgliedern vom TK 64, TK 81 und TK 82 ergänzende Erläuterungen in Form eines Merkblatts verfasst, welche aktuell in der Vernehmlassung sind. Die nachstehenden Bilder 1&2 zeigen als Vorabdruck das Blitzschutzkonzept für ein Gebäude mit Blitzschutz und für ein Gebäude ohne Blitzschutz. Erläuterungen dazu und weitere Beispiele werden im erwähnten Merkblatt aufgeführt sein.

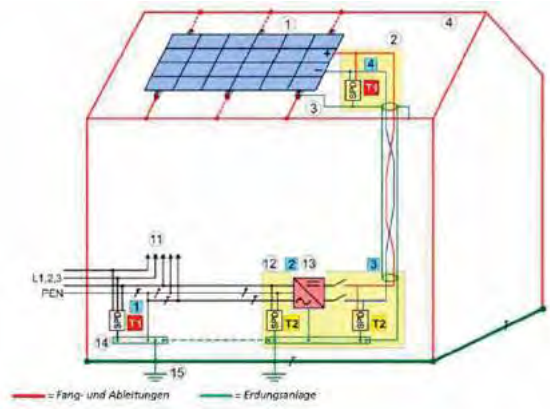

***Bild 1**: Blitzschutz einer PV-Anlage auf einem Gebäude mit Blitzschutz (Vorabdruck aus Lit. 3)*

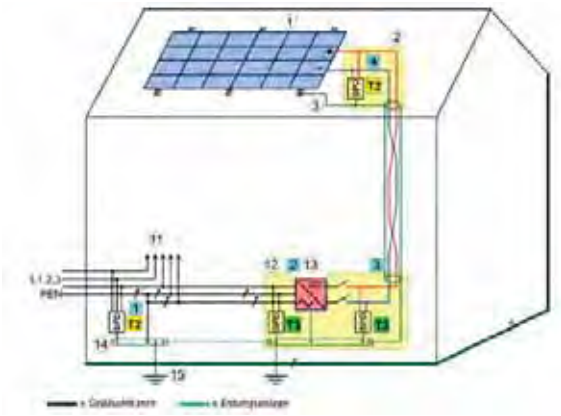

***Bild 2**: Überspannungsschutz bei einem Gebäude ohne Blitzschutz (Vorabdruck aus Lit. 3)*

PV-Installationsnorm als Bestandteil der Hausinstallationsnorm (NIN)

Wegen den vielen neuen Kommentaren und Ergänzungen ist das Dokument 60364-7-712 immer noch in Bearbeitung. Da es viele Überlappungen mit dem Normenentwurf "62548 TS: Design requirements for photovoltaic (PV) arrays" aufweist, wurde die Vorgehensweise am IEC-Meeting in Oslo völlig neu beschlossen. Die Arbeit am 60364-7-712-Dokument wird vorübergehend sistiert. Die aktuelle Version des 62548 soll als TS verabschiedet werden. Parallel dazu wird eine gemeinsame Arbeitsgruppe mit Vertretern aus dem TC 64 und dem TC 82 mit dem Ziel gegründet, aus den beiden Dokumenten (IEC 60364-7-712 IEC-TS 62548) ein einziges, harmonisiertes Dokument zur erstellen. Dieses neue Dokument wird anschliessend nach dem Abstimmungsverfahren in beiden TCs als neues TC 64-Dokument publiziert. In der Schweiz wird es danach in der NIN integriert. In wie weit es für die angelaufene NIN-Revision verwendet werden kann ist noch offen. Als Ersatz kann das TS 62548 als Quelle für die dringend notwendigen Updates benutzt werden.

Abnahme, Inbetriebnahmeprüfung und Systemdokumentation (EN 62446)

Die Mindestanforderungen an Systemdokumentation, Inbetriebnahmeprüfung und Prüfanforderungen regelt die Norm EN 62446. Bis Ende 2011 wurde sie in der Schweiz nicht beachtet. Seit Mitte 2012 wird die EN 62446 von den Kontrollinstanzen in der Schweiz konsequent angewendet. Gleichzeitig wurde auf IEC- und EN-Ebene die Revision dieser Norm gestartet. Ändern sollen vor allem die Informationen zur periodischen Kontrolle und die Pflicht zur Messung des Kurzschlussstromes soll entfallen. Es genügt, wenn ersatzweise der Betriebsstrom gemessen wird.

Swissolar wird demnächst ein Abnahmeprotokoll veröffentlichen, welches die Vorgaben in der EN 62446 erfüllen wird.

Normen und Guidelines für Entwicklungsländer

Für die weiter zunehmenden Bedürfnisse der Entwicklungsländer ist die gemeinsame Arbeitsgruppe mit Vertretern aus drei TCs weiterhin aktiv (JWG TC 82/TC 88/TC 21/SC 21A – Decentralized Rural Electrification).

Die günstigen Modulpreise werden auch in diesem Sektor das Wachstum beschleunigen und somit steigt der Bedarf an Standards.

Netzanschluss

Vom Cenelec-TC 8 zirkuliert per Ende Dezember 2012 ein kombiniertes Dokument (CLC/FprTS 50549-1 and CLC/FprTS 50549-2) für den Anschluss von dezentralen Stromerzeugern an das Niederspannungsnetz ab 16 A oder zweitens für mit Anschluss an die Mittelspannung.

1: Requirements for generating plants larger than 16 A per phase to be connected in parallel with a low-voltage distribution network.

2: Requirements for generating plants to be connected in parallel with a medium-voltage distribution network

In der Schweiz sollen die Anschlussbedingungen vereinfacht und die damit zusammenhängenden Kosten reduziert werden, vor allem für die Zählerbewirtschaftung.

Kommunikation, Publikationen

An verschieden Veranstaltungen wurde über die aktuellen Normen und Vorschriften informiert.

Swissolar organsiert dazu je eine ERFA-Veranstaltung an den Fachhochulen in Burgdorf und Winterthur. Ein weiteres Referat wurde an der Jahrestagung der Elektrokontrolleure gehalten.

Zusammenarbeit mit anderen Normengruppen

Mit folgenden **IEC-TCs** besteht eine regelmässige Zusammenarbeit:

TC 8	Systems aspects for electrical energy supply
SC 17B	Low-voltage switchgear and control gear
TC 21	Secondary cells and batteries
TC 22	Power electronic systems and equipment
SC 23B	Plugs, socket-outlets and switches
SC 23E	Circuit-breakers and similar equipment for household use
SC 32B	Low-voltage fuses
TC 47	Semiconductor devices
TC 64	Electrical installations and protection against electric shock
TC 57	Power systems management and associated information exchange
TC 77 / SC77A EMC	Low frequency phenomena
TC 81	Lightning protection

D-A-CH-CZ

Unter diesem Titel arbeiten die drei deutschsprachigen Länder und CZ eng zusammen, vor allem im Bereich Stromverteilnetze. Unter anderem bearbeitet die Gruppe die Netzanschlussbedingungen.

IEA PVPS Task 14 (High Penetration of PV Systems in Electricity Grids)

Die Zusammenarbeit im Rahmen der Internationalen Energieagentur (IEA) hat teilweise prenormativen Charakter.

PV-Brandsicherheit

Unter der Leitung vom TÜV und dem Fraunhofer ISE Projektes wird in Deutschland ein umfassendes Projekt mit dem Titel "PV-Brandsicherheit" durchgeführt. Zusammen mit anderen Firmen ist auch die Berner Fachhochschule, BFH-TI, Burgdorf im Projektteam vertreten. Es laufen Umfragen und Untersuchungen zu Brandereignissen. Die Zwischenergebnisse wurden in zwei Workshops präsentiert. Die Präsentationen sind auf www.pv-brandsicherheit.de verfügbar. Die Projektverantwortlichen sind in den IEC-Normengremien vertreten und entsprechend wird versucht, die Ergebnisse und die zukünftigen Anforderungen in den einschlägigen Normen zu integrieren.

SIA-Normen

Swissolar hat im Jahr 2012 Kommentare zur Revision der SIA 261 (Einwirkungen auf Tragwerke) beim Schweizerischen Ingenieur- und Architektenverein (SIA) eingereicht. Ziel davon ist, die gültigen Normen für die Statik und Windlast mit den Bedürfnissen für PV-Anlagen zu ergänzen.

Auch international sind im Baubereich mehr Normen in Vorbereitung, unter anderem gibt es bei der europäischen Normenorganisation (CEN) eine Arbeitsgruppe, welche sich mit Solarenergie vom Dach beschäftigt (CEN/TC 128, WG3 WG3"Renewable Energy Systems for Roofs").

Bewertung 2012 und Ausblick 2013

Die enorme Dynamik der Marktentwicklung in der Photovoltaik hat spürbare Auswirkungen auf die Normentätigkeit. Neue Technologien verlangen neue Normen und der Erfahrungsgewinn mit den zahlreichen Anlagen gibt wichtige Rückschlüsse für die Aktualisierung der Normen. Die wesentlichen Ziele konnten erreicht werden und die Zusammenarbeit funktioniert gut.

Die Liste der Dokumente in Arbeit (Beilage 1) ist lang und zeigt erneut, dass auch im neuen Jahr viel Arbeit ansteht. International stehen die Bearbeitungen der Testbedingungen für Lichtbogendetektor und Test- und Produktenormen für Moduldosen mit integrierter Elektronik im Fokus.

In der Schweiz soll im ersten Halbjahr 2013 in Zusammenarbeit zwischen den TK 64, TK 81 und TK 82 das Merkblatt für den Blitzschutz bei PV-Anlagen als Ergänzung zu den Blitzschutzleitsätzen 4022 veröffentlicht werden. Es werden weitere Bemühungen notwendig sein, um die Richtlinien für die Vorsorge bei Brandereignissen und Brandverhütung zu vereinheitlichen und zu vereinfachen. Dies geschieht weiterhin in Zusammenarbeit mit der VKF und einzelnen kantonalen Versicherungen. Als dritter Schwerpunkt steht die Revision der NIN an.

Aktuell geplant und bekannt sind folgende internationale Meetings mit Teilnehmern aus der Schweiz:

- Sydney, April 2013, WG 3 & WG 6 Meetings
- Herbst 2013, WG 3 & WG 6 Meetings

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[3] PV-Anlagen: Überspannungsschutz und Einbindung in das Blitzschutzsystem, Ergänzung zu den Leitsätzen 4022 der Electrosuisse (Publikation bis im Sommer 2013)

[4] www.iec.ch

[5] www.electrosuisse.ch

[6] www.swissolar.ch

***Beilage 1**: Zusammenstellung der IEC TC 82 und CENELEC Normen und Dokumente in Arbeit*

Project Reference IEC	Title	Forecast Publication Date
IEC 60904-11 Ed. 1.0	Photovoltaic devices - Part 11: Measurement of initial light-induced degradation of crystalline silicon solar cells and photovoltaic modules	2014-03
IEC 60904-8 Ed. 3.0	Photovoltaic devices - Part 8: Measurement of spectral response of a photovoltaic (PV) device	2014-01
IEC 61215 Ed. 3.0	Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval	2014-06
IEC 61683 Ed. 2.0	Photovoltaic systems - Power conditioners - Procedure for measuring efficiency	2011-09
IEC 61730-1 Ed. 2.0	Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction	2014-05
IEC 61730-1 am2 Ed. 1.0	Amendment 2 to IEC 61730-1 Ed.1: Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction	2013-03
IEC 61730-2 Ed. 2.0	Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing	2014-05
IEC 61829 Ed. 2.0	Crystalline silicon photovoltaic (PV) array - On-site measurement of I-V characteristics	2013-05
IEC 61853-2 Ed. 1.0	Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral response, incidence angle and module operating temperature measurements	2012-02
IEC 62109-3 Ed. 1.0	Safety of power converters for use in photovoltaic power systems - Part 3: Particular requirements for PV modules with integrated electronics	2014-12
IEC 62109-4 Ed. 1.0	Safety of power converters for use in photovoltaic power systems - Part 4: Particular requirements for combiner box	2013-02
IEC 62116 Ed. 2.0	Test procedure of islanding prevention measures for utility-interconnected photovoltaic inverters	2013-06
IEC 62446 Ed. 2.0	Grid connected PV systems - Minimum requirements for system documentation, commissioning tests and inspection	2015-01
IEC 62670-1 Ed. 1.0	Concentrator photovoltaic (CPV) performance testing - Part 1: Standard conditions	2013-06
IEC 62670-2 Ed. 1.0	Concentrator photovoltaic (CPV) module and assembly performance testing and energy rating - Part 2: Energy rating by measurement	2013-07
IEC 62688 Ed. 1.0	Concentrator photovoltaic (CPV) module and assembly safety qualification	2014-10
IEC 62716 Ed. 1.0	Ammonia corrosion testing of photovoltaic (PV) modules	2013-08
IEC 62759-1 Ed. 1.0	Transportation testing of photovoltaic (PV) modules - Part 1: Transportation and shipping of PV module stacks	2013-01
IEC 62775 Ed. 1.0	Cross-linking degree test method for Ethylene-Vinyl Acetate applied in photovoltaic modules - Differential Scanning Calorimetry (DSC)	2014-12
IEC 62782 Ed. 1.0	Dynamic mechanical load testing for photovoltaic (PV) modules	2015-03
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IEC 62788-1-2 Ed. 1.0	Measurement procedures for materials used in photovoltaic modules - Part 1-2: Encapsulants - Measurement of volume resistivity of photovoltaic encapsulation and backsheet materials	2014-12
IEC 62788-1-3 Ed. 1.0	Measurement procedures for materials used in photovoltaic modules - Part 1-3: Encapsulants - Measurement of dielectric strength	2014-10
IEC 62788-1-4 Ed. 1.0	Measurement procedures for materials used in Photovoltaic Modules - Part 1-4: Encapsulants - Measurement of optical transmittance and calculation of the solar-weighted photon transmittance, yellowness index, and UV cut-off frequency	2014-12
IEC 62788-1-5 Ed. 1.0	Measurement procedures for materials used in photovoltaic modules - Part 1-5: Encapsulants - Measurement of change in linear dimensions of sheet encapsulation material under thermal conditions	2015-03
IEC 62790 Ed. 1.0	Junction boxes for photovoltaic modules - Safety requirements and tests	2014-06
IEC 62804 Ed. 1.0	System voltage durability test for crystalline silicon modules - Qualification and type approval	2014-12
IEC 62805-1 Ed. 1.0	Test method for total haze and spectral distribution of haze of transparent conductive coated glass for solar cells	2014-12
IEC 62805-2 Ed. 1.0	Test method for transmittance and reflectance of transparent conductive coated glass for solar cells	2014-12
IEC 62817 Ed. 1.0	Solar trackers for photovoltaic systems - Design qualification	2014-08
IEC 62852 Ed. 1.0	Connectors for DC-application in photovoltaic systems - Safety requirements and tests	2014-07
IEC/TS 62257-1 Ed. 2.0	Recommendations for small renewable energy and hybrid systems for rural electrification - Part 1: General introduction to rural electrification	2013-05
IEC/TS 62257-9-5 Ed. 2.0	Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-5: Integrated system - Selection of stand-alone lighting kits for rural electrification	2013-06
IEC/TS 62548 Ed. 1.0	Design requirements for photovoltaic (PV) arrays	2013-01
IEC/TS 62738 Ed. 1.0	Design guidelines and recommendations for photovoltaic power plants	2013-11
IEC/TS 62748 Ed. 1.0	PV systems on buildings	2013-06
IEC/TS 62789 Ed. 1.0	Specification of concentrator cell description	2013-09
PNW 82-747 Ed. 1.0	Polymeric materials for photovoltaic (PV) modules - Part 2: Frontsheets and backsheets	2014-10
PNW 82-751 Ed. 1.0	Indoor testing, characterization and evaluation of the efficiency of photovoltaic grid-connected inverters	2015-10
PNW/TS 82-752 Ed. 1.0	Concentrator Photovoltaic (CPV) modules and assemblies - Design qualification and type approval - Part 9: Retest guidelines (proposed project 62108-9)	2014-05
CENELEC		
EN 50530:2010	Overall efficiency of grid connected photovoltaic inverters	2013-12
EN 50548:2011	Junction boxes for photovoltaic modules	
prEN 50583:2012	Photovoltaics in Buildings	

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Bundesamt für Energie BFE

PV ERA NET

NETWORKING AND INTEGRATION OF NATIONAL AND REGIONAL PROGRAMMES IN THE FIELD OF PHOTOVOLTAIC (PV) SOLAR ENERGY RESEARCH AND TECHNOLOGICAL DEVELOPMENT (RTD) IN THE EUROPEAN RESEARCH AREA (ERA)

Annual Report 2012

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Project- / Contract Number	PV ERA NET / CA-011814
Duration of the Project (from – to)	01.12.2009 – 30.11.2012
Date	December 2012

ABSTRACT

PV ERA NET was a European network of programme coordinators and managers in the field of photovoltaic solar energy (PV) research and technological development (RTD). The consortium involved major key stakeholders in the field of national and regional RTD programmes dealing with photovoltaics (PV).

The general objectives of the network was to further enhance the cooperation between regional and national RTD programmes in an efficient, pragmatic and flexible way, thereby providing substantial added value to the individual programmes, to the network and to the European Research Area as a whole. This cooperation resulted in further improving the effectiveness of the RTD programmes both on an individual and global level in terms of programme management and RTD activities.

Two dedicated transnational calls initiated by PV ERA NET allowed some 40 companies and research institutions for joint activities in PV RTD across Europe. In total, 7 projects were funded with some 4 MEUR.

PV ERA NET had a leading role in submitting a proposal for a network for the Implementation of the Solar Europe Industry Initiative. This proposal was accepted by European Commission and officially started on 1 November 2012, taking over as well the mission of PV ERA NET.

Introduction and goals

PV ERA NET was a European network of programme coordinators and managers in the field of photovoltaic solar energy (PV) research and technological development (RTD). The consortium involved major key stakeholders in the field of national and regional RTD programmes dealing with photovoltaics (PV).

PV ERA NET started in October 2004 as a project supported by the EC within the ERA-NET scheme. After the official project ended in 2009, the network continued its activities supported and managed by the participating partners.

The general objectives of the network were to further enhance the cooperation between regional and national RTD programmes in an efficient, pragmatic and flexible way, thereby providing substantial added value to the individual programmes, to the network and to the European Research Area as a whole. This cooperation resulted in further improving the effectiveness of the RTD programmes both on an individual and global level in terms of programme management and RTD activities.

PV ERA NET was based on two premises: First, PV is seen as a relevant RTD area and a specific thematic focus is desired. Second, international cooperation is understood as a strategic element strengthening the regional / national programmes.

PV ERA NET brought together expertise and ownership, i.e. stakeholders that can actually define and implement concrete actions within and between RTD programmes in the European Research Area.

The working principles were:

- PV ERA NET develops and uses a set of tools that enable and facilitate information exchange and implementation of PV RTD projects. The tools are pragmatic and target-oriented.
- PV ERA NET is complementary to other types of international bodies and flexible in providing essential contributions to international initiatives and activities in a highly dynamic context.
- PV ERA NET taps synergies and seizes opportunities for fomenting PV RTD activities between programmes creating benefits for research and industry both on a national and international level.
- PV ERA NET operates on trustful face-to-face relationships and willingness to actively cooperate.

Nine states (eight countries and one region) were the key members of PV ERA NET (see Table 1).

Brief description of the project

According to the objectives and approach, transnational cooperation focussed on six key activities:

1. To lead the update and to publish survey reports on regional/national PV RTD programmes
2. To coordinate the database on ongoing PV RTD projects
3. To publish relevant information on the website
4. To co-organise and hold consortium meetings and workshops with external stakeholders (one or two times a year according to the needs)
5. To support the implementation of RTD projects
6. To assist the identification of joint activities with other relevant RTD networks (e.g. smart grids; materials)

The first four items were summarised as structured information exchange which was carried out by the individual partners and managed by the PV ERA NETwork secretariat providing basic support and guidance to keep the network running.

The fifth and sixth items led to dedicated transnational activities (e.g. clustering of projects, joint calls, pooling of experts and evaluators) involving the individual partners effectively interested. The PV ERA NETwork secretariat supported the process of identifying, selecting and implementing RTD projects on photovoltaics and related areas.

Table 1: PV ERA NET Partners and Contact Points	
States	Partners
Austria	Federal Ministry for Transport, Innovation and Technology
Denmark	Energinet.dk
France	French Agency for Environment and Energy Management (ADEME)
Germany	Research Center Jülich GmbH
Greece	General Secretariat for Research and Technology, Ministry of Development (GSRT) Centre for Renewable Energy Sources (CRES)
The Netherlands	NL Agency, Directorate Energy and Climate Change
North-Rhine-Westphalia	Cluster EnergyResearch.NRW
Sweden	Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy (SFOE) NET Nowak Energy & Technology Ltd.

Work performed and results achieved

The network activities covered:

- Management of transnational calls and international PV RTD projects
- Survey Report on regional/national PV RTD programmes (1 / year)
- Updating PV RTD Projects Database
- Updating of website
- Workshops for programme peers (1 - 2 times a year)
- Transition to new ERA NET

The **added value** for participating programmes and states was:

- Direct and regular contacts to RTD programme peers
- First hand information and experience on PV, RTD and programming
- Compact and comprehensive information tools (survey, database)
- Strategic basics for RTD programme management and positioning
- Efficient assessment of synergies and opportunities for transnational activities
- More effective PV RTD projects and research by reaching critical mass, defragmentation and cross fertilisation

Some of the main results of PV ERA NET were:

- Dedicated transnational calls (see also Table 2): Two dedicated transnational calls were launched. PV^+ Grid – call on Simulation and System Requirements for High Level Penetration of Photovoltaics in the Electricity Grid – was carried out in 2009 / 2010 with the participation of Austria, Denmark, France, Germany, Greece, North-Rhine-Westphalia, Sweden and Switzerland. POLYMOL – a call on Polymer and Molecular Solar Photovoltaic Cells and Modules with the participation of Denmark, Flanders (Belgium), the Netherlands, Sweden, Switzerland and the United Kingdom – was carried out in 2007 / 2008. The calls allowed some 40 companies and research institutions for joint activities in PV RTD across Europe. In total, 7 projects were funded with some 4 MEUR.
- Survey Reports were annually updated and published. They presented key features of the PV ERA NET states and their programmes. The goal of these reports was to provide an essential overview over each of the country and t he programme(s) involved. The internal report sent to partners provided some additional, mainly financial information.

- Database & Tools: The Projects Database was continuously completed and updated by the individual PV ERA NET partners. The number of projects assessed grew up to over 500. The website provided up-to-date information on the network's ongoing activities and results. It also listed the most recent related documents like PV Status Report, PV NMS NET Status Report, IEA PV Roadmap.
- Network: PV ERA NET allowed for direct and efficient information exchange and joint activities improving cooperation between national and regional programmes. Finally, the network succeeded in submitting a proposal for a new and larger network (SOLAR-ERA.NET) being funded by FP7.

Table 2: PV+ Grids and POLYMOL Projects Funded by PV ERA NET Members

Project acronym	Project full title	Austria	Denmark	Flanders	France	Germany	Greece	The Netherlands	NRW	Sweden	Switzerland	Other	Project costs in kEUR	Requested funds in kEUR
SmoothPV	Smart modelling of optimal integration of high penetration of PV		x			o			x	x		x	1'094	797
HiPe-PV	High-penetration of PV systems in electricity grids	o				x	x				x		775	721
DPVG	Simulation approach to investigate the impact of distributed power production with PV on a power grid	x				x					o		442	240
APOLLO	Efficient areal organic solar cells via printing							x			o	x	1'286	587
POLarge	Polymer solar cells; stabilised morphology and upscaling							x		o			739	619
HIOS-Cell	Nanoscale structuring of hetrojunction ionic organic solar cells by liquid-liquid dewetting							x			o		200	200
PolyStaR	Novel materials and processes for polymer solar cells with improved stability and reliability		o	x									2'118	1'022

o = coordinating project partner x = participating project partner(s)

Evaluation and outlook

PV ERA NET greatly contributed to improving information exchange and cooperation between national/regional programmes dealing with PV RTD. One has to admit that in the early phase of PV ERA NET and the ERA NET scheme in general, launching a joint call was considered something very ambitious or even too ambitious by many stakeholders. Stepping up the subsequent levels of cooperation from information exchange up to dedicated joint activities like transnational calls allowed for gaining experience and trust in new types of collaboration between programmes and countries on one hand, and between companies and research institutions across Europe on the other hand.

In the context of the Strategic Energy Technology Plan (SET-Plan) and the related Solar Europe Industry Initiative (SEII), PV ERA NET played a key role in successfully proposing a large network for the Implementation of SEII on the transnational level: SOLAR-ERA.NET.

Bibliography

The website **www.pv-era.net** provides information on participating RTD programmes and ERA NET with respect to PV technology as well as reports on PV ERA NET activities and funded projects.

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SOLAR-ERA.NET

ERA-NET ON SOLAR ELECTRICITY FOR THE IMPLEMENTATION OF THE SOLAR EUROPE INDUSTRY INITIATIVE

Annual Report 2012

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Project- / Contract Number	SOLAR-ERA.NET / EC FP7 321571
Duration of the Project	01.11.2012 – 31.10.2016
Date	December 2012

ABSTRACT

SOLAR-ERA.NET is a network that brings together more than 20 RTD and innovation programmes in the field of solar electricity technologies in the European Research Area.

The network of national and regional funding organisations has been established in order to increase transnational cooperation between RTD and innovation programmes and to contribute to achieving the objectives of the Solar Europe Industry Initiative (SEII) through dedicated transnational activities (especially transnational calls).

SOLAR-ERA.NET is an EU funded FP7 project running from 2012 to 2016. Through the support of the funding organisations, more than 100 MEUR shall be mobilised for transnational RTD and innovation projects.

Aims of the project / network

The overarching objective of SOLAR-ERA.NET is to effectively implement the Solar Europe Industry Initiative. On this purpose, SOLAR-ERA.NET needs also to:

- build a strong network involving key stakeholders of national and regional RTD and innovation programmes relevant for solar energy (PV and CSP)
- create critical mass and mobilise resources for accelerated technology development and deployment
- apply an efficient and coherent approach for effective transnational collaboration
- support concrete joint activities and projects

If the SOLAR-ERA.NET is effectively implemented, it will:

- contribute to Europe's leading position in solar technologies and sustainable development
- enhance coherency and durable cooperation in ERA

Description of the project

SOLAR-ERA.NET is a FP7 funded European network of national and regional funding organisations and RTD and innovation programmes in the field of solar electricity generation, i.e. photovoltaics (PV) and concentrating solar power (CSP) / solar thermal electricity (STE). Participants are:

- NET Nowak Energy & Technology, Switzerland (coordinator)
- Federal Department for Environment, Transports, Energy and Communication, Switzerland
- Forschungszentrum Jülich, Germany
- Teknologian Ja Innovaatioiden Kehittaemiskeskus (TEKES), Finland
- Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME), France
- Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain
- Service Public de Wallonie (SPW), Belgium
- Agentschap voor Innovatie door Wetenschap en Technologie (IWT), Belgium
- Narodowe Centrum Badan i Rozwoju (NCBR), Poland
- Turkiye Bilimsel ve Teknolojik Arastirma Kurumu (TUBITAK), Turkey
- Ministerie van Economische Zaken, Landbouw en Innovatie / NL Agency, The Netherlands
- Kentro Ananeosimon Pigon ke Exikonomisis Energeias (CRES), Greece
- The Technology Strategy Board (TSB), United Kingdom
- Research Promotion Foundation (RPF), Cyprus
- Regione Puglia, Italy
- Regione Sicilia, Italy
- Bundesministerium für Verkehr, Innovation und Technologie (BMVIT), Austria
- Klima- und Energiefonds, Austria
- Swedish Energy Agency, Sweden

***Figure 1**: Map with countries and regions involved in SOLAR-ERA.NET*

SOLAR-ERA.NET has a double mission: i) as a network in the ERA-NET scheme, it shall improve coordination and cooperation between national / regional RTD and innovation programmes and ii) as a network in the context of the European Strategic Energy Technology Plan (SET-Plan) and Solar Europe Industry Initiative (SEII), it shall implement the SEII on the transnational level (complimentary to actions taken on national and EU level). Altogether SOLAR-ERA.NET shall contribute to reaching the objectives of the Solar Europe Industry Initiative (SEII) by carrying out the coordination and support actions for the implementation of the SEII between national and regional RTD and innovation programmes.

The SEII is embedded in the European Strategic Energy Technology Plan (SET-Plan) which aims to increase, coordinate and focus EU support on key low-carbon energy technologies in order to achieve Europe's 2020 energy objectives in the future. The SEII is a joint initiative of the industry sector, EC and member states. The objective of the SEII is to boost the development of the PV and CSP sector beyond "business-as-usual" in the areas of Research and Development, Demonstration and Deployment. For the concerned solar electricity technologies Implementation Plans have been developed setting out priorities for RTD in Europe.

Key activities of SOLAR-ERA.NET are to undertake joint strategic planning, programming and activities for RTD and innovation in the area of solar electricity generation. Joint activities, namely joint calls, are defined for key topics and priorities in accordance with the SEII. Four transnational calls are planned (one per year) that shall mobilise 50 MEUR of public funding and, in total, 125 MEUR for industry-led RTD and innovation projects.

Work carried out and results achieved

SOLAR-ERA.NET officially started on 1st of November 2012. Its kick-off meeting took place in conjunction with the SEII Team meeting in Brussels mid-November (see figure 2).

***Figure 2**: SOLAR-ERA.NET kick-off meeting in conjunction with SEII Team meeting in Brussels*

One focus was on the organisational and administrative set-up of the new network. But from the very beginning, most important focus was on the first joint calls. Based, SOLAR-ERA.NET prepared the first set of transnational calls PV1 and CSP1 with, among other issues, defining subjects based on the priority topics identified by the SEII Team. The following topics were adopted for this first set of transnational calls:

- PV1.1 Innovative processes for inorganic thin-film cells & modules
- PV1.2 Dedicated modules for BIPV design and manufacturing
- PV1.3 Grid integration and large-scale deployment of PV
- PV1.4 High-efficiency PV modules based on next generation c-Si solar cells
- PV1.5 Solar glass and encapsulation materials
- CSP1.1 Cost reduction and efficiency increase in components
- CSP1.2 Dispatchability through storage and hybridisation
- CSP1.3 New fluids for STE plants

Intense discussion and preparation was also needed in order to define procedures and synchronise the timeline within and between the different countries and programmes involved. In this first round, 15 countries and regions are already prepared to participate with their RTD and innovation programmes in these calls. The total public funding budget for the first set of calls can be estimated at 12 million euros, covering topics both in photovoltaics (PV) and concentrating solar power (CSP).

Innovative project proposals are sought on transnational level between different European countries strengthening the competitive position of the European solar power industry. The project proposals shall clearly demonstrate i) potential commercial impact / relevance to industrial and market needs / contribution to the Solar Europe Industry Initiative and added transnational value, ii) scientific and technological excellence and iii) high quality and efficiency of the implementation and the management. Preproposals must be submitted not later than 15th of May 2013, full proposals by 9th October 2013 with first projects possibly starting end of 2013 / early 2014.

National and international cooperation

International cooperation is in the very core of SOLAR-ERA.NET with the goal to enhance coordination and collaboration between more than 20 RTD and innovation programmes from 17 countries and regions.

Evaluation 2012 and outlook 2013

The official start of SOLAR-ERA.NET was only late in 2012 but first tangible results are already available with a first set of transnational calls being ready for early 2013. The current situation and competition in the PV and CSP industry sector can be characterised as harsh and presents a challenging context as well for SOLAR-ERA.NET. SOLAR-ERA.NET strives to cope best with these challenges and translate them in opportunities for both Europe as a whole and the participating states individually. This will be particularly true in terms of industrial benefits but also in terms of sustainable development and energy supply.

Bibliography

Information can be found on the network's website **www.solar-era.net**.

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SWISS INTERDEPARTMENTAL PLATFORM FOR RENEWABLE ENERGY AND ENERGY EFFICIENCY PROMOTION IN INTERNATIONAL COOPERATION (REPIC)

Annual Report 2012

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Duration of the Project (from – to)	01.04. 2011 – 31.12.2013
Date	June 2013

ABSTRACT

The Swiss State Secretariat for Economic Affairs (SECO), the Swiss Agency for Development and Cooperation (SDC), the Swiss Federal Office for the Environment (FOEN) and the Swiss Federal Office of Energy (SFOE) have been operating the interdepartmental platform for the promotion of renewable energy in international cooperation since 2004. In 2012, phase III of the REPIC Platform was in the second year of operation mainly focusing on the realization of application-oriented projects and possible multiplication of promising project approaches. The REPIC-Platform contributes to the implementation of global climate protection agreements and to a sustainable energy supply in developing and transition countries. The activities represent an important part in the implementation of the Swiss policy for sustainable development on the international level. The REPIC-Platform thereby contributes to the creation of a coherent policy and strategy in Switzerland, for the promotion of renewable energy in international cooperation. The specific goals of the REPIC-Platform in relationship with renewable energy in international cooperation are:

1. Project promotion and project realization
2. Information and communication
3. Coordination

Einleitung

Die seit 2004 bestehende REPIC-Plattform ist eine gemeinsame Initiative des Staatssekretariates für Wirtschaft (SECO), der Direktion für Entwicklung und Zusammenarbeit (DEZA), des Bundesamtes für Umwelt (BAFU) sowie des Bundesamtes für Energie (BFE) zur Förderung der erneuerbaren Energien und der Energieeffizienz in der internationalen Zusammenarbeit – Renewable Energy and Energy Efficiency Promotion in International Cooperation.

Die REPIC-Plattform stellt seit ihrem Bestehen eine neue Form der interdepartementalen Zusammenarbeit dar. Während früher die einzelnen an der Plattform beteiligten Ämter in der Regel individuell und punktuell Projekte mit erneuerbaren Energien und Energieeffizienz in der internationalen Zusammenarbeit gefördert haben, erfolgt heute ein koordinierter Ansatz zur Förderung solcher Projekte. Damit werden ein besser abgestimmtes und einheitlicheres Vorgehen sichergestellt. Die Plattform wirkt subsidiär zu bestehenden Instrumenten der beteiligten Ämter und soll insbesondere dort Wirkung entfalten, wo früher keine oder wenig Aktivitäten stattgefunden haben.

Die REPIC-Plattform leistet einen wichtigen Beitrag zur Umsetzung einer kohärenten Politik und Strategie der Schweiz zur Förderung der erneuerbaren Energien und der Energieeffizienz in der internationalen Zusammenarbeit. Sie trägt zur Umsetzung der globalen Klimaschutzvereinbarungen und zur Förderung einer nachhaltigen Energieversorgung in Entwicklungs- und Transitionsländern ebenso wie in der Schweiz bei und ist damit ein wertvoller Bestandteil der Umsetzung der schweizerischen Politik im Bereich der nachhaltigen Entwicklung auf internationaler Ebene. Der vorliegende neunte Jahresbericht beschreibt die Projektaktivitäten, Resultate und Erfahrungen im neunten Jahr der Plattform.

REPIC versteht sich in ihrem Aufgabengebiet als marktorientiertes Dienstleistungszentrum. Unter Berücksichtigung der vorhandenen Erfahrungen kann diese Plattform Anschubfinanzierungen für neue konkrete und erfolgversprechende Projekte mit erneuerbaren Energien und Energieeffizienz unter vermehrter Mitwirkung von Schweizer Unternehmen und Organisationen leisten. Sie baut dazu ihr Netzwerk zur Information und Sensibilisierung interessierter Kreise laufend aus, pflegt den Erfahrungsaustausch zwischen verschiedenen Akteuren und fördert die Kenntnis von lokalen Rahmenbedingungen und Projektmöglichkeiten. Zusätzlich erfolgt über die REPIC-Plattform die Mitwirkung in internationalen Netzwerken.

Die REPIC-Plattform umfasst die folgenden Arbeitsebenen:

1 Strategische Leitung, gebildet durch die Direktoren der beteiligten Bundesämter
2. REPIC-Steuergruppe, gebildet durch Vertreter der beteiligten Bundesämter
3. REPIC-Sekretariat, bei NET Nowak Energie & Technologie angesiedelt

Die einzelnen Ansprechpartner sind im REPIC-Leitfaden [1] aufgeführt.

Im Jahr 2011 wurde die dritte REPIC Phase gestartet. In dieser Phase wird verstärktes Gewicht auf die konkrete Umsetzung von Projekten und mögliche Multiplikation gelegt.

Schwerpunkte 2012, durchgeführte Arbeiten und Ergebnisse

Die Schwerpunkte der REPIC-Plattform lauteten für 2012 wie folgt:

1. Projektbezogene Aktivitäten
2. Information und Kommunikation
3. Koordination innerhalb der Trägerschaft, mit einschlägigen Finanzorganisationen und mit internationalen Netzwerken

Projektbezogene Aktivitäten

Durch die budget- und verfahrensbedingte Zurückstellung von Projektskizzen und -gesuchen im 2010 gab es nach dem Start der dritten Phase eine hohe Anzahl Projektskizzen und -gesuche zu bearbeiten. 2011 wurden 23 neue Projekte bewilligt und gestartet. Im Jahr 2012 wurden 10 Projekte genehmigt, und 39 Anfragen, Projektskizzen und –gesuche bearbeitet. Die einzelnen Projekte werden weiter hinten in diesem Bericht ausführlich beschrieben.

Information und Kommunikation

Der Fokus in der dritten REPIC-Phase gilt verstärkt der Umsetzung und Multiplikation von erfolgversprechenden Projektansätzen. Unter anderem wurde hierzu vermehrt der Medienkontakt gesucht, um interessierte Kreise, Investoren und Politiker auf erfolgreiche Projekte aufmerksam zu machen und die Multiplikation dieser Projektansätze zu fördern.

Das REPIC-Sekretariat führte diverse Veranstaltungen durch: Am 31. Mai 2012 fand an der Tech4Dev (EPFL, Lausanne) ein Side-Event statt. Nach dem Vorstellen der REPIC-Plattform wurden drei unterschiedliche Projekte präsentiert und anschliessend über deren Zusammenhang mit der Armutsbekämpfung diskutiert. Mit über 30 Teilnehmenden war der Anlass gut besucht. Weiter fand am 29.10.12 der REPIC Workshop Finanzierungs – und Business-Modelle mit über 50 Teilnehmenden [2, 3] statt. Drei Referenten der Stiftung myclimate, der Firmen MicroEnergy International und Impact Finance Management SA sowie die Projektleiter von vier Projekten haben mit ihren Fachbeiträgen den Anstoss für angeregte Diskussionen gegeben. Zudem fand auch in diesem Jahr zur weiteren Vernetzung ein REPIC-Projekttag (siehe unten) innerhalb der Bundesämter statt. Über die Teilnahme an weiteren Veranstaltungen konnten neue Kontakte geknüpft und bestehende gepflegt werden.

Die bewährten REPIC Kommunikationsaktivitäten wurden weitergeführt. Die Website (www.repic.ch) wurde laufend aktualisiert, der REPIC-Leitfaden [1] und der REPIC Flyer [4] standen und stehen weiterhin zur Verfügung. Der REPIC-Leitfaden [1] wurde Anfang 2011 aufgrund der Änderungen der dritten REPIC-Phase aktualisiert. Auch die Schlussberichte abgeschlossener Projekte werden jeweils auf der REPIC-Website aufgeschaltet.

Koordination innerhalb der Trägerschaft, mit einschlägigen Finanzorganisationen und mit internationalen Netzwerken

Die REPIC Plattform wurde auch 2012 intensiv genutzt, um Informationen zu den Tätigkeiten der beteiligten Bundesämter im Bereich der erneuerbaren Energien und der Energieeffizienz in der internationalen Zusammenarbeit auszutauschen und Aktivitäten allenfalls abzusprechen. Unter anderem wurde auch der Kontakt mit den Kooperationsbüros in den Genehmigungsprozess der REPIC-Projekte integriert und so ein intensivierter lokaler Austausch in den Zielländern gesucht. Im Hinblick auf die strategisch verstärkte Umsetzungsorientierung und Multiplikationswirkung wurden vermehrt Kontakte mit anderen Programmen und Initiativen aufgebaut und erweitert. Im 2011 und 2012 betraf dies vor allem Organisationen im Bereich CO_2-Kompensation. Am 14. Juni 2012 wurde zum zweiten Mal ein REPIC-Projekt-Tag im SECO in Bern durchgeführt. Dazu wurden ausgewählte Interessierte innerhalb der REPIC-Bundesämter und einschlägige Finanzorganisationen eingeladen. Es wurden typische abgeschlossene REPIC-Projekte sowie Projekte in der Abschlussphase vorgestellt. Anschliessend fanden angeregte Diskussionen statt. Ziel war es, die Erfahrungen und Resultate aus den Projekten auszutauschen und mit den über 20 Teilnehmenden zu diskutieren. Die Veranstaltung wurde sehr positiv wahrgenommen und soll auch in Zukunft weitergeführt werden.

Projektaktivitäten und Kennzahlen

Die Projektaktivitäten im 2011 waren nach dem Start der dritten Phase sehr intensiv. Bedingt durch eine budget- und verfahrensbedingte Rückhaltezeit von Projekten im 2010 war die Zahl an Projektskizzen und –gesuchen anfangs hoch. Im 2012 ging die Nachfrage etwas zurück:

2011: 45 Projektanfragen / 23 Genehmigte Projekte
2012: 39 Projektanfragen / 10 Genehmigte Projekte

Das Verfahren der Projektbearbeitung und -genehmigung funktioniert gut, vorhandenes Verbesserungspotential wird laufend erkannt und Massnahmen dazu umgesetzt. Bei der Mehrzahl der Projekte kann das Verfahren effizient und wirksam abgewickelt werden.

Im Jahr 2012 lagen die Anfragen mehrheitlich im Bereich der Photovoltaik, die genehmigten und laufenden Projekte hingegen lagen jeweils zu gleichen Teilen im Bereich der Photovoltaik, der Energieeffizienz und der Biomasse.

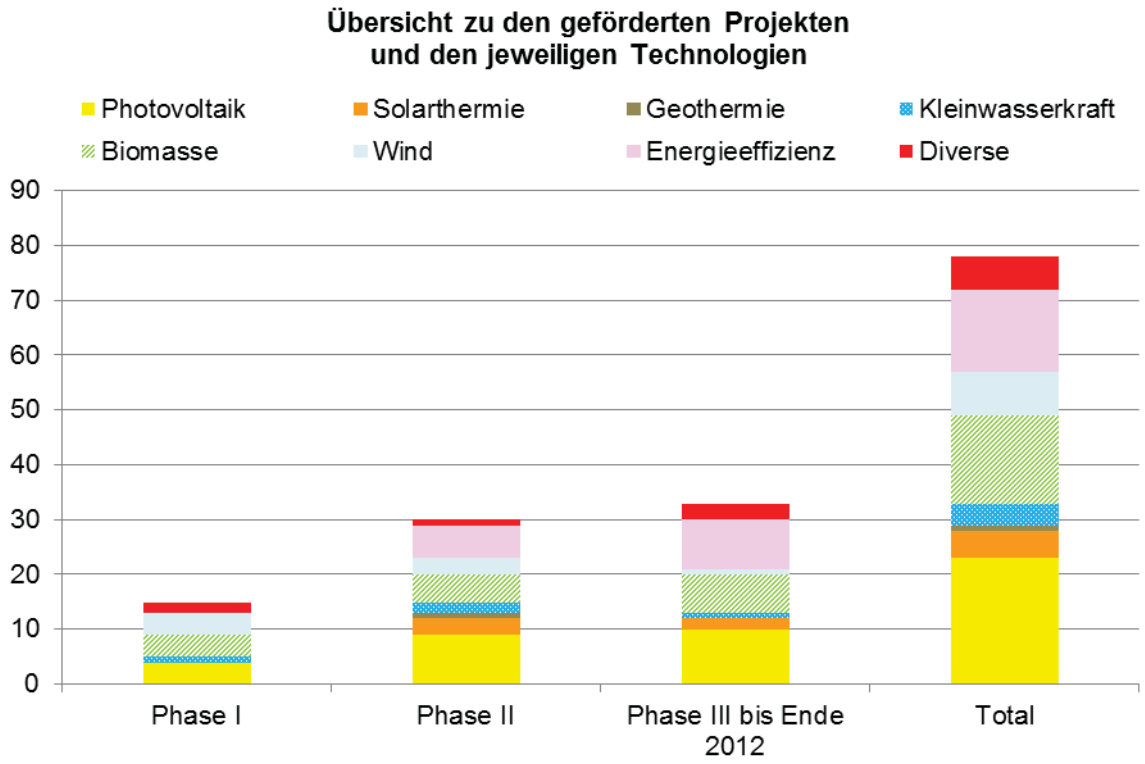
Über alle Phasen hinaus wurden bis Ende 2012 durch REPIC 78 Projekte gefördert. Im Kapitel 8 werden sämtliche im Jahr 2012 laufenden und abgeschlossenen Projekte ausführlicher erläutert.

Phase I
- 15 unterstützte Projekte / das letzte Projekt wurde 2011 abgeschlossen

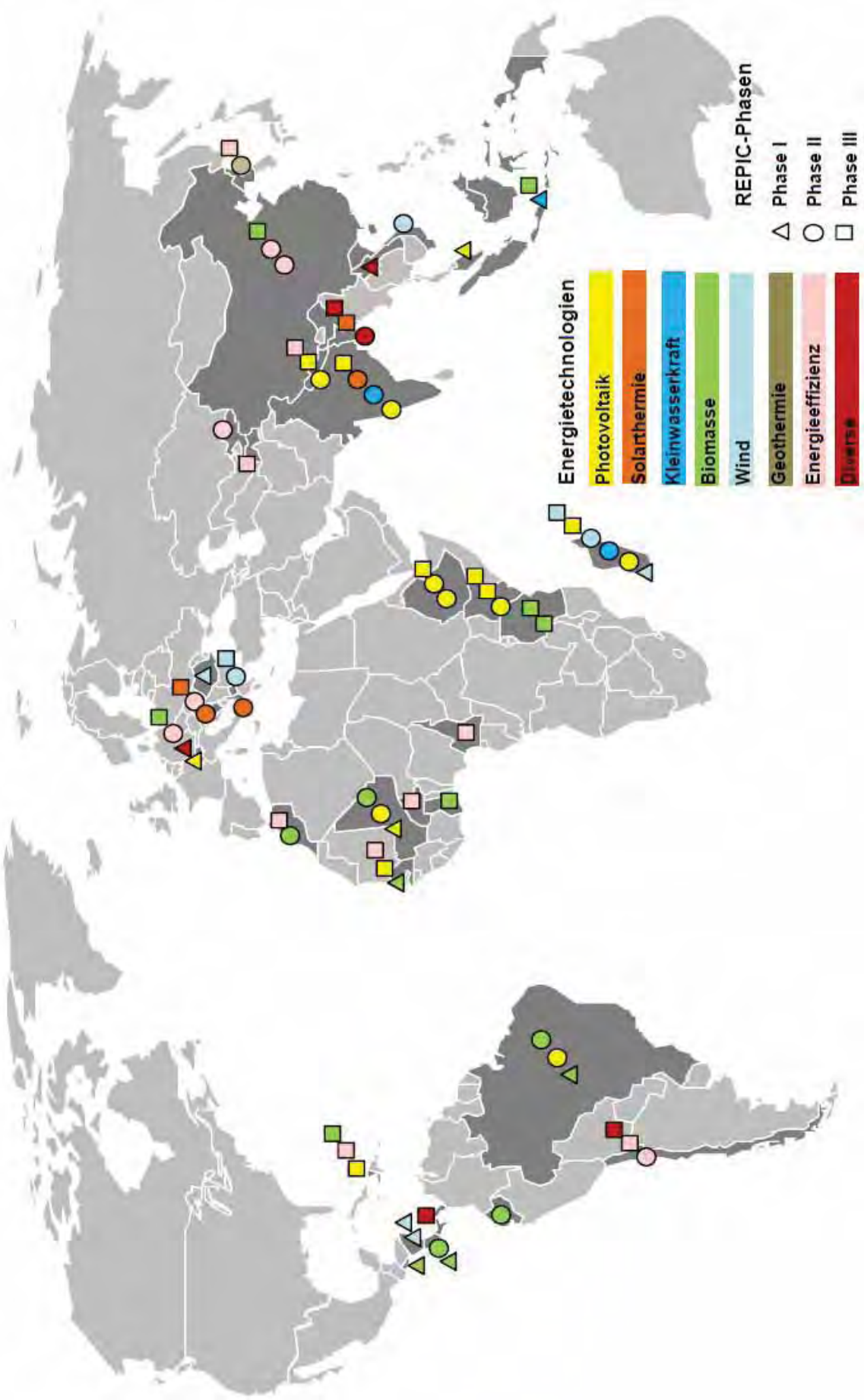
Phase II
- 30 unterstützte Projekte / 29 abgeschlossene Projekte

Phase III
- Bisher 33 unterstützte Projekte, davon 10 im Jahr 2012 / 5 abgeschlossene Projekte

Die Figuren 1 und 2 geben einen Überblick über sämtliche Projektaktivitäten aus allen REPIC-Phasen und deren Verteilung auf die verschiedenen Energietechnologien und Regionen.



Figur 1: *Projektaktivitäten und Technologien aller REPIC Phasen bis Ende Jahr 2012*



Figur 2: *Verteilung aller unterstützten Projekte aus allen Phasen nach Region und Technologiebereich*

Stand der bewilligten REPIC-Projekte aus früheren REPIC-Phasen mit Bezug zur Photovoltaik

Abgeschlossene Projekte mit Bezug zur Photovoltaik

Die erste REPIC Phase wurde hinsichtlich Projektverpflichtungen per Ende 2007 abgeschlossen und sämtliche Projekt aus dieser Phase konnten im Laufe des Jahres 2011 abgeschlossen werden.

Aus der zweiten Phase konnte im Jahr 2012 ein Projekt mit Bezug zur Photovoltaik erfolgreich abgeschlossen werden:

- Sahay Solar Solutions, Äthiopien: Aufbau eines Solar Kompetenz Zentrums, Arbaminch Universität.

Laufende Projekte mit Bezug zur Photovoltaik

- Muntwyler Engineering, Indien: Demonstrationsprojekt Solare Elektrofahrzeuge im öffentlichen Verkehr in Clean Air Island.

Solarkompetenzzentrum an der Arba Minch Universität in Äthiopien

Projektart :	Ausbildung und Qualitätssicherung	**Technologie :**	Photovoltaik
Land :	Äthiopien	**Projektstatus :**	Abgeschlossen
Partner :	Sahay Solar Solutions GmbH, Winterthur, www.sahay-solar.com, Max Pohl ISAAC-SUPSI, Canobbio, www.supsi.ch, Roman Rudel		

© Sahay Solar Solutions

© Sahay Solar Solutions

Schweizer Beitrag

Mit der Schweizer Fachhochschule SUPSI und der Schweizerischen Sozialunternehmung Sahay Solar Solutions steht den äthiopischen Partnern umfassendes Know-How zur Verfügung.

Portrait

Das gemeinsame Ziel der Arba Minch Universität (AMU) in Äthiopien, der Fachhochschule der italienischen Schweiz (SUPSI) in Lugano sowie der Sahay Solar Solutions GmbH aus Winterthur ist der Aufbau von selbsttragenden Ausbildungs- und Marktstrukturen im Bereich Solarenergie.

Der erste Schritt auf diesem Weg ist die Gründung eines äthiopischen Kompetenzzentrums für Solartechnik innerhalb der AMU. Das Kompetenzzentrum umfasst sowohl ein entsprechend ausgerüstetes Solarlabor für Forschungs- und Schulungszwecke als auch die Etablierung eines Lehrstuhls für erneuerbare Energien. Parallel zum Kompetenzzentrum wird ein Konzept für Solarelektrifizierungsprojekte entwickelt, um zukunftsfähige Arbeitsplätze für die ausgebildeten Fachkräfte zu generieren und eine nachhaltige Entwicklung der Initiative unabhängig von Drittmitteln zu ermöglichen.

Resultate

Das Solarkompetenzzentrum an der Arba Minch Universität wurde erfolgreich aufgebaut und ein erweitertes Solarlabor sowie eine PV-Testanlage sind nun integraler Bestandteil des Ingenieurdepartements. Rund 70 Angestellte und Studenten der AMU haben theoretische und praktische Solarschulungen durch SUPSI- und Sahay-Experten besucht. Dadurch konnten in fünf ländlichen Schulen Solaranlagen als praktische Übungen installiert werden. Zudem wurde im Frühling 2012 ein erstes Solar-System als kommerzielles Projekt auf einer Lodge eigenständig durch eines der neu geschulten Teams installiert und die entsprechenden Materialien beschafft.

Wirkung

Das Projekt wird in einer weiteren Phase zusammen mit GIZ weitergeführt und die Trainings werden ausgeweitet. An der AMU konnten vier halbe Stellen geschaffen werden.

Dokumentation

Schlussbericht „Solar Competence Centre (SCC) Arbaminch University, Ethiopia“ [5] zu beziehen bei NET AG, Sahay Solar Solutions oder www.repic.ch.

Demonstrationsprojekt Solare Elektrofahrzeuge im öffentlichen Verkehr in Clean Air Island, Mumbai

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Indien	**Projektstatus :**	Laufend
Partner :	Solarcenter Muntwyler AG und Berner Fachhochschule, Technik und Informatik, Burgdorf, www.ti.bfh.ch, Urs Muntwyler		

© Clean Air Island

© Clean Air Island

Schweizer Beitrag

Der Schweizer Experte bringt mit seinen umfassenden Erfahrungen sowohl im Bereich der Solarenergie als auch im Bereich der Elektrofahrzeuge eine optimale Kombination von Kenntnissen mit, um dieses Projekt zu unterstützen. Weitere Schweizer Technologiepartner werden nach Bedarf einbezogen.

Portrait

Die indische Partnerorganisation Clean Air Island (CAI) ist seit mehreren Jahren bestrebt, die Lebensqualität im Stadtzentrum Mumbais zu verbessern. Ihre Aktivitäten stützen sich dabei hauptsächlich auf die drei Aktionsbereiche Begrünung von Strassen und Parks, Kompostierung von organischen Abfällen und Einsatz von Elektrofahrzeugen.

Im Rahmen dieses Demonstrationsprojekts sollen nun zum ersten Mal Elektrofahrzeuge im öffentlichen Verkehr zum Einsatz kommen und gleichzeitig sollen die Batterien der Elektrofahrzeuge mit Solarstrom gespeist werden. Der elektrische Bus (30 Personen) und das elektrische Sammeltaxi (10 Personen) werden auf einem Rundkurs zwischen zwei Bahnhöfen und dem Geschäftsviertel Nariman Point verkehren und damit einen Teil der tausenden von Pendlern in diesem Gebiet transportieren. Auf dem Dach des Busdepots soll die Photovoltaikanlage installiert werden. Die Fahrzeuge können dort jeweils ihre Batterien mit Hilfe eines Schnelladesystems aufladen oder leere Batterien gegen eine geladene austauschen.

Resultate

Der Elektro-Bus fährt und das Elektro-Taxi wurde getestet. Es entspricht den Erwartungen und ist für den vorgesehenen Fahrbereich in Mumbai geeignet. Es sind noch Detailarbeiten und Verbesserungen im Passagierbereich auszuführen. Es ist vorgesehen, den Betrieb der PV-Anlage und des E-Busses Ende 2013 zu starten.

Stand der bewilligten REPIC-Projekte aus der REPIC-Phase III mit Bezug zur Photoltaik

Projekte in Abschlussphase mit Bezug zur Photovoltaik.

- DT-Power, Kenia: Mobisol – Solar Home Systeme mit GSM Modem für die ländliche Elektrifizierung
- WirzSolar, Haiti: Einführung von Solarpumpen zur Wasserversorgung in der Landwirtschaft

Laufende Projekte mit Bezug zur Photovoltaik

- Entec, International: Schweizer Beitrag im IEA PVPS-Projekt Task 9, Photovoltaic Services for Developing Countries (PVSDC)
- Tritec, Madagaskar: Elektrifizierung der letzten Meile – Stromversorgung mittels Solarenergie in abgelegenen Gebieten in Madagaskar
- Swiss Fresh Water, Senegal: Pilotprojekt eines low-cost und dezentralen Entsalzungssystems im Sine Saloum Delta in Senegal
- SUPSI-ISAAC, Nepal: Netzgekoppelte PV-Pilotanlage
- Berner Fachhochschule, Indien: Mikro-Unternehmen und Kleinbäuerinnen im ländlichen Indien: Innovation durch nachhaltige Energietechnologien, mit der „Swiss Solar Water Pump“

Neue Projektunterstützungen im Jahr 2012 mit Bezug zur Photovoltaik

- Stiftung Solarenergie, Äthiopien: Sun-Control: Verbesserte Technik zur Handhabung und Finanzierung von Solar-Home-Systemen in Äthiopien
- Ernst Basler und Partner AG, Chile: Umweltfreundliche Mobilität auf den Flüssen in Valdivia

Mobisol – Solar Home Systeme mit GSM Modem für die ländliche Elektrifizierung

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Kenia	**Projektstatus :**	In Abschlussphase
Partner :	DT-Power GmbH, Zug, www.dt-power.ch, Dirk Junghans (Geschäftsführer), Thomas Gottschalk (Technischer Direktor)		

© DT-Power

© DT-Power

Schweizer Beitrag

DT-Power ist ein junges Schweizer Unternehmen, welches für das Produkt Mobisol gegründet wurde. Die Verantwortlichen haben mehrere Jahre Erfahrung im Bereich der erneuerbaren Energien.

Portrait

Die Entwicklung der Elektrifizierung in Kenia konzentriert sich hauptsächlich auf das städtische Gebiet. Das Solar-Home-System (SHS) „Mobisol“ wurde entwickelt, um auch den Bedarf in den ländlichen Gebieten zu decken. Dieses System besteht aus einem Photovoltaik (PV) Modul, welches mit einem „Global System for Mobile Communication“ (GSM) Modem ausgerüstet ist und eine Fernkontrolle des Produkts erlaubt. Das Angebot beinhaltet ein Zahlungssystem (pay-as-you-go) welches speziell an die Zahlungsmöglichkeiten der lokalen ländlichen Bevölkerung angepasst ist. Für das Angebot, die Verteilung und das Monitoring wird das Netz eines nationalen Mobiltelefonanbieters genutzt. Das Pilotprojekt hat zum Ziel, die Vertrauenswürdigkeit der technischen Komponenten, der Vermarktung und die Wirtschaftlichkeit von 100 Mobisol-Systemen in Kenia zu prüfen. Das Mobisol-Projekt versucht, ein System zur Verfügung zu stellen, welches sowohl für die Kunden wie auch für die Investoren finanziell machbar ist.

Resultate

Das Projekt hat im Dezember 2011 angefangen, es konnten 100 Mobisol Solar Home Systeme installiert und erfolgreich betrieben werden. Die Zahlungen der Kunden trafen über M-Pesa ein, mit diesem Zahlungssystem wurden die SHS deutlich erschwinglicher. Das Pilotprojekt hat wertvolle Erfahrungen im Feld ermöglicht, welche zu Verbesserungen der Dienstleistungen sowie des Systems geführt haben. Bereits nach dieser ersten Phase kann das Projekt erfolgreich weiterlaufen.

Vorbereitung zur Multiplikation des Mali-Solarpumpenprojekts in Haiti

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Haiti	**Projektstatus :**	In Abschlussphase
Partner :	WirzSolar GmbH, Sissach, Fredy Wirz		

© *WirzSolar*

© *WirzSolar*

Schweizer Beitrag

WirzSolar GmbH besitzt langjährige konkrete Erfahrung mit Solarpumpenprojekten in Entwicklungsländern, insbesondere in Mali, wo bereits solche durch REPIC unterstützte Projekte stattgefunden haben.

Portrait

In Haiti können Solarpumpen optimal und nachhaltig eingesetzt werden, um das teure und weitverbreitete Verteilen von Trinkwasser mit Zisternenwagen (Watertrucking) zu ersetzen und günstig mehr sauberes Trinkwasser auf bestehenden oder jetzt neu errichteten Brunnen zu fördern.

Dieses Projekt beinhaltet die Vorbereitung für ein möglicherweise grösseres Solarpumpenprojekt ab 2012 in Haiti. Zusammen mit den Wasserbehörden und UNICEF soll ein Programm zur nationalen Ausbildung von lokalen Technikern und Sensibilisierung aller Akteure erarbeitet werden. Zudem sollen durch den Einsatz von Demo-Solarpumpensystemen und dem Austesten von drei in der Schweiz entwickelten Mini-Solarpumpen zum Ausrüsten von Handpumpen konkrete Verbesserungen in der Trinkwasserversorgung vor allem in Schulen im Erdbebengebiet Leogane erzielt werden.

Der vorgesehene Süd-Süd Know-How Transfer der Erfahrungen aus Mali nach Haiti enthält Ausbildungskomponenten zur erfolgreichen Weiterführung und zur Multiplikation der Erfahrungen aus dem Mali Solarpumpenprojekt.

Resultate

Fünf Demonstrationsanlagen in Schulen konnten aufgebaut und Tests mit den neuen Mini-Solarpumpen für Handpumpen durchgeführt werden. Zu Beginn wurden die ersten Anlagen zusammen mit dem malischen Techniker installiert und ein kleines haitianisches Installationsteam aufgebaut und trainiert.

Schweizer Beitrag im IEA PVPS-Projekt Task 9
Photovoltaic Services for Developing Countries (PVSDC)

Projektart :	Netzwerk	**Technologie :**	Photovoltaik
Land :	Internationales Projekt	**Projektstatus :**	Laufend
Partner :	entec AG, St. Gallen; www.entec.ch, Alex Arter, Thomas Meier		

© IEA PVPS

© Entec

Schweizer Beitrag

Die Schweizer Erfahrung in der internationalen Zusammenarbeit und das bei entec verfügbare Know-how aus einem verwandten Gebiet (Kleinwasserkraft) stellen wesentliche Beiträge zu diesem Projekt dar, insbesondere auch in Bezug auf die Übertragbarkeit der Resultate auf andere Technologien.

Portrait

Gestützt auf die umfangreichen weltweiten Erfahrungen mit Photovoltaik Anlagen in Entwicklungsländern strebt dieses Netzwerk die Erhöhung von erfolgreich und nachhaltig betriebenen Anlagen dieser Art für unterschiedliche Zwecke an. Die internationale Expertengruppe umfasst auf diesem Gebiet eine breite Projekterfahrung und konzentriert ihre Arbeit insbesondere auf die nicht-technischen Aspekte dieser Anwendungen. Durch den Status eines internationalen Netzwerkprojektes ist die Expertengruppe in permanentem Kontakt mit zahlreichen internationalen Entwicklungsorganisationen.

Dieses Netzwerkprojekt startete 1999 und wird in verschiedene Arbeitsperioden gegliedert. Seit 2010 steht das Thema Photovoltaik und Wasserpumpen im Mittelpunkt und wird von der Schweiz koordiniert. Hauptanliegen ist die Verbreitung der Erkenntnisse aus diesem Netzwerk. Die Arbeitsperiode 2012 schliesst das Thema Photovoltaik und Wasserpumpen ab und setzt den Fokus auf das Herstellen und Umsetzen einer Partnerschaft mit dem ASEAN Center for Energy (ACE). Die Aktivitäten bestehen aus entsprechenden Koordinationsaufgaben, der Erarbeitung und Publikation von Studien sowie der Organisation von Workshops und Veranstaltungen.

Resultate

Die verfolgten Ziele wurden erreicht und das Thema Photovoltaik und Wasserpumpen konnte an einem Treffen abgeschlossen werden. Die Berichte „PHOTOVOLTAIC SERVICES FOR DEVELOPING COUTRIES (PVSDC)“ working period 2012 und „Pico Solar PV Systems for Remote Homes“ sind wichtige Dokumente für die Verbreitung der Erkenntnisse. Die Publikationen zum IEA PVPS Task 9 stehen unter http://www.iea-pvps.org/tasks/task9.htm zur Verfügung.

Elektrifizierung der letzten Meile
Stromversorgung mittels Solarenergie in abgelegenen Gebieten in Madagaskar

Projektart :	Infrastrukturorientiertes Projekt	**Technologie :**	Photovoltaik
Land :	Madagaskar	**Projektstatus :**	Laufend
Partner :	TRITEC International AG, Allschwil, www.tritec-energy.com, Giordano Pauli		

© *Tritec*

Schweizer Beitrag

TRITEC ist seit über 20 Jahren ein Photovoltaik-Systemlieferant und hat anlässlich eines früheren Entwicklungsprojektes bereits an der Implementierung von dezentralen Photovoltaiksystemen in Madagaskar mitgewirkt. Der Schweizer Beitrag bezieht sich hauptsächlich auf das Training der lokalen privaten Operateure und Mitarbeitern von ADER sowie auf das Solarmaterial der ersten Gemeinde.

Portrait

87% der madagassischen Familien haben keinen Zugang zum Stromnetz und benützen Kerzen oder Kerosinlampen um ihre Zimmer nachts zu beleuchten. Soziale Infrastrukturen wie Schulen, Gesundheitszentren, Rats- oder Gemeindehäuser und öffentliche Plätze verfügen in ländlichen Gebieten oft über keinen Strom. Das gemeinsam mit der madagassischen ADER (Agence de Développement de l'Electrification Rurale) und der Deutschen Gesellschaft für Internationale Zusammenarbeit (GIZ) durchgeführte Projekt verfolgt die folgenden zwei Ziele:

1. Bereitstellung von Elektrizität für soziale Infrastrukturen in 4 prioritären ländlichen Gemeinden im Süden Madagaskars, betrieben durch eine lokale private Firma.

2. Information und Ausbildung über die Vorteile von Solarenergie für einkommensschwache Haushalte in den ländlichen abgelegenen Gebieten durch Mobil-Kommunikation.

Der Zugang zu Pico-Solarsystemen und die Verwendung der Mobil-Kommunikations-Einheiten erfolgen durch erschwingliche Verkaufs-/Mietsysteme. Das Projekt visiert ca. 20'000 Haushalte in den ärmsten ländlichen Regionen Madagaskars an, in denen heutzutage noch keine modernen Energiedienstleistungen verfügbar sind.

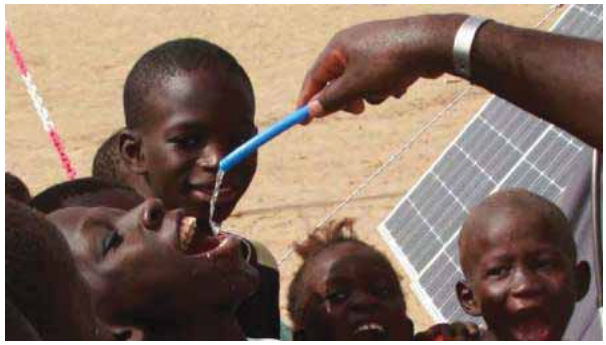
Resultate

Für ortsansässige Ingenieure und Firmen wurden Schulungen in Tulear und in Antananarivo durchgeführt, diese stiessen auf grosses Interesse. Zudem wurden neben diversen Abklärungen in zwei Gemeinden sozialen Einrichtungen wie Schulen und Krankenstationen als Zielobjekte für Solarstromanlagen ausgesucht. Die Planung, die Bestellung und Lieferung der Systeme ist erfolgt.

Pilotprojekt eines low-cost und dezentralen Entsalzungssystems im Sine Saloum Delta in Senegal

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Senegal	**Projektstatus :**	Laufend
Partner :	Swiss Fresh Water, Lausanne, www.swissfreshwater.com, Renaud de Watteville		

© Swiss Fresh Water



© Swiss Fresh Water

Schweizer Beitrag

Swiss Fresh Water ist ein neues Start-up-Unternehmen der ETH Lausanne. Die Leiter weisen breite Erfahrung im Projektmanagement und der Wasserbehandlung auf. Das Projekt wird in enger Zusammenarbeit mit der Firma Impact Finance aus Genf durchgeführt. Sie ist auf die Entwicklung und Finanzierung von Projekten in Entwicklungsländern spezialisiert.

Portrait

Swiss Fresh Water (SFW) entwickelte ein low-cost Entsalzungssystem für Salz- und Brackwasser, welches eine Produktion im kleinen Massstab erlaubt. Das System wurde für eine einfache Benutzung entwickelt, es ist einfach im Unterhalt und konsumiert wenig Energie.

SFW hat entschieden, ein Pilotprojekt im Sine Saloum Delta durchzuführen, in dem 225‘000 Menschen leben. Ausserhalb der Regenzeit, d.h. ca. 8-9 Monate des Jahres, trinkt die Bevölkerung vor allem Wasser aus Brackwasser-Bohrungen. Dieses Wasser ist stark Fluor-belastet und bewirkt ernsthafte Gesundheitsprobleme. Wenn es sich die Bevölkerung leisten kann, kauft sie sich regelmässig importiertes Trinkwasser, welches per Boot, Auto oder Lastwagen zu den Inseln gebracht wird. Das Projekt von SFW will dazu beitragen, die Auswirkungen der Wasserversorgung auf die Gesundheit und den Bedarf an Zeit, Geld und Energie (Transport) zu verringern.

Gemäss den Erwartungen des SFW wird der Erfolg des Pilotprojektes bestätigen, dass das low-cost und dezentrale Konzept ein grosses Potenzial in Senegal hat. Dort wurden auch bereits andere Regionen identifiziert, welche sich für eine Replikation des Projekts eignen würden.

Resultate

Die Maschinen funktionieren problemlos und ohne Ausfälle. Zu Beginn des Projekts konnten mit dem Einsatz von Sonnenenergie bis zu 400 l Trinkwasser/Tag, mit der Weiterentwicklung der Maschinen und je nach Stromversorgung und Betrieb können nun bereits bis zu 4‘000 l Trinkwasser/Tag dem Filter entnommen werden. Ein Upscaling-Projekt ist in Planung.

Netzgekoppelte PV-Pilotanlage in Nepal

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Nepal	**Projektstatus :**	Laufend
Partner :	SUPSI-ISAAC, Canobbio, www.isaac.supsi.ch, Domenico Chianese, Roman Rudel		

© *ISAAC*

© *ISAAC*

Schweizer Beitrag

Der Schweizer Partner bringt breite Erfahrung im Bereich netzgekoppelter Photovoltaik und Ausbildung mit. Die Photovoltaik-Abteilung des ISAAC ist ein Schweizer Kompetenz-Zentrum für das Testen von PV-Modulen.

Portrait

Das Projekt handelt von der Realisierung und dem Monitoring einer netzgekoppelten Photovoltaik-Pilotanlage im Kathmandu-Tal. Es hat sich weiterentwickelt aus den ermutigenden Resultaten der bereits durchgeführten REPIC-Machbarkeitsstudie zu netzgekoppelter Photovoltaik in Nepal. Der aktuelle Mangel an einem zuverlässigen Stromnetz und die gestiegenen Bedürfnisse der Nutzer (kleine und mittlere Unternehmen, Bevölkerung) können durch eine dezentrale und partiell autonome Stromversorgung gelöst werden.

Das Pilotprojekt sieht den Entwurf, den Bau und das Monitoring einer 1 kWp netzgekoppelten PV-Anlage vor. Dazu gehört ein Back-Up-System, welches als Mini-Grid funktionieren kann. Zusätzlich zur Realisierung der Pilotanlage beinhaltet das Projekt Ausbildungskomponenten. Ein weiterer wichtiger Teil besteht aus der Demonstration und Verbreitung der Installationsresultate und der gesamten technischen Charakteristiken. Die Erfahrung aus dem Projekt soll auch als Referenz für ähnliche mögliche Entwicklungen in anderen einkommensschwachen Ländern dienen.

Resultate

Inzwischen wurden fünf Anlagen inklusive Überwachung in Betrieb genommen. Die Messungen zeigen die Grenzen des lokalen Netzes auf. Häufige Netzausfälle und grosse Spannungs- und Frequenzschwankungen sind ein Herausforderung für die Netzeinspeisung. Nach Anpassung der Wechselrichter-Parameter laufen die Anlagen mit einer hohen Verfügbarkeit und einer Performance Ratio von > 80%. Unter http://www.pvnepal.supsi.ch können vier der fünf Anlagen online abgerufen werden. Im November 2012 wurde an der Tribhuvan Universität in Kathmandu ein Seminar zum Thema ‘Netzgekoppelte Solarstromanlagen‘ mit 60 Teilnehmern durchgeführt. Es nahmen viele Ingenieure und Studenten teil. Zum Thema elektrische Netze konnten namhafte Entscheidungsträger des Centre of Energy Study der Tribhuvan Universität und der Nepal Electricity Authority als Referenten eingebunden werden.

Mikro-Unternehmen und Kleinbäuerinnen im ländlichen Indien: Innovation durch nachhaltige Energietechnologien, mit der „Swiss Solar Water Pump“

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Indien	**Projektstatus :**	Laufend
Partner :	Berner Fachhochschule, Technik und Informatik, Biel, www.bfh.ch, Eva Schüpbach		

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Schweizer Beitrag

Das Labor für Industrieelektronik an der Fachhochschule Bern in Biel hat für die Entwicklung der Wasserpumpe eng mit Fachpersonen der Entwicklungszusammenarbeit wie Caritas und Seecon zusammengearbeitet. Frau Prof. Dr. Eva Schüpbach pflegt im Bereich der globalen Veränderungen die regelmässige Zusammenarbeit mit den indischen Hochschulen.

Portrait

Das Ziel des Pilotprojekts ist die Einführung einer nachhaltigen Energietechnologie in kleinen indischen Landwirtschaftsbetrieben. Für den Anfang beschränkt sich das Projekt auf die Region Karnataka. Die angewandte Technologie « Swiss Solar Water Pump » ist ein einzigartiges, kleines und günstiges Wasserpumpsystem, welches mit Strom aus 80W Photovoltaikanlagen gespeist wird. Diese Technologie wurde von der Berner Fachhochschule entwickelt. Sie ist flexibel und von langer Lebensdauer und kann lokal produziert und gewartet werden. Die Umsetzungsstrategie des Projekts richtet sich an Frauengruppen und Unternehmerinnennetzwerke. Der Wissenstransfer ist in Form von Seminaren und Arbeitsgruppen vorgesehen, woran auch die Hochschulen und Schweizer sowie Indische Unternehmen teilnehmen werden.

Resultate

Das Projekt startete im Februar 2012 mit einem Kick-off-meeting in Bangalore. Im Verlaufe des letzten Jahres wurde ein erster Teil der Pumpen installiert. Es konnte bisher eine Frauengruppe im Projekt miteinbezogen werden, die Resultate deren Betriebsweise wird mit jenen aus den von Männern dominierten Regionen verglichen. Mittels einer Umfrage und den Erfahrungen während dem Projekt konnte Verbesserungspotential erkannt werden, welches im Projekt laufend eingebaut wird.

Sun-Control: Verbesserte Technik zur Handhabung und Finanzierung von Solar-Home-Systemen in Äthiopien

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Äthiopien	**Projektstatus :**	Laufend
Partner :	Stiftung Solarenergie, Zürich, www.stiftung-solarenergie.ch, Harald Schützeichel		

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Schweizer Beitrag

Die Stiftung Solarenergie hat mit REPIC-Unterstützung bereits verschiedene Solar-Center, welche Solartechniker-Ausbildungen anbieten, aufgebaut und diese anschliessend weitergeführt und ausgebaut. Sie verfügt dadurch über sehr viel Erfahrung in Äthiopien im Bereich Solarenergie.

Portrait

Im vorliegenden Pilotprojekt sollen in Äthiopien 500 neuartige Solar-Home-Systeme eingesetzt und getestet werden. Diese werden vor Ort zusammengebaut und verkauft, während der Pilotphase jedoch noch mit Subventionierung. Die neuartigen Solar-Home-Systeme sollen die Verbreitung der Solartechnik erleichtern, indem sie einen neu entwickelten Laderegler einsetzen. Damit sollen die Nutzer bessere Informationen über den Zustand des Solar-Home-Systems erhalten inklusive der verbleibenden Nutzungsdauer sowie direkt mittels integriertem Prepayment-System eine Unterstützung durch Mikrokreditorganisationen erhalten. Die neuartigen Solar-Home-Systeme werden im Pilotdorf oder in zwei bestehenden Solarcentern eingesetzt.

Resultate

Die Komponenten für die Solar Home Systeme wurden bestellt und sollen vor Ort zusammengebaut und programmiert werden. Verbesserungen in der Software des innovativen Ladereglers konnten eingefügt werden, womit das Programmieren der CODES zur Bezahlung erheblich erleichtert wird. Eine ausführliche Schulung in Zusammenbau, Programmierung und Wartung der Laderegler ist erfolgt.

Umweltfreundliche Mobilität auf den Flüssen in Valdivia

Projektart :	Pilotprojekt	**Technologie :**	Photovoltaik
Land :	Chile	**Projektstatus :**	Laufend
Partner :	Ernst Basler und Partner AG, Zollikofen, www.ebp.ch, Roger Walther		

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Schweizer Beitrag

Der Schweizer Projektpartner EBP verfügt über viel Erfahrung mit Energieffizienzprojekten und Mobilität und der Projektleiter kennt die Situation vor Ort sehr gut. Beim Projekt soll auch von den Erfahrungen vom Schweizer Pilotprojekt „Alpmobil“ im Goms profitiert werden, in welchem rund 50 Elektrofahrzeuge eingesetzt und von Touristen und Einheimischen tageweise gemietet werden können.

Portrait

Im Süden Chiles liegt die Stadt Valdivia, die von zahlreichen Flüssen umgeben ist und mit den üblichen Verkehrsproblemen lateinamerikanischer Städte zu kämpfen hat. Endziel und Wirkung des vorliegenden Pilot- und Demonstrationsprojektes soll sein, mittelfristig einen Teil des motorisierten Individualverkehrs auf Solar- bzw. Elektroboote umzulenken. Dafür soll auf den Flüssen für Studenten und Berufstätige ein öffentliches Verkehrssystem aufgebaut werden. Basis sind zwei erste solarbetriebene Elektroboote, welche von der bedeutenden lokalen Schiffsbaufirma Alwoplast bereits entwickelt und für den Passagiertransport im Pilotprojekt zur Verfügung gestellt werden. Weitere Elemente des Projektes sind eine schwimmende Solarstation, welche u.a. zum zusätzlichen Aufladen der Boote dient, und Anlegestege für die Verbindung mit dem öffentlichen Verkehr. Hauptinhalt des Pilotprojektes ist es, diese zwei Elektroboote auf den ersten drei Routen einzusetzen, neue Anlegestege einzurichten und Verbindungen mit dem öffentlichen Verkehr zu schaffen. Der Betrieb der Elektroboote wird getestet und evaluiert in Bezug auf Wirtschaftlichkeit, Organisation und soziale Akzeptanz. Gleichzeitig soll das Pilotprojekt in der Öffentlichkeit kommuniziert werden. Durch den Einbezug der lokalen Universität, bei der die operative Projektleitung liegt, soll auch Forschung und Entwicklung im Bereich der erneuerbaren Energien gefördert werden.

Resultate

Die Elektroboote sowie die Solarstation sind in Betrieb und funktionieren problemlos, sechs weitere Anlegestege konnten für den Wassertransport integriert werden. Die staatliche Stelle vor Ort nimmt mittel- und langfristig eine zentrale Rolle ein.

Beurteilung 2012

Nach dem Start der dritten REPIC Phase Anfang 2011 kann nach zwei Jahren eine Zwischenbeurteilung bezüglich der formulierten Ziele erfolgen.

In der dritten Phase wurden bis jetzt mehr Projekte gefördert als in der gesamten zweiten Phase, nämlich total 33 bis Ende 2012. Das bisher in der dritten REPIC Phase ausgelöste Projektvolumen ist über 3-mal grösser als die verpflichteten REPIC-Beiträge. Zudem sind bereits 2/3 der für die Projektförderung zur Verfügung stehenden Mittel für konkrete Aktivitäten in Entwicklungs- und Transitionsländern reserviert.

Bei den bisher abgeschlossenen Projekten aus der dritten Phase ist ersichtlich, dass diese insgesamt tiefer in die Umsetzung gehen, allerdings abhängig vom Entwicklungsgrad der verwendeten Energietechnologie. Vor allem bei der Biomasse müssen häufig noch weitere Erkenntnisse für eine erfolgreiche, dem Standort angepasste Umsetzung gewonnen werden. Pilotprojekte mit konkreten Anlagen haben deutlich zugenommen und es wird darauf geachtet, dass weitere Schritte für die Multiplikation eingeleitet werden. Bei Folgeprojekten stellt sich die Finanzierung oft als grösste Schwierigkeit heraus. Häufig zeichnet sich zwischen Pilotphase und Markteintritt eine Finanzierungslücke ab. Hingegen entsteht bei Capacity Building Projekten im Allgemeinen eine anhaltende Wirkung. Konkrete Aussagen über die langfristigen Wirkungen der Projekte sind noch nicht möglich, da dies einen längeren Betrieb der Anlagen voraussetzt. Mittels Rückfragen, Einladung zu Veranstaltungen und der Netzwerkpflege werden die Projekte laufend weiterverfolgt.

Die REPIC-Plattform ist unter den relevanten Akteuren bekannt. Sie ist gut etabliert und spielt im schweizerischen Kontext eine wichtige Rolle. Entsprechend wird die Plattform aktiv genutzt, was sich unter anderem mit den bereits 33 geförderten Projekten zeigt.

REPIC war auch im 2012 bei relevanten Tagungen und Workshops im Bereich erneuerbare Energien präsent. Zudem organisierte REPIC einen Workshop zu aktuellen Fragen zu Finanzierungs- und Businessmodellen, welcher auf grosses Interesse stiess und positive Rückmeldungen erhielt.

Die Koordination zwischen den beteiligten Bundesämtern verlief wie bis anhin effizient und die Plattform wird rege zum Austausch genutzt. Die Qualität der Projekte und Massnahmen sind mit wohl begründeten Entscheiden gesichert. Doppelspurigkeiten konnten vermieden werden.

Weiteres Verbesserungspotential einer möglichen nächsten Phase wird unter Einbezug der Erfahrungen und Meinungen der relevanten Akteure systematisch untersucht.

Ausblick 2013

Für 2013 steht weiterhin die Umsetzung der Schwerpunkte und Ziele der dritten REPIC Phase im Vordergrund. Zudem werden Abklärungen für eine weitere REPIC Phase durchgeführt, insbesondere bezüglich des Verbesserungspotentials und Anpassungsbedarfs. Unter anderem stellen sich Fragen im Bereich der Finanzierungsinstrumente, der Netzwerkpflege zu weiteren Finanzierungspartnern und eine verstärkte Vernetzung zu anderen Initiativen.

In der Projektförderung läuft noch ein letztes Projekt der zweiten Phase weiter, aus der dritten Phase werden die gut 25 laufenden Projekte sowie die zukünftigen im Jahr 2013 genehmigten Projekte weiter betreut, so dass die Projekte so gut wie möglich und erfolgreich im vorgesehenen Zeitplan durchgeführt werden können.

Bei abgeschlossenen Projekten wird das Monitoring des weiteren Projektverlaufs sichergestellt und die Entwicklung von Folgeprojekten aktiv begleitet. Es ist wiederum ein REPIC-Tag zur Vorstellung erfolgsversprechender Projekte in einem weiteren Kreis von Finanzierungsgebern und Akteuren vorgesehen. Dieser bietet die Gelegenheit, Ergebnisse und Erfahrungen aus laufenden und abgeschlossenen Projekten in Hinsicht auf Erfolgskriterien und lessons learned auszutauschen.

Auch die Koordinations-, Kommunikations- und Vernetzungsaktivitäten werden weitergeführt. Die Informationstätigkeit der REPIC-Plattform erfolgt an spezifischen Anlässen wie auch über ausgewählte Medien, damit REPIC in breiten Kreisen und insbesondere in der Politik bekannter wird. Angesichts der vielfältigen und vermehrt umsetzungsrelevanten Aktivitäten zu erneuerbaren Energien und Energieeffizienz von REPIC wird der Koordination und Kommunikation innerhalb der Plattform, aber auch mit Finanzdienstleistern sowie internationalen Organisationen und Netzwerken, eine besondere Bedeutung beigemessen.

Referenzen

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