Impact of Technology Developments and Cost Reductions on Market Growth

REMAC 2000

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Work Package 1 : Technology

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Technical reports of work package 1 of the REMAC2000 project

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The report is mainly based on the internal technical reports (incl. references given in more detail):

Part 1: Bioelectricity
Part 2: Geothermal Electricity
Part 3: Small Hydro Power
Part 4: Solar Photovoltaic Electricity
Part 5: Solar Thermal Electricity / Concentrating Solar Power
Part 6: Wind energy

Notice to the reader

The structure of the reports (part 1 to 6) is based on common sections generally defined for all technologies under consideration. Subsections can contain similar or identical (thus overlapping) issues relevant to each of the subsections concerned. The approach is to make each subsection as complete as possible and subsequently facilitate the search of information. In this sense, the reports (part 1 to 6) are considered as working document.

CONTENTS

PART A : Executive Summary

PART B : Contents of technology specific summaries

1 Introduction

1.1 Objectives

The objective of this technical work package is to analyse the impact of technology developments and cost reductions on RE market growth.

The overall objective of the project is the acceleration of the RE market(s) by selecting and bringing together influential public and private sector decision makers, and in gathering the most up-to-date information on RE technologies, industries and markets.

The technology section of the project seeks to cover the relevant aspects in the field of technology development with respect to the overall objective set, i.e. mainly up-to-date information on RES-E technologies.

1.2 Issues

The analysis and synthesis emphasise the relevant technological aspects that allow for improving the situation of the electricity coming from renewable energy sources (RES-E) on the market (see table below), i.e. mainly:

- Cost reduction: investment and energy costs decrease
- Performance increase: operation and efficiency of the system and its components is improved
- Applicability enhancement: better and new products and applications to conquer the market(s)

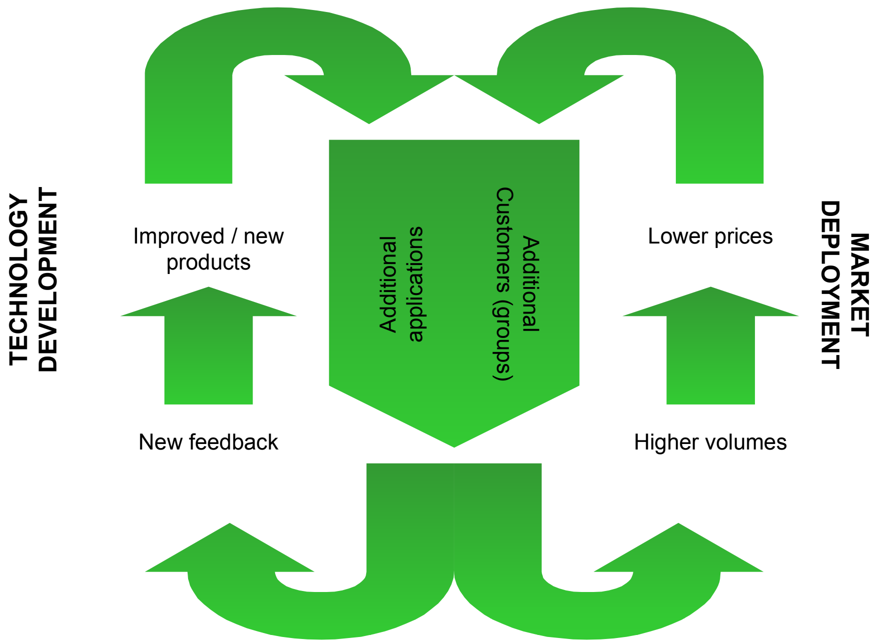


Figure 1 : Positive effects on technology development and market deployment based on technology improvement and innovation respectively customer's appreciation of RE value. Policy and business can positively effect both sides, investments on the technology development side (e.g. R&D, capital cost grants) and market expansion on the market deployment side (e.g. monetising added values).

Table 1: Renewable electricity technologies / sources assessed and analysed in the REMAC project

RE technology based electricity / power
1. Biomass electricity / bioelectricity
2. Geothermal electricity / power
3. Solar photovoltaic electricity / power
4. Solar thermal electricity / Concentrating solar power
5. Small hydro electricity / power
6. Wind electricity / power

Accordingly, the issues dealt with and the results generated allow for drawing a synoptic picture of the RES-E from the techno-economic point of view. Main issues are:

- Techno-economic development including major steps and trends
- Costs and cost reduction opportunities
- Potential
- Market and market growth opportunities
- Needs and measures including focal points for R&D activities

1.3 Method

The approach comprises three main elements: literature review, interviews and analysis as well as synthesis. The techno-economic development of selected renewable electricity technologies is analysed and assessed with respect to their cost reduction and market growth opportunities.

The data base varies considerably both between the different RES-E technology groups and within RES-E technology groups. This is mainly due to two factors:

- different *technological stage* of the various RES-E technology (groups): more mature technologies tend to have more and better data

- different degree of *organisational structure*: highly organised and more homogenous associations tend to provide more and better data

1.4 Evaluation

The technology synthesis is a product capitalising on the wealth of project internal and other documents. With respect to the road map of RE market acceleration, roughly two types of conclusions can be drawn:

- some conclusions show *generic features and fundamentals* that are of utmost importance and must be respected for efficient and successful RE market and policy

- some conclusions lead to more *concrete actions* that can be recommended in order to accelerate RE markets

The project sought to cover all relevant aspects (see issues). Obviously, every aspect cannot be thoroughly analysed to gather all data being potentially useful. The conclusions however are clear and based on technical information as well as on expertise coming from professionals and stakeholders. The wealth of data is structured to the key issues identified. This clear structure allows for easy finding the data searched for in the technical annexes.

The report tries to provide information and conclusion aiming at increasing the degree of certainty in the field of RES-E technologies. Nevertheless, even knowing all the details, it is not possible and realistic to fully anticipate the technology development.

1.5 Results and Conclusions

The results and the conclusions are presented for the five topics defined:

- Techno-economic development including major steps and trends
- Costs and cost reduction opportunities
- Potential
- Market and market growth opportunities
- Needs and measures including focal points for R&D activities

1.5.1 Techno-economic development

The historical perspective and analysis of the RES-E technologies (see illustrations in the figures below) leads to two generic main conclusions

- The technological development brings about major innovative steps in materials, processes, designs and products that can considerably advance the technology systems and components (see triple figure below).

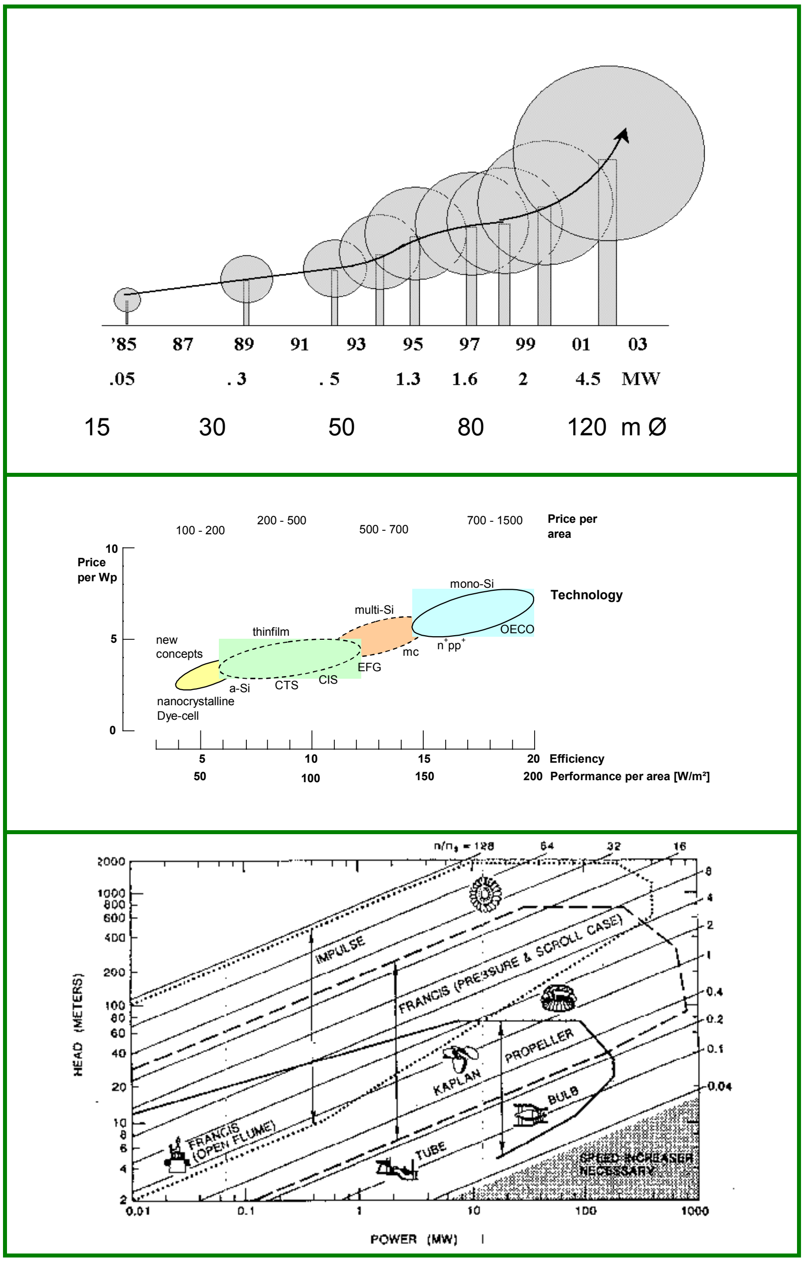
- Generally and globally, the progress of the technology, its applications and markets as a whole is a fairly continuous process.

From a very basic technology perspective, two features (fuel and spinning generator) allow for a fundamental typology of energy technologies (see figure below) which also reflects some of the pre-determinant technical characteristics.

Fuel ?	Spinning generator? YES	Spinning generator? NO
NO	**Hydro** **Wind** **Geothermal** **Concentrating solar power**	**Photovoltaics**
YES	**Nuclear** **Coal** **Natural gas** **Synthetic fuels** **Biomass**	**Hydrogen / fuel cells**

Figure 2 : Basic common and different aspects of energy technologies according to the subdivisions of fuel input and spinning generator. Source: Solar International Management, Inc.

The state of the art of the different RES-E technologies and their corresponding manufacturing industry and application fields cannot be generalised. Some of the RES-E technologies have already gained a historical dimension and their industry is mature. Small hydro power is well established like some parts of the biomass industry or the manufacturing of components that are not specifically related to one RES-E technology system. Wind has been going through a vigorous market development and has reached a considerable market share in several countries. The solar photovoltaic market is still comparatively small but tripled its volume in the last four years. Geothermal has been successfully operating for a long time especially for heat production and almost for a century in the electricity field which is currently gaining more importance. The geothermal as well as the solar thermal projects still have some exploratory and experimentary traits. This is mainly due to the site specific and novel characteristics of the projects including systems that are not mass produced but more likely made to measure.



Figures 3a, 3b and 3c : Technology development brings major innovative steps in materials, processes, designs and products. The figure on the top illustrates the increase of rotor diameter size and capacity of wind turbines. The figure in the middle shows different solar cell technologies with various technology development advances including efficiency and costs. The figure at the bottom locates different types of small hydro turbines in the context of head and rated power. Sources: Van Kuik G.A.M., RWE Solar GmbH, Gulliver, adapted through NET Ltd, St.Ursen, Switzerland

The maturity of each RES-E technology can be roughly assessed within the RTD process from feedstock to competitive markets. The values given from * to ***** are indicative for the prevailing RTD process stages of each RES-E technology and RTD step / focal point (see table below). To indicate the maturity of RES-E technologies is a hazardous enterprise and should be interpreted with caution. As a matter of fact, each RES-E technology is composed of a multitude of components at different degrees of advancement and can be used for a relatively wide range of applications with variable configurations and competitiveness.

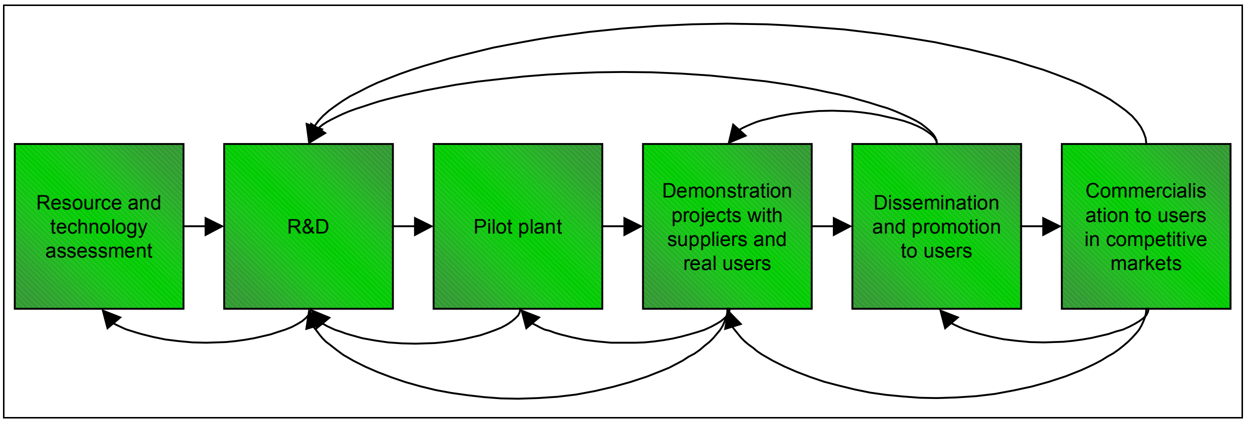


Figure 4 : RTD process assessed and analysed from feedstock to competitive markets. Source: ATLAS

Table 2 : Overview over the state of the art of the RES-E technologies analysed within the RTD process from feedstock to competitive markets. The values given from * to ***** are indicative for the general degree of importance within the RTD process at each step / focal point. This classification is of synoptic value and – like any other table at that level and degree of detail - cannot reflect the wide range of applications and components for each RES-E technology at different development status.

RTD process assessed and analysed from feedstock to competitive markets	Resource and technology assess-ment	R&D	Pilot plant	Demonstra-tion pro-jects with suppliers and real users	Dissemina-tion and promotion to users	Commer-cialisation to users in competitve markets
Biomass electricity / bioelectricity	**	***	***	***	***	*****
Geothermal electricity / power	***	****	****	***	***	***
Solar photovoltaic electricity / power	**	****	***	****	***	****
Solar thermal electricity / concentrating solar power	****	****	****	**	*	*
Small hydro electricity / power	**	***	***	***	****	*****
Wind electricity / power	**	***	***	***	****	*****

Virtually any RES-E technology system is composed of fully commercial and innovative components as well as applied in competitive markets and trying to conquer new markets. Small hydro power systems as a whole are almost business as usual but, for instance, turbines and electronic steering device can be optimised for different sites / applications given. Bioelectricity has its traditional competitive applications but in its large field comprising various kinds of biomass material (fuel) new processes and gears emerge and promise higher efficiency and effectiveness. Solar photovoltaics is generally expensive but has its highly competitive products and reliable applications. Even though PV systems work with only little O&M, there is still an urgent need to bring down costs and it is not clear whether today's standard will be the standard of tomorrow. Single- and multi-crystalline based cells and modules dominate the market. The thin film technology is getting more and more developed and many experts expect it to be dominant in the mid and long term future. The thin film technology is not just one technology but there are different approaches - be it on materials and / or processes. Solar thermal electricity / concentrating solar power systems have been working for more than a decade. However, there hasn't been a single commercial system installed for the last ten years. Technological improvement is there but future forecasts on costs are somewhat speculative and theoretical due to the lack of (market) experience. Nevertheless there is hardly any doubt about a future successful comeback from the laboratory exile to the market.

The example of solar thermal electricity / concentrating solar power systems is used to illustrate both the global technology development and major innovative steps. New designs and processes are important steps to further develop technology and reduce costs and contribute to a continued, globally rather smooth evolution of the solar thermal electricity / concentrating solar power technology and as a whole.

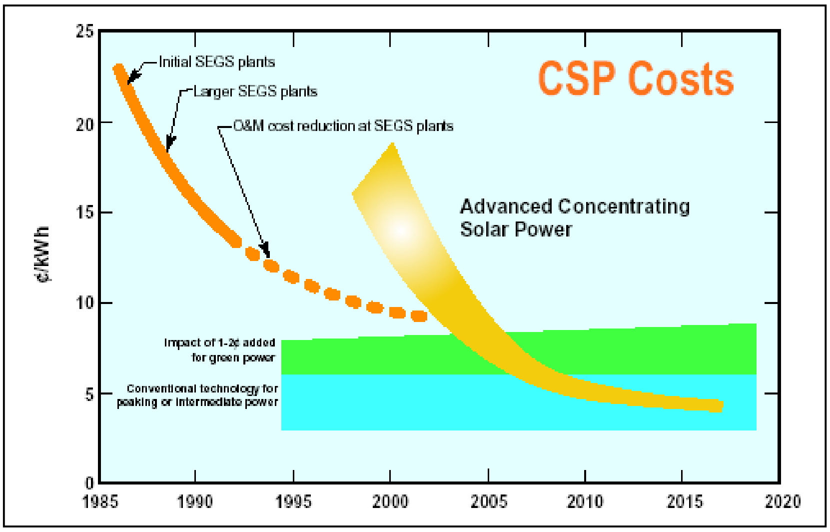


Figure 5 : Major innovative steps (new designs, processes, systems, etc.) contribute to further develop technology and reduce costs and, finally, to a continued, globally rather smooth evolution of the solar thermal electricity / concentrating solar power technology and as a whole. Source: SolarPaces

Although this report and project focusses the electricity part of the renewable energy sources, it must be mentioned that costs can be decreased and efficiency increased by hybridisation of systems and / or combining heat and power production. This is of particular pertinence for geothermal, solar thermal and biomass but hybridisation for stand-alone and (micro) grid systems are also implemented for other RES-E technologies. Not to be omitted that storage and hybridisation are important R&D issues, too.

The techno-economic development comprises a wide range of aspects. Some common general conclusions can drawn here and are presented in more details in the following sections.

- Costs and cost reduction opportunities: Each RES-E technology has its specific cost reduction opportunities. Within this analysis, three main opportunities are identified and quantified for each RES-E technology where possible: 1) progress through R&D, 2) economy of (manufacturing) volume and 3) economy of scale. The structure and nature of each RES-E technology's cost reduction opportunities should be considered to optimally exploit its inherent qualitative and quantitative technological (learning) capacity.

- Potential: The potential for RES-E is tremendous. Different geofactors limit the technical potential. Technology development contributes to make RES-E technologies even more benign and versatile to exploit the potential.

- Market and market growth: There is a wide range of (competitive) applications. It is important to be fully aware of the variety of applications and to orient technology development towards these applications and markets thus enhancing and propelling the RES-E technology through a competition oriented diffusion process.

- The technological development is / should be a continuous process - the best environment for technology development is a steady support. Most RES-E technologies are present on the market but need - to some variable degree - R&D measures to improve technology and competitiveness.

Conclusions for the general techno-economic development:

- There is no overall technological breakthrough that would bring about a sudden market push (more likely to happen with market incentives), but only for individual and specific application.
- Technology development is a continuous process over time.

Message

- Respect continuity and build up long-term strategies.

1.5.2 Costs and cost reduction opportunities

Topics of the costs and cost reduction opportunities are:

- Capital costs
- Generation costs
- Cost reduction opportunities
- Cost reduction forecasts

Capital costs

The cost structures of RES-E technologies have some common and specific characteristics. Almost all RES-E technology installations have high up-front costs as most investments / costs occur before the system even gets started. Operation and maintenance costs are mostly low. Fuel costs are zero with the exception of biomass (see material availability). The capital costs are thus the most important costs to be taken into account. The system costs depend on the technology used and / or on the construction site. System costs are basically similar for the same main type of application and RES-E technology (solar photovoltaics and solar thermal, wind and biomass) and should not vary much in a mature market environment. On the other side, small hydro and geothermal installation costs depend very much on the construction specificities of the site.

Table 3: Range of current investment costs (in $€_{2000}$) per kWp installed for the RES-E technologies assessed. Source: compilation through NET Ltd, St.Ursen, Switzerland

	Low investment costs	High investment costs
Bioelectricity	1200	4000
Geothermal	1200	5000
Small hydro	1000	5000
Solar photovoltaics	5000	7500
Solar thermal	3000	6000
Wind onshore	900	1000
Wind offshore	1500	2000

Generation costs

Electricity generation costs from RES-E technologies - roughly speaking - do depend on the capital costs per installed capacity and the energy input / output. The dependance on an energy input - that is pre-defined by geofactors (see section “Potential”) and varies stochastically variable in time - is a typical feature for most RES-E technologies.

Table 4 : Range of current generation costs (in €$_{2000}$ cents) per kWh produced for the RES-E technologies assessed. Source: compilation through NET Ltd, St.Ursen, Switzerland

	Low generation costs	High generation costs
Bioelectricity	3	18
Geothermal	5	14
Small hydro	3	15
Solar photovoltaics	35	120
Solar thermal	12	20
Wind onshore	5	15
Wind offshore	6	15

1.5.3 Cost reduction opportunities

The cost reduction opportunities vary greatly from one RES-E technology to another. Generally, the more expensive the RES-E technologies is the better are the cost reduction opportunities. This is also true for RES-E technology components. New innovative components are more expensive but have the potential to considerably reduce their costs.

There are basically three types of (interrelated) cost reduction opportunities:

- progress through R&D
- economy of (manufacturing) volume
- economy of scale

Progress through R&D: Through research activities (and / or feedback from target groups) technology can be improved, for instance improvements related to materials, processes, designs and products.

Economy of (manufacturing) volume: Higher manufacturing volumes allow for more efficient production processes. Larger production plants (upscaling) can lower the unit price, bigger production brings about learning effects that can be positively implemented in new / upgraded plants. For instance, bigger photovoltaic production capacity per plant reduces capital costs per capacity unit, subsequent upgrading of the plant allows for further cost reductions per capacity unit for the plant due to process improvements.

Economy of scale: Installations can be optimised in size and dimension according to the components and their cost structure, i.e. the system is optimally dimensioned and harmonised within / among its components and / or an installation uses repetitive components to bring down costs per installation unit. For instance, the upsizing of the rotor and installation of wind generator units is likely to reduce installation costs per generation capacity installed. Or a power tower causes certain costs for the system and civil works and it makes sense to put as many mirrors (repetitive components --> better purchase conditions) as to optimally use the power tower capacity.

These three (interrelated) cost reduction - progress through R&D, economy of (manufacturing) volume and economy of scale - exist for all RES-E technologies but at different degrees. Their influence / impact on the techno-economic development cannot be accurately assessed as their effects overlap. However, estimates can be given on the ground of the data made available (see table below).

Table 5 : Estimates of the three main cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale). Each * is the approximate equivalence of 4% - 6% of cost reduction within a decade including expected technological learning and market growth. Source: NET Ltd, St.Ursen, Switzerland

	R&D	Manufacturing volume	Economy of scale
Bioelectricity	***	*	**
Geothermal	**	*	***
Small hydro	**	*	**
Solar photovoltaics	*****	****	*
Solar thermal	***	***	****
Wind onshore	**	*	***
Wind offshore	***	*	***

1.5.4 Cost reduction forecasts

The learning curve is a tool / approach to assess the overall effect of these cost reduction opportunities. The learning / experience curve has become fairly widespread in the last years although it is not really a very accurate tool. Its simplicity and capacity to assess and show the techno-economic development makes it however a very powerful tool. Experience gained in the past - volumes produced and costs resulted - reflect the overall techno-economic development and performance and allows for forecasting the future evolution by attributing the future costs to the future volumes produced. Nevertheless caution is needed when future costs are extrapolated, experience curves could in fact reflect very specific sitautions which may not be reproductible in the future. Plausibility checks are needed for each new circumstance. As the range of electricity generation costs is very wide (see second figure below) and the gaps between the forecasted and actually realised volumes in the future tend to become greater in time (see third figure below), very accurate data cannot be given on such a general level of information. However, achievements (for RES-E technologies in 1998) and trends (for RES-E technologies in 2010 respectively 2020) can be clearly detected.

An example of the learning curve and the cost reduction potential is given in the figure below. It incorporates not only the basic axis of the learning curves (electricity unit costs per kWh and the cumulative installed capacity) but also the range of the generation costs as well as a schematic and differentiated progress ratio for the different technology and cost bands. It can be seen that typically more expensive and more recent applications and systems tend to have a greater cost reduction potential and this also within the frame of a globally rather traditional and classic RES-E technology which is small hydro power.

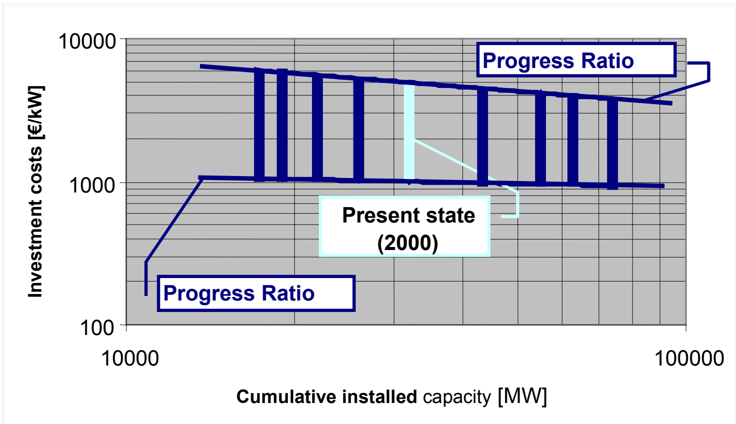


Figure 6 : Schematic example of the learning curve and the cost reduction potential for small hydro power. The figure incorporates not only the basic axis of the learning curves (electricity unit costs per kWh and the cumulative installed capacity) but also the range of the generation costs as well as a schematic and differentiated progress ratio for the different technology and cost bands. Typically, more expensive and more recent applications and systems tend to have a greater cost reduction potential thanks to greater learning capacities and potentials. Source: NET Ltd, St.Ursen, Switzerland

The cost reduction potential can be roughly classified into three categories - reminding again of the hazardous character of such a global indication:

- Highest cost reduction potential can be identified among the RES-E technologies that are a) expensive and b) recent in development. They tend to have a steep learning curve with a progress ratio of about 80% meaning that every doubling of the volume manufactured leads to a cost reduction of about 20%. Globally, solar RES-E technologies are expected to reduce their costs by some 30% - 50% by 2010 and another 30% - 50% by 2020.

- Medium cost reduction potential can be identified among the RES-E technologies that are a) low to medium-priced and b) relatively recent in development. They tend to have a learning curve with a progress ratio of about 90% to 95% meaning that every doubling of the volume manufactured leads to a cost reduction of about 5% to 10%. Globally, wind is expected to reduce their costs by some 25% by 2010 and another 25% by 2020. Specifically, more recent developments (bioelectricity, small hydro, geothermal) are expected to contribute to cost reductions.

- Moderate cost reduction potential can be identified among the classic and traditional RES-E technologies. The learning curve for these technologies and / or components is fairly flat. Globally, small hydro and biomass are proven RE technologies where technological development is in a mature phase. Specifically, classic components (civil works, turbines) offer low cost reduction potential. The cost reduction potential is some 5% - 10% by 2010 and another 5% - 10% by 2020.

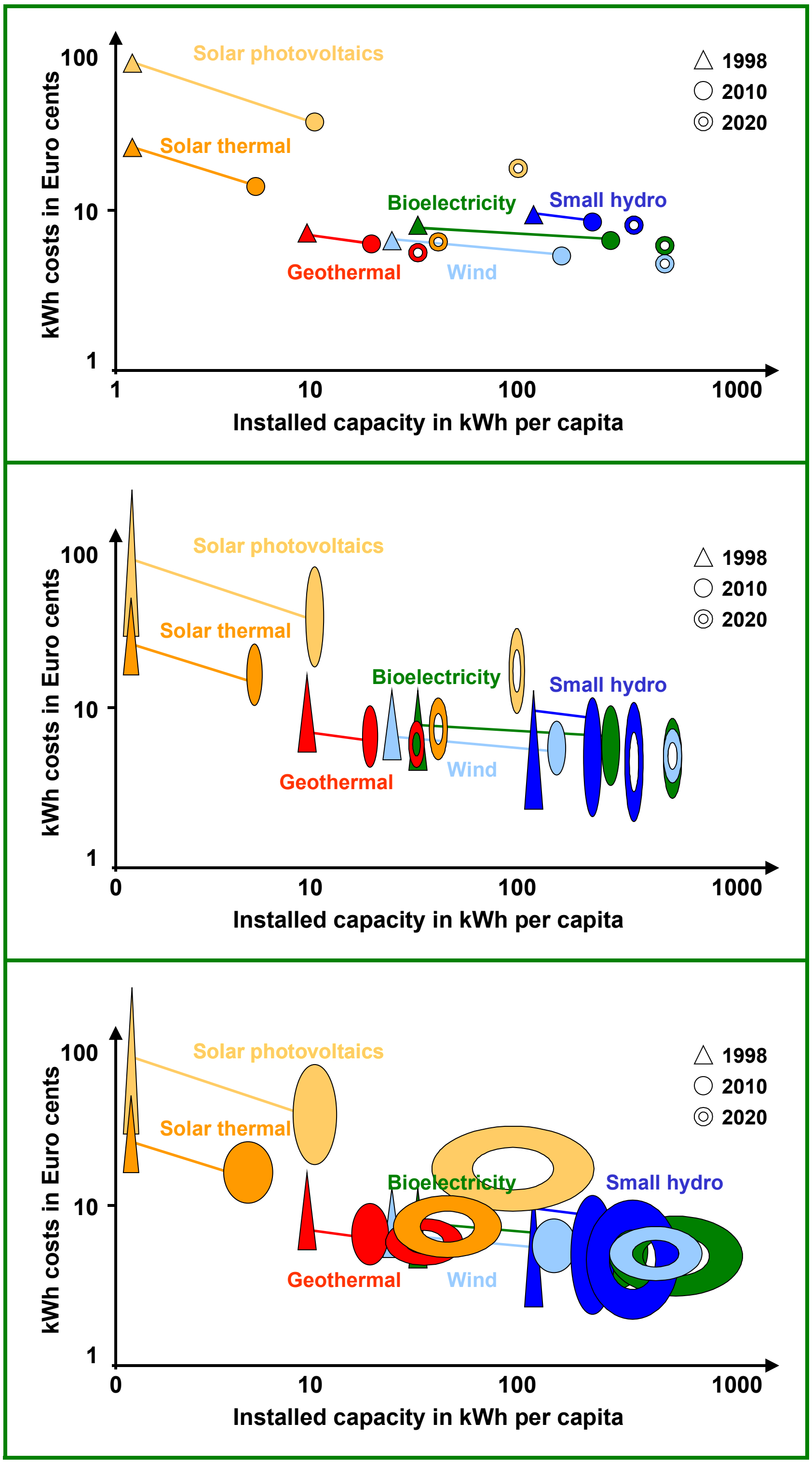
Combining the current investment and generation costs with the forecast cost reduction opportunities, future costs can be estimated for the RES-E technologies assessed (see tables below). It must be emphasised that range of investment and generation costs is supposed to be fairly large for most RES-E technologies as they keep on being very diverse and diversifying.

Table 6: Range of estimated future (2010) investment costs (in €$_{2000}$) per kWp installed for the RES-E technologies assessed. Source: compilation through NET Ltd, St.Ursen, Switzerland

	Low investment costs	**High investment costs**
Bioelectricity	1000	3000
Geothermal	1000	3500
Small hydro	950	4500
Solar photovoltaics	2500	4000
Solar thermal	2000	3500
Wind onshore	700	800
Wind offshore	950	1400

Table 7 : Range of estimated future (2010) generation costs (in €$_{2000}$ cents) per kWh produced for the RES-E technologies assessed. Source: compilation through NET Ltd, St.Ursen, Switzerland

	Low generation costs	**High generation costs**
Bioelectricity	2.5	12
Geothermal	3.5	10
Small hydro	2	10
Solar photovoltaics	20	60
Solar thermal	7	12
Wind onshore	3.5	12
Wind offshore	4	12



Figures 7a, 7b and 7c : Potential development of RES-E technologies in Europe (EU15 and Switzerland) taking into account current costs and achieved potentials as well as future cost and potential estimates. The first figure includes starting points with an average cost and potential estimates. The second figure additionally includes the span of generation costs. The third figure additionally includes the span of capacity potentially installed. Sources: some estimates are based on the recently published studies “ElGreen” and “REBUS”, adapted through NET Ltd, St.Ursen, Switzerland

Conclusions

- RES-E technologies have different costs and cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale).
- For the two decades to come, cost reductions will be twice 10% to 50% depending on the technological dynamics.

Message

- Respect and take advantage of the technology-specific opportunities in R&D, economy of scale and economy of volume.

1.5.5 Potential

The potential of RES-E technologies is tremendous. The sun injects abundant energy into the Earth's atmosphere that can be directly harvested or used indirectly in the shape of blowing wind, dynamic waters and growing biomass. Furthermore, the Earth's reactor represents a quasi inexhaustible source of energy (geothermal), too.

To use and produce power based on renewable sources, certain very basic premisses have to be fulfilled. A first assessment of the potential deals with availability of the ressources. Solar photovoltaics and solar thermal, wind and biomass (crops) all need large areas where RES-E technologies can harvest the energy. For small hydro and geothermal, some specific site characteristics are more important than just „area". This site availability plays a role also for the other sources if good sites are increasingly used up and the need grows for extended site inspection and assessment. Biomass experiences furthermore the restriction of material availability especially in the context of using organic waste / crop (see figure below).

The market relevant potential not only deals with technical and economic aspects but also with issues, restrictions and barriers coming from society and policy. To exploit and realise the potentials is furthermore time-dependent (see figure below). This all makes the (assessment of the) potential very delicate - particularly because renewable electricity involves a lot of variable (technological, site-specific etc.) characteristics and applications. The realisable potential by 2010 in kWh per year and capita according to the most recent studies "ElGreen" and "REBUS" is given in the table below.

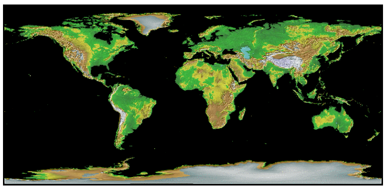
Some RES-E technologies have fairly corroborated values, others vary a lot. Although the position of RES-E might be strategic, the database and methodology seem inconsistent. The potential assessment of RES-E technologies comprise a variety of factors. Basically, some factors (e.g. available sites, social acceptance) can be assessed on a local level in a bottom-up approach, other factors are more likely to be assessed on a more global level in a top-down approach (e.g. grid issues).

Bioelectricity

Geofactor no1: biomass growth (fuel)

Limit: area and material availability

Potential (p.a.+cap): 150 - 200 kWh by 2010 (+++)

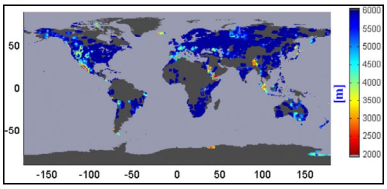


Geothermal electricity / power

Geofactor no1: enthalpy (temperature gradient)

Limit: site availability

Potential (p.a.+cap): 50 - 100 kWh by 2020 (++)

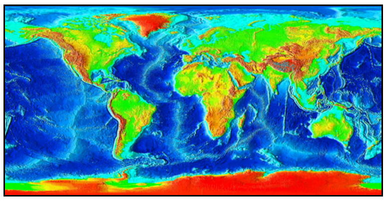


Small hydro power

Geofactor no1: flow and head (p=7qh)

Limit: site availability

Potential (p.a.+cap): 150 - kWh by 2020 (++)

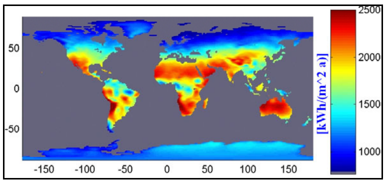


Solar photovoltaic electricity / power

Geofactor no1: global irradiation

Limit: grid (load) capacity

Potential (p.a.+cap): 100 kWh by 2020 (++++)

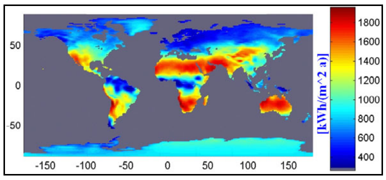


Solar thermal electricity / power

Geofactor no1: direct irradiation

Limit: area availability / grid capacity

Potential (p.a.+cap): 50 kWh by 2020 (+++)



Wind electricity / power

Geofactor no1: wind speed (E = 3.2 V^3)

Limit: site availability / grid (load) capacity

Potential (p.a.+cap): 250 kWh by 2010 (+++)

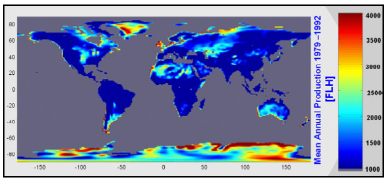


Figure 8a, 8b and 8c : Potential of RES-E technologies. For each RES-E technology the decisive geofactor and limits are indicated as well as forecast potential values (annual production per capita in kWh) for Europe (EU15 and Switzerland). The very indicative values from + to ++++ stand for further achievable potential beyond the term year given (starting with + for very low to ++++ for very high in relative terms). Sources: Data on achievable potentials are partly from the studies “ElGreen” and “REBUS” and estimates from NET Ltd, St.Ursen, Switzerland. World maps and pictures are from NOAA and ISET / Czisch.

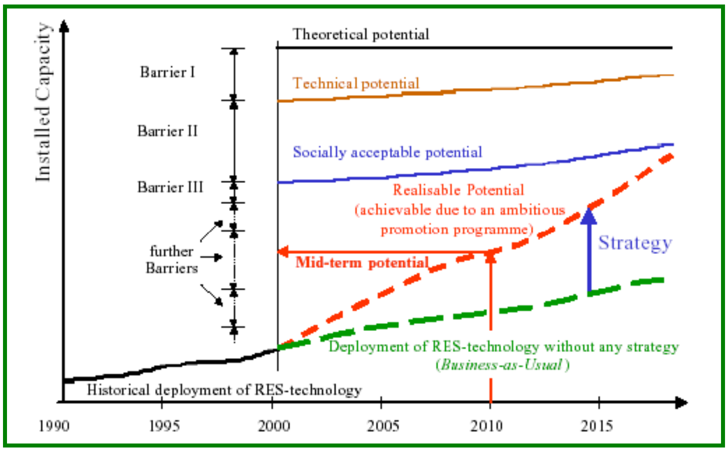


Figure 9: Potential terms incorporating different barriers. Source: ElGreen

Table 8: The realisable potential by 2010 in kWh per year and capita in EU15 according to the studies "ElGreen" and "REBUS". The values for solar photovoltaics suffer from assessment inherent inaccuracy - the values given can be almost set to zero according personal communications (G. Resch and M. de Noord). Sources: "ElGreen" and "REBUS", figures adapted by NET Ltd, St.Ursen, Switzerland

	Capacity installed by 1998 in kWh per year and capita	**Capacity installed in kWh per year and capita according to ElGreen in 2010**	**Capacity installed in kWh per year and capita according to REBUS in 2010**
Bioelectricity	40	477	457
Geothermal	11	9	25
Small hydro	103	56	156
Solar photovoltaics	0	652	69
Solar thermal	0	132	n.a.
Wind onshore	32	341	184
Wind offshore	0	158	44

Conclusions

- Database and methodology of the potential assessment seem inconsistent.
- Potentials and forecasts are found to be between scientifically and politically correct.
- Modelling often experiences difficulty in dealing with RES-E that is a)" expensive" and b) nevertheless having" niche markets".

Message

- Improve the decision base in order to fully profit of the strategic position of RES-E (technologies).
- Potential assessment includes a locally anchored bottom-up approach of regional RES-E potential combined with a top-down approach for grid and storage issues to create a consistent data and decision base.

1.5.6 Market and market growth opportunities

As mentioned in the section “Techno-economic development”, wind and PV are experiencing a vigorous market growth (rate) in Europe, especially in countries with attractive market incentives (often price-driven push, see table below). Generally, RES-E technologies are more and more considered in energy portfolios, strategies and marketing.

Markets and marketability for RES-E are not defined by a global ultimate break-even criteria. This criteria is a chimera. On one hand, electricity prices are highly variable in space and time - especially in the context of liberalised markets and uncertain fuel ressources. On the other hand, there are different applications and values that make competitive prices flexible. Obviously, this does not mean that costs and prices do not play an important role but there is no ubiquitous clear „starting point“ in the shape of a kWh price for RES-E technology.

Furthermore, the electricity market is not really a free and transparent market. The liberalisation is about to bring more regulations than ever an electricity market has experienced before. The electricity generation and supply also deals with environmental, social and security issues and is therefore highly „political“. Hence, costs and prices are not a purely economic product but also a political result. As such, electricity policy can influence markets more than technology. For instance, wind technology certainly progressed a lot in the last decades and is fundamental for market success. The actual „breakthrough“ is not due to some recent technology change but to the political will to make pay a certain feed-in tariff that makes this technology competitive.

Table 9: Drivers for markets and market growth. Source: compilation NET Ltd., St.Ursen, Switzerland

Drivers for markets and market growth	
Price	RES electricity is inexpensive, a budget given allows for procuring a relatively great amount of RES electricity.
Application	RES-E technology offers unique features that make applications competitive.
Society and culture	RES electricity is appealing and conveys messages to the society. Furthermore, there are no / hardly any external costs to be paid by the society. It is likely to enhance social and cultural cohesion.
Environment	RES electricity is environmentally benign and sustainable.
Business	RES electricity offers interesting business opportunities.
Industry	RES electricity allows for settling innovative industry with export opportunities.
Policy and politics	RES electricity brings about overall benefits to society, economy and environment. Furthermore, the global responsibility can be taken by promoting RES electricity thus also transferring sustainable technology to the less developed countries with an increasing demand for power.

Markets and marketability for RES-E have to be assessed in terms of applications and values (see table below). This is a more flexible and maybe less clear concept. Different areas in Europe and in the world have different potentials, cost structures and needs. This automatically leads to a variety of electricity supply problems and solutions in a purely technical sense. Furthermore, the liberalised electricity markets will bring highly differentiated tariff structures and will subsequently create different market schemes. On top of it, green power marketing takes into account that electricity is not just electricity but a type of products that is differently perceived and valued by the customers. RES-E is likely to present a higher value to the customers than conventional electricity, thus the potential willingness to pay is partly higher for RES-E.

An important feature of RES-E technologies is that a technology is neither globally cost-effective nor globally non-competitive. Some market segments are fully cost-effective and some are not. RES-E technologies can be enhanced in diffusion process where most competitive markets are opened up to propel the technology and make its costs shrink and subsequently more competitive and attractive for new markets. This way it is going to be a virtuous circle helping to get out of the chicken and egg of market development where buyers are waiting for the prices to fall and the producers are waiting for the demand to increase.

Table 10 : Common aspects for all or most RES-E technologies for market and market growth opportunities. Source: compilation NET Ltd, St.Ursen, Switzerland

Common aspects for all or most RES-E technologies are	
Green power	RES-E technologies can be successfully implemented in and for marketing.
Values	RES-E technologies contribute to consider energy not only from a price perspective but from the perspective of values
Services	RES-E technologies can be part in the marketing approach from “power only“ delivery to global service packages
High value niche markets and products	RES-E technologies have high value niche markets and products.
Integrated applications	RES-E technologies offer opportunities for integrated applications (BIPV, CHP, marginal hydro power, agro-forest multifunctionality, etc.)
Developing countries	RES-E technologies offer adapted sustainable solutions to energy supply problems in developing countries.
Remote areas	RES-E technologies can provide competitive stand-alone and micro-grid applications and independant island renewable energy systems in remote areas without setting up inadequate oversized infrastructures.
Decentralisation and grid support	RES-E technologies can support decentralisation and the grid.
Supply security	RES-E technologies provide more autonomy and sustainability than fuels to be imported and depleted.

Conclusions

- There is no uniform market nor price.
- There is a wide range of applications in different markets in time, place and price.

Message

- Promote the diversification and take advantage of the most competitive applications (diffusion model).
- Promote industry partnerships.

1.5.7 Needs and measures including focal points for R&D activities

The starting point of the R&D needs and measures is the technology - market relationship offering three main issues and opportunities:

1) Improvement of performance and development of new designs taking advantage of R&D
2) Opening up new markets taking advantage of the economy of (manufacturing) volume
3) Optimisation of size and application taking advantage of the economy of scale

Market oriented technology developments imply that competitive and promising applications should be promoted and envisaged. Market orientation means that R&D should be linked with the industry and markets in order to get the feedback for further improvements and new designs.

Whilst the "cheap" RES-E technologies experience much market push and an industry "more voluntarily" investing in R&D, the "expensive" RES-E technologies are often promising in the mid- to long-term future and need more R&D to realise the promise.

Hence, R&D sould both denote the whole sequence of innovation phenomena from feedstock to finite products and from research to dissemination as well as orient towards specific and strategic goals. Issues to be addressed for all or most RES-E technologies are given in the table below.

There is obviously a wide range of R&D needs and measures. The ultimate goal is to improve RES-E technologies in order to set up a sustainable electricity market taking into account the different values and characteristics of RES-E technologies and a balanced energy portfolio. R&D policy itself should be sustainable that is embedded in a stable long-term framework with clear focal points.

Table 11 : Key technical issues for R&D. Source: compilation NET Ltd, St.Ursen, Switzerland

Key technical issues	Examples
Feedstock	• agro-refinery • silicon feedstock
Materials	• light and robust materials for rotors • thin film solar cells
Components	• adapted turbines for small hydro and wind
Systems and applications	• hot dry rock • building integrated photovoltaics
Process	• flash pyrolysis • low temperature deposition
Operation and monitoring	• computerised, electronic control
Recycling and environmental mitigation	• recyclable materials, non-/less invasive installations • pollution-free combustion
Storage	• solar thermal storage tank for better dispatchability • batteries for stand-alone applications
Hybridisation	• solar thermal and biogas, solar and wind
Grid aspects	• micro-grids • load management • system integration

Table 12 : Key non-technical issues for R&D. Source: compilation NET Ltd, St.Ursen, Switzerland

Key non-technical issues	Examples
Potential assessment	• assessment techniques and tools • resource predictability • site assessment
Identification and diffusion of value-enhanced RES-E	• assessment and promotion of competitive applications
Finance architecture	• life cycle assessment • adapted loan and grant systems • insurance issues
Pricing instruments	• monetise values • coherent pricing structure for and from distributors and generatorss
Added values	• incorporation of values due to environmental and social (but also technical) benefits, like displacement of hazardous fuels and their depletion
Strategic partnerships and networks	• coherent and harmonised R&D strategies between countries • research and industry link
Standardisation / harmonisation of codes and rules	• equipment • cross-border energy transfer • quality assurance
Education and training	• training and education schemes both for specialist and general public • university degree on RES-E technologies
Information	• dissemination of information to decision makers and potential end-users and consumers
Entrepreneurial culture	• awareness of potential contribution through RES-E technologies to products and process as well as image and attitude • provide familiarity and experience with RES-E technologies
Marketing	• green power marketing • use of local resources • technical and logistic infrastructure for after sales services
Policy synergies	• promotion for use of indigenous resources and employment • balanced energy portfolio
Legislation	• land planning issues • favourable regulation concerning grid connection
Labelling	• clarification of an acceptable number of clear labels
Administrative approval process	• grid connection issues • facilitation of installation approval process (faster with respect to innovation speed and cheaper with respect to lowering project costs)
International co-operation	• encouragement of international co-operation in R&D and other programmes
Supra-national institutions	• integration of RES-E in development and demonstration programmes
Environment	• reduction of emissions • preservation of habitats

Conclusions

- There is no optimal technology development by one singular type of action on the market side only.
- There is no optimal electricity supply by dominant singular technology.

Message

- Warrant for strong technology-market-relationships.
- Set up energy portfolios by taking into account balanced RE fractions and reducing supply interruption risks.

2 Bioelectricity

Figure 10 : CHP plant in Varnamo, Sweden with installed capacity of 8 MWe. Source: ATLAS

Figure 11 : McNeil generation station (50 MWe) in Burlington, Vermont, USA. Source: NREL

Figure 12 : Power station (Grayling) burning waste-wood is providing 36.2 MW of electricity to a city in Michigan, USA. Source: NREL / CADDET

2.1 Techno-economic development

An important specificity of bioelectricity relates to technical, environmental and policy areas. Biomass is not just used for power generation but also for heat production (combined heat & power plants) and fuel-use related environmental aspects (burning of organic and fossil material) on one hand, and on the other hand deals with waste and agricultural crops. Thus, these areas are also covered by this report to give a more complete picture of biomass. The focus is, however, on biopower generation.

The biomass industry and technology differs from many other renewables in that it encompasses both the farming and forestry communities and the power generation industry [ATLAS]. Due to a wide range of diverse feedstocks and conversion technologies, the biopower sector is particularly large and offers manifold approaches.

There are four primary classes of biopower systems [DOE]:

- Combustion / direct-fired
- Cofiring
- Gasification
- Modular systems

Most of today's biopower plants are **direct-fired** systems [18] that are similar to most fossil-fuel fired power plants. The biomass fuel is burned in a boiler to produce high-pressure steam. This steam is introduced into a steam turbine, where it flows over a series of aerodynamic turbine blades, causing the turbine to rotate. The turbine is connected to an electric generator, so as the steam flow causes the turbine to rotate, the electric generator turns and electricity is produced.

For pure electricity generation [19] the steam is expanded down to a very low pressure in a condenser. If CHP is required then the steam condenses at a higher pressure in the water heater. The higher the steam temperature and pressure used the greater is the efficiency of the overall plant.

While steam generation technology [DOE] is very dependable and proven, its efficiency is limited. Biomass power boilers are typically in the 20-50 MW range, compared to coal-fired plants in the 100-1500 MW range. The small capacity plants tend to be lower in efficiency because of economic trade-offs; efficiency-enhancing equipment cannot pay for itself in small plants. Although techniques exist to push biomass steam generation efficiency over 40%, actual plant efficiencies are in the low 20% range.

Cofiring [DOE] involves substituting biomass for a portion of coal in an existing power plant furnace. It is the most economic near-term option for introducing new biomass power generation. Because much of the existing power plant equipment can be used without major modifications, cofiring is far less expensive than building a new biopower plant. Compared to the coal it replaces, biomass reduces sulphur dioxide (SO_2), nitrogen oxides (NOx), and other air emissions. After "tuning" the boiler for peak performance, there is little or no loss in efficiency from adding biomass. This allows the energy in biomass to be converted to electricity with the high efficiency (in the 33-37% range) of a modern coal-fired power plant.

Extensive research and development field validation tests and trials [DOE] have shown that biomass energy can be substituted for up to 15% of the total energy input by modifying little more than the burner and feed intake systems. Since large-scale power boilers in the current 310 GW capacity fleet range from 100 MW to 1.3 GW, the biomass potential in a single boiler ranges from 15 MW to 150 MW. The way in which the biomass is fired depends upon the proportion [ATLAS]:

- for minor quantities (2- 5%) the biomass can be mixed with the coal at the inlet to the mill;
- for larger quantities (5 - 25%) the biomass should be shredded finely and fired through dedicated burners - implying some expense and energy;

- and for major quantities (above 25%) there will be a substantial impact on the furnace and ash behaviour that will probably necessitate gasifying the fuel and firing it through a gas burner - implying substantial expense.

Cofiring is of (increasing) interest in the USA, some of the developing countries like China where coal firing plays an important role and in some Northern European states. The advantages and disadvantages are listed in the table below.

Table 13 : Advantages and disadvantages of cofiring of biomass. Source: ATLAS

Advantages	Disadvantages
• Capital cost reduction • High conversion efficiency • Emissions reduction (nitrogen oxides, sulphur oxide)	• Amount of biomass fired is limited • No / hardly any strengthening of the local distribution networks • Ashes have not quality of nutrient replacement

Biomass gasifiers [DOE] operate by heating biomass in an environment where the solid biomass breaks down to form a flammable gas. This offers advantages over directly burning the biomass. The biogas can be cleaned and filtered to remove problem chemical compounds. The gas can be used in more efficient power generation systems called combined-cycles, which combine gas turbines and steam turbines to produce electricity. The conversion process - heat to power - takes place at a higher temperature than in the steam cycle making advanced conversion processes thermodynamically more efficient.

Power generation [ATLAS] using advanced conversion processes offers advantages for all fuels, exemplified by the move to gas turbine cycles for modern coal plant. It is particularly useful for biomass. This is because the size of a biomass power plant will be constrained by the availability of the resource. Plant using conventional steam cycles at these small scales would have a low conversion efficiency of around 25%. Gasification and pyrolysis have the potential to raise this to over 36% now, and 45% in the medium to long term. The indications are that capital costs per kW_e generated will be comparable with steam plant.

Gasification systems [DOE] will be coupled with fuel cell systems for future applications. Fuel cells convert hydrogen gas to electricity (and heat) using an electro-chemical process. There are very little air emissions and the primary exhaust is water vapor. As the costs of fuel cells and biomass gasifiers come down, these systems will proliferate.

Modular systems [DOE] employ some of the same technologies mentioned above, but on a smaller scale that is more applicable to villages, farms, and small industry. These systems are now under development and could be most useful in remote areas where biomass is abundant and electricity is scarce. There are many opportunities for these systems in developing countries.

Size and feedstock

Biomass power systems range in size from a few kW for on-site generation units, up to 80 MW for power plants [DOE]. Limitations on locally available biomass resources generally make it uneconomical to exceed 100 MW in size according to DOE. ATLAS summarises that the maximum size is likely to be around 30 MW_e in most of the EU with perhaps up to 70 MW_e in heavily wooded areas.

The most economic forms of biomass for generating electricity are residues. These are the organic byproducts of food, fiber, and forest production. Common examples used for power are sawdust, rice husks, and bagasse (the residue remaining after juice has been extracted from sugar cane). Low-cost biomass sources are also common near population and manufacturing centers where clean wood waste materials are available in large quantities. Examples are pallet and crate discards and woody yard trimmings.

Feedstock-related issues constitute a main factor for the low market penetration of biomass, determining the feasibility of all bioenergy vectors in two ways:

- By increasing real biomass procurement costs, incorporating production, harvesting, transportation, handling and other such cost items.

- Through biomass logistics affecting - besides costs - the seasonal availability, the transportation and storage requirements, and even the technical suitability (in the cases of varying composition feedstocks) of bioresources.

The present stucture of the bioenergy techno-economic chains is shown in table 14. Only available feedstocks and technically mature technologies are listed.

Table 14 : Present structure of the bioenergy techno-economic system. Source: Koukios

Energy Vectors	Biomass Feedstocks	Conversion Technologies	Major Constraints
Bioheat	• Fuelwood • Wood wastes • Agro-residues • Municipal and various wastes	• Combustion • Gasification • Anaerobic digestion • Landfill gas use	• Feedstock • Logistics • Feedstock cost
Bioelectricity	• Fuelwood • Wood wastes • Agro-residues • Municipal and various waste	• Co-firing • Combustion • Gasification • Anaerobic digestion • Landfill gas use	• Feedstock • Logistics • Feedstock cost • Suitability of new feedstocks • Technical improvements
Transportation Biofuels	• Sugar crops • Starch crops • Vegetable oils	• Fermentation to Bioethanol • Oil Esterification to • Bio-diesel	• Feedstock logistics • Feedstock cost • Product logistics

2.2 Costs and cost reduction opportunities

Cost reduction is continuously achieved through technological improvements (see figure below). As there is a very wide range of different biopower technologies with different fuels, conversion processes and system designs, it is very difficult to draw a clear and homogenous picture of the biopower cost reductions. Furthermore, some system components come from non-biopower specific industrial areas and other components have prototype-like features.

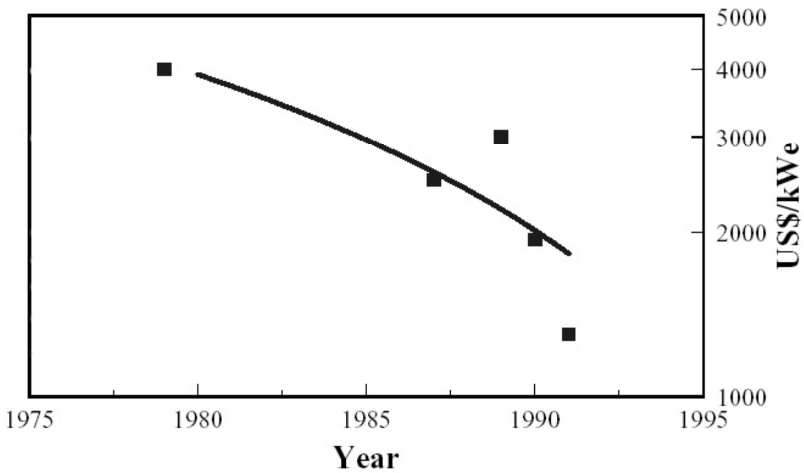


Figure 13 : Reduction of investment costs of CHP projects / Rankine power plants with design capacities ranging from 7 - 15 MWe for the City of Pieksämäki in Finland based on estimates 1979 - 1990 and construction in 1991. Source: IEA [17]

In some areas, biopower is competitive but electricity generation costs for combustion and gasification plants are - roughly speaking - still in the order of 5 to 10 €cents whereas fossil fuel based plants produce electricity at 4 €cents (see figure below).

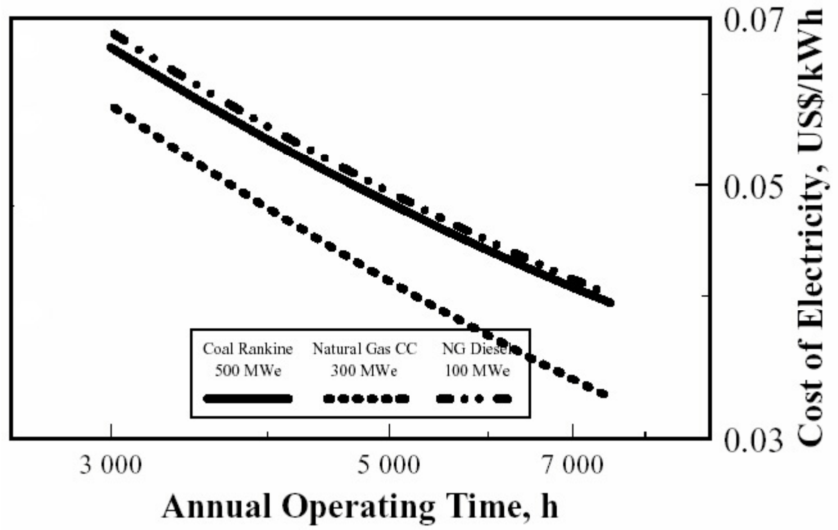


Figure 14 : Cost of electricity for commercial large scale power (coal at 2.2 US$ / GJ, natural gas at 2.5 US$ / GJ, capital cost with 20 years service life and interest rate 10%). Source: IEA 1999

Due to the diversity of biopower plants, it is suggested to understand the cost reduction opportunities by using examples: a) biomass IGCC (Integrated Gasification and Combined Cycle) capital costs, b) 2 MWp biopower plants and c) cogeneration biopower plants. Mainly two effects can be identified in the biopower area und reflected in the related literature: a) scale of economy and b) progress through R&D. These two cost reduction opportunities are expounded in more details below although their effects can only be separated in theory but not in reality.

Biomass IGCC

The IGCC bioelectricity learning curve according to Craig's understanding comprises mainly four elements:

- Capacity
- Temperature
- Gas cleaning
- Steam conditions

Improving the technical conditions leads to higher efficiency rates and lower capital costs.

Once a technology has reached the stage of the prototype or pioneer plant we [NREL 1995] expect that a number of improvements will be made *commercially* on an incremental basis. Using the biomass gasifier IGCC concept as an example, we can demonstrate some of the trends that are anticipated to take place. The first unit will be designed and operated in a very conservative fashion (just as the Varnamo unit is being operated) For example, the system specification for the first complete IGCC may have the characteristics of 20 MW output; 1650 ºF turbine inlet e temperature; gas cleaning by means of cooling the gas and quenching prior to an ambient temperature bag-house filter; a heat recovery steam generator at 800 psig pressure; an overall efficiency of 32%, and an installed cost of $2400/kW. Table 3 shows the anticipated learning curve that proceeds by means of a proposed series of technology improvements. Each succeeding improvement is gained only through increased experience and investment in development. A process of limiting returns does set in as can be seen from the cost of electricity curve in Figure 4. The final stage of improvement would probably come from the U.S. DOE's Advanced Turbine Systems (ATS) program in this instance, and would lead to a system that has 100 MW output; a greater than 2300 ºF turbine inlet temperature; high temperature gas cleaning; e a multiple stage heat recovery steam generator possibly linked as a steam injection unit to the gas turbine; and an overall efficiency of 45%, and an installed cost of approximately $1000/kW.

Some of the learning curve effect is gained simply by increasing the scale of operation. This is gained through increased confidence in the technology as operators and designers evaluate the systems operation enabling them to undertake such a scale increase without increasing the risk of failure. Typically if a power unit is scaled up by a factor of 2, the price does not double in going from say 50 MW to 100 MW, rather the price of an installed kW may go down from $1400/kW at 50 MW (for a total of $70 M) to a total cost of $114 M at 100 MW, or an installed cost of $1140/kW. The reason for this is that the capital investment is scaled with an exponent of approximately 0.7 so that doubling the size does not double the cost but rather increases it only by a factor of 1.62.

Table 15 : Hypothetical series of biomass gasification IGCC developments leading to a learning curve. Source: Craig et al [NREL 1995]

Capacity (MW)	TIT (°F)	Gas Cleaning	Steam Conditions	Efficiency (%,HHV)	Capital Cost ($/kW)
20	1650	Cool+ quench	800 psig	32	2,400
30	1850	Cool + Baghouse	900 psig	34	2,100
50	1900	hot gas cleanup	1250 psig	35	1,900
60	2100	hot gas cleanup	1250 psig	37	1,700
75	2100	hot gas cleanup	1450 psig	38	1,600
100	2200	hot gas cleanup	1450 psig, re-heat	40	1,450
120	2350	hot gas cleanup	1450 psig, re-heat	41	1,350
100	>2300	hot gas cleanup	N/A	45+	>900

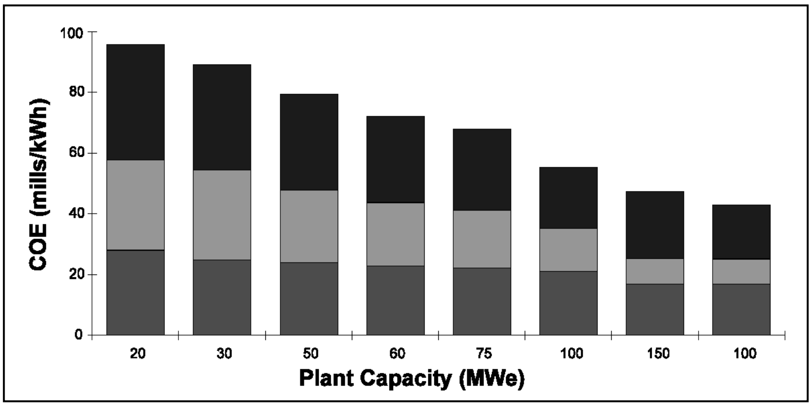


Figure 15 : Cost of electricity learning curve including fuel cost (bottom), O&M (middle) and capital cost (top) for a hypothetical series of biomass gasification IGCC developments. Source: Craig et al [NREL 1995]

Doubling the plant capacity from 30 MWp up to 60 MWp or from 50 MWp up to 100 MWp according to Craig's hypothetical series (given in the table above) brings about specific investment cost reductions of some 20% - 25% per kWp. These capital cost reductions are also due to some changes in the technical configuration.

Generally, the economy of scale has a higher impact in the lower capacity classes (say, 2 to 40 MWp) and is turning less important for higher capacity classes (see figure below). Furthermore, the effect of economy of scale for the specific investment costs of biopower plants can be partly or wholly off-set by increasing biomass fuel (transportation) costs for increasing plant size, that is power generation can get more expensive with increasing plant size.

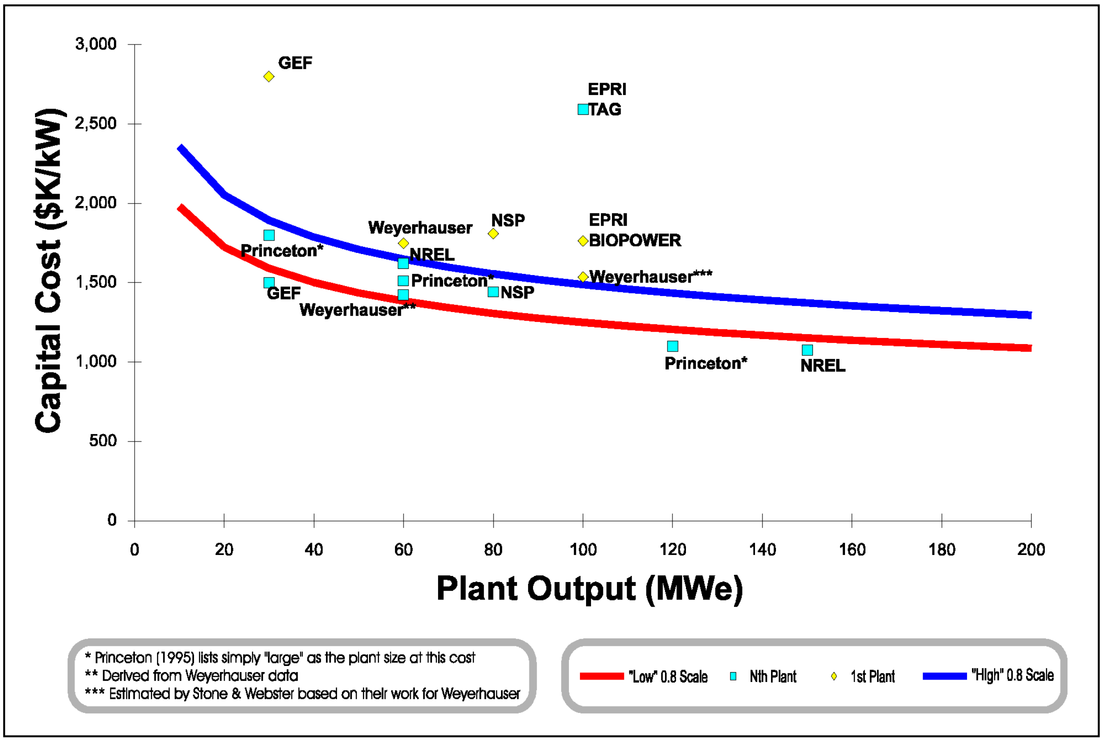


Figure 16 : Biomass IGCC capital cost estimates. Source: Craig et al [NREL 1995]

2 MWp biopower plants

Improved technology and related cost reduction opportunities are shown for small scale biopower plants with each 2 MWp of installed capacity. The concepts are: a) rankine cycle, b) gasification-gas engine and c) fast pyrolysis. The analysis and comparison of the near term potential of the three 2 MWp biopower plants that is a) rankine / steam cycle power plant, b) gasification (gas-engine) power plant and c) pyrolysis-diesel power plant shows that the:

- Overall efficiency increase is expected to be in the order of 30% - ranging from 27.5% for the pyrolysis-diesel power plant to 35.5% for the gasification (gas-engine) power plant
- Investment cost reductions are about 13% for the rankine / steam cycle power plant, 25% for the pyrolysis-diesel power plant and 38% for gasification (gas-engine) power plant, that is the more expensive the current investment costs the higher the cost reduction potential not only in absolute but also in relative terms
- Increasing annual operating time leads to lower generation costs per kWh especially for rankine / steam cycle power plant as well as for the gasification (gas-engine) power plant

Table 16 : Summary of near-term potential improvements and developments assumed for 2 MWp power plants. Source: IEA 1999

	Rankine power plant		Gasification - gas engine		Pyrolysis diesel	
	Base	Future	Base	Future	Base	Future
Power plant efficiency	17.5	23.0	33.0	38.0	38.0	43.0
Gasification efficiency			72.5	85.3		
Liquid prod. efficiency					65.0	73.3
Overall efficiency	17.5	23.0	23.9	32.4	24.7	31.5
Investment costs (US$ / We)	2.3	2.0	4.2	2.6	3.6	2.7

Table 17 : Summary of near-term potential overall efficiency increase and investment cost reduction assumed for different 2 MWp power plants. Source: IEA 1999, adapted through NET Ltd, St. Ursen, Switzerland

	Rankine power plant	Gasification - gas engine	Pyrolysis diesel
Overall efficiency increase	31.4%	35.5%	27.5%
Investment cost reduction	13.1%	38.1%	25.0%

Table 18 : Generation costs of electricity for different 2 MWp power plants. Source: IEA 1999, adapted through NET Ltd, St. Ursen, Switzerland

Generation costs of electricity in UScents per kWh (approximate values)	Current generation costs based on 5000 h annual operating time	Current generation costs based on 7000 h annual operating time	Near term generation costs based on 5000 h annual operating time	Near term generation costs based on 7000 h annual operating time
Rankine power plant	12.5	10.5	10	8.5
Gasification - gas engine	19	14	12	9.5
Pyrolysis diesel	16	14.5	12.5	11

Cogeneration power plant concepts

The analysis and comparison of the near term potential of the three biopower cogeneration plants that is a) rankine power plant 2.0 MWe / 6.8 MWth, b) gas engine 5.0 MWe / 6.0 MWth and c) pyrolysis-diesel 6.2 MWe / 6.5 MWth shows that the:

- Overall efficiency increase is expected to be in the order of some % - ranging from 2.3% for the rankine power plant 2.0 MWe / 6.8 MWth to 12.8% for pyrolysis-diesel power plant 6.2 MWe / 6.5 MWth

- Co-generation cost reductions are about a third for the gas engine 5.0 MWe / 6.0 MWth and pyrolysis-diesel 6.2 MWe / 6.5 MWth and about a tenth for the rankine power plant 2.0 MWe / 6.8 MWth, that is the more expensive the current generation costs the higher the cost reduction potential not only in absolute but also in relative terms

- Increasing annual operating time leads to a lower generation costs per kWh especially for rankine / steam cycle power plant as well as for the gasification (gas-engine) power plant.

Table 19 : Summary of near-term potential performance assumed for cogeneration power plant concepts. Source: IEA 1999

	Rankine power plant		Gasification - gas engine		Pyrolysis diesel	
	Base	Future	Base	Future	Base	Future
Power production MWe	2.0	2.0	5.0	5.0	6.2	6.2
Heat production MWth	6.8	5.8	6.0	5.7	6.5	6.5
Power production efficiency	17.5	23.0	23.9	32.4	24.7	31.5
Overall efficiency	88.0	90.0	85.0	90.0	58.5	66.0
Power-to-heat ratio	0.30	0.35	0.83	0.88	0.95	0.95

Table 20 : Summary of near-term potential power efficiency increase and shift of power to heat ratio assumed for rankine power plant 2.0 MWe / 6.8 MWth, gas engine 5.0 MWe / 6.0 MWth and pyrolysis 6.2 MWe / 6.5 MWth. Source: IEA 1999, adapted through NET Ltd, St. Ursen, Switzerland

	Rankine power plant	Gasification - gas engine	Pyrolysis diesel
Power efficiency increase	31.4%	35.5%	27.5%
Overall efficiency increase	2.3%	5.9%	12.8%
Shift of power to heat ratio	16.7%	6.0%	0.0%

Table 21 : Co-generation costs of electricity for rankine power plant 2.0 MWe / 6.8 MWth, gas engine 5.0 MWe / 6.0 MWth and pyrolysis 6.2 MWe / 6.5 MWth. Source: IEA 1999, adapted through NET Ltd, St. Ursen, Switzerland

Co-generation costs of electricity in UScents per kWh (approximate values)	Current co-generation costs based on 5000 h annual operating time	Current co-generation costs based on 7000 h annual operating time	Near term co-generation costs based on 5000 h annual operating time	Near term co-generation costs based on 7000 h annual operating time
Rankine power plant	7.5	5.5	7	5
Gasification - gas engine	11.5	9	8	6
Pyrolysis diesel	13	12.5	9.5	8.5

In today’s direct-fired biomass power plants, generation costs [DOE] are about 9 US¢/kWh. In the future, advanced technologies such as gasification-based systems could generate power for as little as 5 US¢/kWh. For comparison, a new combined-cycle power plant using natural gas can generate electricity for about 4 to 5 US¢/kWh at today’s gas prices.

It is clear from different analyses [DOE] that gasification/turbine systems can produce electricity at up to twice the average efficiency of today's biomass power industry. Very high efficiency systems using an advanced utility-scale gas turbines benefit not only from economy of scale, but from the increased turbine efficiency and, perhaps most significantly, the reheat steam cycle that is feasible at this scale and turbine exhaust temperature. ATLAS concluded that cost projections for gasification combined cycle plant show low energy prices in the future that are within striking distance of current fossil prices. If environmental costing were used they would probably be competitive.

Historically, generating systems of very large scale (> 100 MW_e) have been deemed infeasible for biomass-based systems because of the associated feedstock requirements. However, the use of advanced combined-cycle technology reduces fuel requirements to manageable levels because of the striking increase in generating efficiency. Also, smaller, industrial-scale, gas turbines with very high efficiencies are being developed under the UDSOE's Advanced Turbine System (ATS) program. These are likely to be attractive for biomass systems as they will require reduced quantities of biomass to access high efficiency turbine systems.

Complementary to this trend is the development of dedicated feedstock supply systems that are intended to sustainably supply larger quantities of feedstock than were heretofore available. (The USA seems to be more favourable also to incorporate genetically modified feedstock.) ATLAS also emphasises this issue and states that it is not enough to just develop the conversion technology but a steady decrease in fuel price is also necessary and can only be achieved by increasing the yield of energy crops and optimising the fuel supply chain. Properly managed, these trends are positioned to merge and provide a new generation of high-efficiency and cost-competitive biomass-based electricity generating stations.

It is also clear from different studies however that even the most promising electricity cost from biomass is higher than currently quoted avoided costs and new, high-efficiency natural gas combined cycle systems. This is certainly one of the challenges faced by the industry today.

To summarise, the cost reduction opportunities and generation costs are indicated in the tables below. It must be emphasised that these vary much according to the subtechnologies used and the indications represent only global approximated values.

Table 22 : Estimates of the three main cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale). Each * is the approximate equivalence of 4% - 6% of cost reduction within a decade including expected technological learning and market growth. Source: NET Ltd, St.Ursen, Switzerland

	R&D	Manufacturing volume	Economy of scale
Bioelectricity	***	*	**

Table 23 : Summary of important cost figures. Source: compilation NET Ltd, St.Ursen, Switzerland

Cost figures	
Current investment costs in €$_{2000}$ per kWp	• low investment costs: 1200 • high investment costs: 4000
Potential investment costs in €$_{2000}$ per kWp in 2010	• low investment costs: 1000 • high investment costs: 3000
Current generation costs in €cents$_{2000}$ per kWh	• low generation costs: 3 • high generation costs: 18
Future generation costs in €cents$_{2000}$ per kWh in 2010	• low generation costs: 2.5 • high generation costs: 12

2.3 Potential

A key attribute of biomass is its availability upon demand – the energy is stored within the biomass until it is needed. Other forms of renewable energy are dependent on variable environmental conditions such as wind speed or sunlight intensity.

As biomass / organic material is ubiquitious, biopower has everywhere its potential depending on the phytoclimatic conditions. Two types of biopower potential maps are shown below. The first map gives an overview of the US potential in relative terms (concentrations). The second map highlights – in absolute terms – countries with high bioenergy potential greater than 5 GW.

The Earth's natural biomass replacement represents an energy supply of around 3000EJ (3×10^{21} J) a year, of which just under 2% is currently (1998) used as fuel [Australian Greenhouse Office]. It is not possible, however, to use all of the annual production of biomass in a sustainable manner. One analysis carried out by the United Nations Conference on Environment and Development (UNCED) estimates that biomass could potentially supply about half of the present world primary energy consumption by the year 2050 (Ramage & Scurlock 1996).

Biomass comes from organic material, mainly plants. Plants, through photosynthesis, take up carbon. The plants convert carbon dioxide into organic carbon, which provides plants with the energy to grow. The more they grow, the more carbon dioxide they absorb. When the plant dies, bacteria and fungi decompose the plant, converting the organic carbon back into its inorganic form - carbon dioxide. If the plant material can be harvested before it falls to the ground or dies, then the carbon remains stored in the plant material. This stored carbon has energy potential, available for human use. Once the plants are harvested, biomass can be converted to energy by burning the dried plant material directly (or turning it into a gas) to generate electricity or heat [www.puaf]. In many respects electricity from biomass is different from other renewable energies in that the primary energy resource encompasses a variety of feedstock with wide ranging properties. Also, a number of technologies have grown up, and more are proposed, to convert these fuels to electricity [Koukios, ATLAS www].

$$CO_2 + 2H_2O \underset{heat}{\overset{light}{\longleftrightarrow}} ([CH_2O] + H_2O) + O_2$$

Equation for photosynthesis

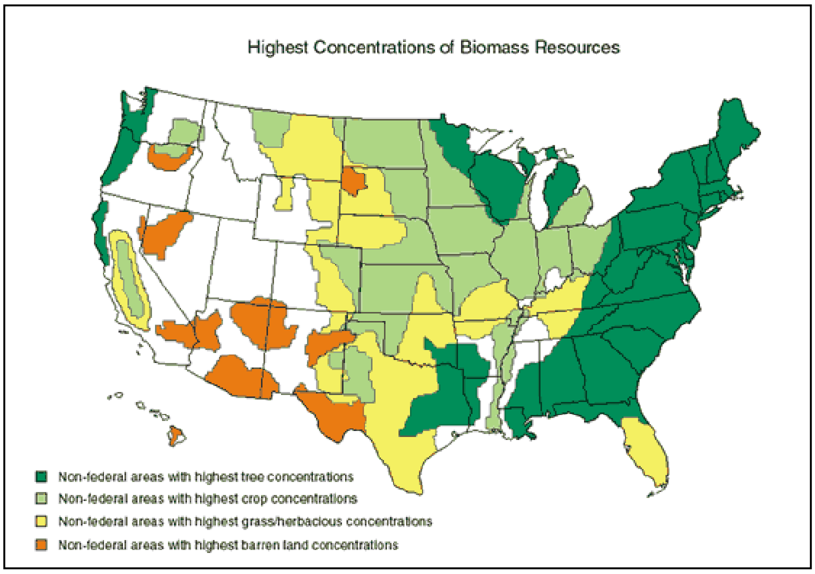


Figure 17 : Concentrations of biomass resources in USA. Source: DOE Biopower

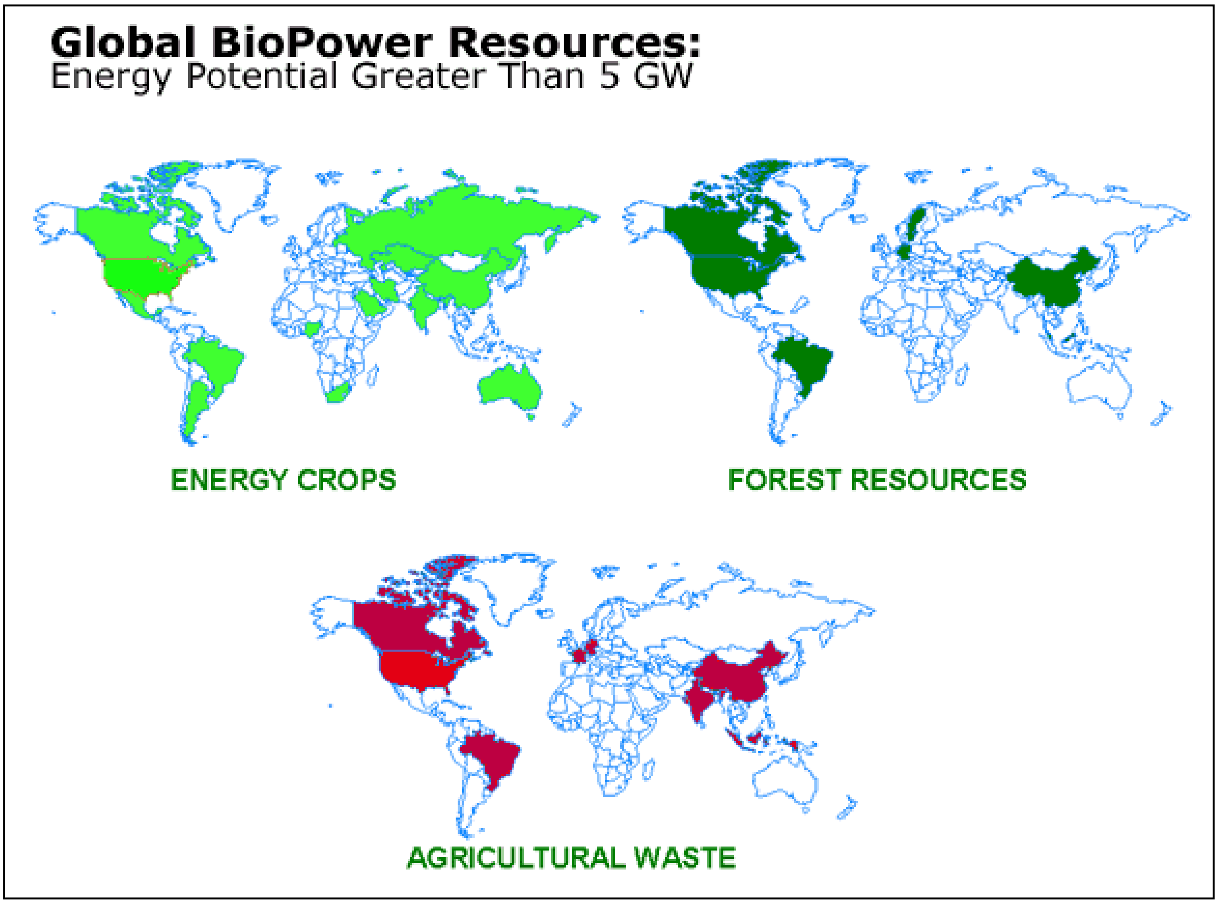


Figure 18 : Global biopower resources biomass resources – in absolute terms – showing countries with high bioenergy potential greater than 5 GW. Source: DOE Biopower

The main biomass resources can be listed as follows:

- short rotation forestry (willow, poplar, eucalyptus),
- herbaceous ligno-cellulosic crops (miscanthus),
- sugar crops (sugar beet, sweet sorghum, Jerusalem artichoke),
- starch crops (maize, wheat),
- oil crops (rape seed, sunflower),
- wood wastes (forest residues, wood processing waste, construction residues),
- agricultural residues and wastes (straw, animal manure, etc.),
- organic fraction of municipal solid waste and refuse,
- sewage sludge, and
- industrial residues (e.g., from the food and the paper industries).

Biomass resources [Australian Greenhouse Office] that can be used for energy production cover a wide range of materials. The use of biomass energy can be separated into two categories, namely modern biomass and traditional biomass. Modern biomass usually involves large-scale uses and aims to substitute for conventional fossil fuel energy sources. It includes forest wood and agricultural residues; urban wastes; and biogas and energy crops. Traditional biomass is generally confined to developing countries and small-scale uses. It includes fuel wood and charcoal for domestic use, rice husks other plant residues, and animal dung.

Current and future available biomass resources in the European Union are given in table 2:

Table 24 : Biomass potential in the EU. Source: Koukios

Raw Material	Current Resources Mt (dry)/year	Future Resources Mt (dry)/year
Co-products of other activities:		
- Wood Wastes	50	70
- Agricultural Residues	100	100
- Municipal Solid Wastes	60	75
- Industrial Wastes	90	100
Dedicated land for biomass::		
- Short Rotation Forestry	5	75-150
- Energy Crops	-	250-750
TOTAL BIOMASS	200	1,000
(TOTAL BIOENERGY, Mtoe)	(80)	(400)
(% current EU Primary Energy)	(5-6 %)	(25-30 %)

It can be seen from table 2 that, in the long term, energy crops - to be grown on land set-aside from agriculture - could be a very important biomass fuel source. However, at present, co-products of other production activities are the major biomass sources and are the priority feedstocks for energy production. There is also an added environmental benefit in using presently available secondary flows, such as municipal solid waste and sewage sludge as raw materials, as these are potential pollutants.

Although in the long term energy crops can be an important biomass feedstock. At present, however, wastes, either in the form of wood wastes, agricultural wastes, municipal or industrial wastes, are the major biomass sources and, consequently, the priority fuels for energy production. There is also an additional environmental benefit in the use of residues such as municipal solid waste and slurry as feedstocks as these are withdrawn from polluting landfilling.

Research on biomass energy crops is concentrating on generating reliable data on potential yield, environmental impact, limitations and economics. Developments are done through networks of research groups such as the Miscanthus Network, the Sweet Sorghum Network, etc. There are also a number of other European and national projects which carry out research on a range of biomass materials.

Table 25 : Summary of important potential factors. Source: compilation NET Ltd, St.Ursen, Switzerland

Top potential factors	
Geofactor influencing energy input	• biomass growth (fuel)
Limit (availability / capacity)	• area availability • material availability
Capacity installed in 1998 in kWh per year and capita in EU15 and Switzerland	• 40 kWh
Potential in kWh per year and capita in EU15 and Switzerland	• 150 - 200 kWh by 2010
Future potential beyond term year given	• high
Rule of thumb for conversion ratio* (installed power to electric output)	• 1 kWp --> 5400 kWh per year • 1 kg of biomass --> 1.6 kWh

* Assumptions: U.S. data with 60 million tons of biomass per year converted into 37 billion kWh of electricity with 7 GWp installed capacity [DOE].

2.4 Markets

Worldwide biopower generation is expected to grow to more than 30 000 MW by 2020 [DOE]. In many countries, local environmental conditions and global climate change concerns are further stimulating the demand for clean energy.

The current biopower market / production in EU15 and Switzerland is given in the table below.

Table 26 : Biopower production in kWh per year and capita for EU15 and Switzerland in 1998. Source: ElGreen for EU15 data [Huber]

Country	Biopower production in kWh per year and capita
Finland	1454.8
Sweden	290.7
Austria	193.4
Denmark	81.5
EU15	39.7
Spain	21.4
Switzerland	20.0
France	15.8
Belgium	9.3
Germany	8.3
Italy	4.8
Portugal	0.1
Greece	0.0
Ireland	0.0
Luxembourg	0.0
Netherlands	0.0
UK	0.0

Deregulation is likely to bring many opportunities as well as challenges however. Among these are capturing the market for "green power" demonstrated by innumerable public surveys. Also promising is deployment of these technologies into the cogeneration and distributed generation markets. This avoids head-to-head competition with large central station fossil-fueled plants. Additionally, such systems may have access to low cost feedstocks or favorable treatment by regulatory bodies. Smaller scale distributed generations systems employing industrial turbines or fuel cells are also applicable to the burgeoning international market for electricity generation.

Market growth can be enhanced mainly by price-driven and application-driven markets.

Price-driven markets

Today, *cofiring* [DOE] offers power plant managers a relatively low cost and low risk route to add biomass capacity. These projects require small capital investments per unit of power generation capacity. Cofiring systems range in size from 1 to 30 MW of Biopower capacity. When low cost biomass fuels are used, cofiring systems can result in payback periods as low as 2 years. A typical existing coal fueled power plant produces power for about 2.3 US¢/kWh. Cofiring inexpensive biomass fuels can reduce this cost to 2.1 US¢/kWh.

Investment levels are very site specific and are affected by the available space for yarding and storing biomass, installing size reduction and drying facilities, and the type of boiler burner modifications. Investments are expected to be between \$50 to \$200/kW of biomass capacity, with a median in the \$180 to \$200/kW range. ElGreen [Huber] calculates investments costs of 1100 € per kWp for upgrading a cofiring station and concludes that this option is the cheapest one for biopower. Koukios indicates €500 per kW.

Cofiring is of (increasing) interest in the USA, some of the developing countries like China where coal firing plays an important role and in some Northern European states.

For the Netherlands, the Marsroute study [van Hilten] shows that combustion and co-combustion will be the most important biomass technologies in the near future. In the Netherlands, co-combustion in coal-fueled electricity plants is the most economically feasible option, followed by co-combustion in gas-fueled plants.

A threat to the growth of the biomass sector is the lack of availability (or possible increases in price) of biomass fuel. Waste needs to be separated for use as fuel instead of incineration in waste treatment plants. Also co-combustion in coal-fueled plants is dependent on the support for coal-fueled plants. Coal-fueled electricity plants are being substituted by gas-fired plants all over Europe.

The *most economic forms of biomass* for generating electricity are *residues*. These are the organic byproducts of food, fiber, and forest production. Common examples used for power are sawdust, rice husks, and bagasse (the residue remaining after juice has been extracted from sugar cane). Low-cost biomass sources are also common near population and manufacturing centers where clean wood *waste* materials are available in large quantities. Examples are pallet and crate discards and woody yard trimmings. Using these residues for biopower production often present the solution for a potential waste disposal problem [ATLAS].

Not to be omitted are other industries like the pulp and paper industry where traditionally a lot of cheap organic material is available for producing power which is partly used in the industrial processes on the spot. For biomass to be economical as a power plant fuel – biomass has a relatively low energy density compared to conventional fuels - , transportation distances from the resource supply to the power generation point must be minimized, with the maximum economically feasible distance being less than 100 - 150 km. In other words: the most economical conditions exist when the energy use is located at the site where the biomass residue is generated (i.e., at a paper mill, sawmill, or sugar mill). Modular biopower generation technologies will minimise fuel transportation distances by locating small-scale power plants at biomass supply sites.

For the medium term (2010), the only interesting stand-alone biomass options indicated by the Marsroute analysis [van Hilten] are pyrolysis for waste and ‘CFB-vergassing’ (Circulating Fluidized Bed pyrolyse) STEG (Steam and Gas turbine) for clean biomass fuel and separated waste.

Application-driven markets

Deregulation and green power

Deregulation of the electricity industry is providing consumers with choices on who their power supplier will be and the content of the power product. Several states have passed laws that set a minimum requirement for renewable power, and there are consumers who are willing to pay more for electricity generated from renewable resources.

Green power programs have emerged largely in response to this consumer demand. In a green power program, the power provider gives customers the option to buy electricity generated from environmentally friendlier sources. Usually this option costs a little more because, on average, it is still more expensive to generate environmentally friendly power than traditional power using coal, natural gas, and nuclear.

Off-grid modular systems and developing world

Modular systems employ some of the same technologies mentioned above, but on a smaller scale that is more applicable to villages, farms, and small industry. These systems are now under development and could be most useful in remote areas where biomass is abundant and electricity is scarce. There are many opportunities for these systems in developing countries. Off-grid, modular systems offer the most viable international market opportunity for biopower. A wide range of developing countries present top markets because they meet several criteria:

- rapid economic growth
- burgeoning demand for electricity
- mounting environmental problems
- need for rural electrification
- need for reliable electricity
- significant agricultural/forestry residues

China and India are considered to be the prime candidates. Estimates show that by 2015, China will have between 3500 and 4100 MW of biopower capacity and India will have between 1400 and 1700 MW. This is a sharp rise from their current levels of 154 MW and 79 MW, respectively. These two countries may also be good targets for cofiring operations because they have many older coal-fired power plants where biomass cofiring could be used to economically improve environmental performance. Other countries that show promising growth for a variety of biopower systems are Brazil, Malaysia, Philippines, Indonesia, Australia, Canada, England, Germany, and France.

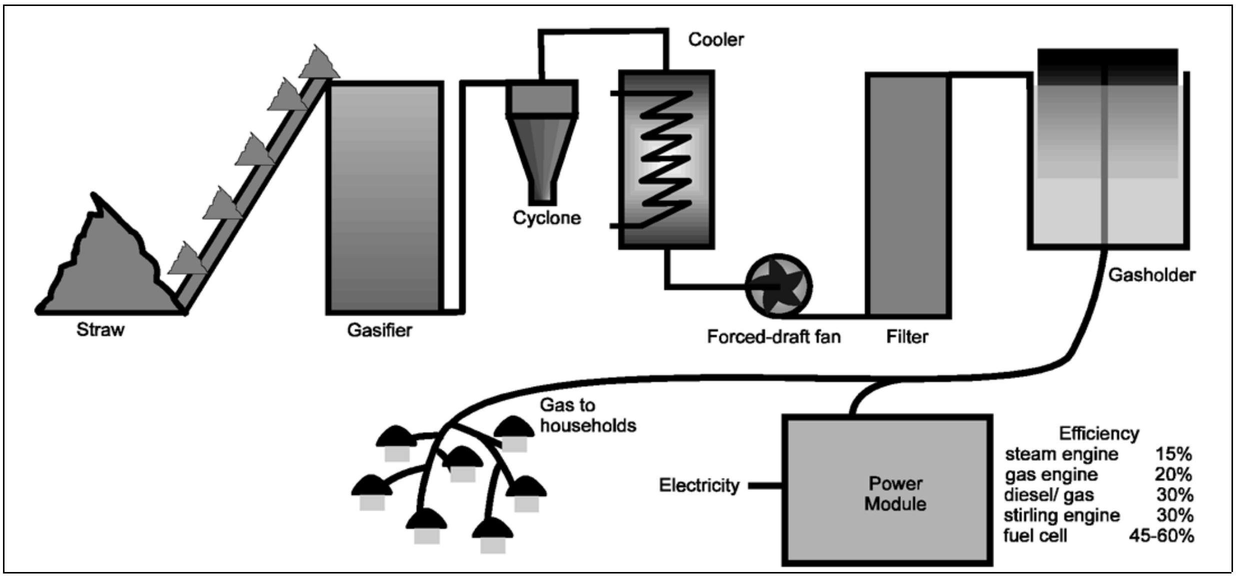


Figure 19 : Village thermal gasification system as an example for using different price and application related market opportunities. Source: Overend and Craig

Distributed generation markets and electricity infrastructure

The arguments like “the most economical conditions exist when the energy use is located at the site where the biomass residue is generated” hold also for distributed generation markets. Locally produced biomass and biopower can be partly competitive also in function of the grid characteristics on the base of so-called “avoided costs”.

Although most biomass in developing countries is used for cooking and space heating, a significant amount is also used in industry for process steam and power generation [ATLAS]. These industrial uses are almost exclusively in the agro-processing and wood processing sectors. Up until recently the priorities for these generators has been the disposal of residues and the lowest capital cost commensurate with the required availability.

Efficiency has never been a priority because there has rarely been a customer for the surplus electricity that the improvements would create. Thus, efficiencies have typically been below 20% and often in single figures. However, as *developing countries expand their electricity infrastructure* these agro-processing plants present an interesting opportunity to develop sources of low cost electricity by installing more efficient generation equipment. For example a typical sugar mill could export approximately 8 MW_e by implementing simple improvements. This output could be doubled by the installation of more advanced technology.

2.5 Needs and measures

Both present and potential markets for bioenergy look extremely fragmented. In addition to an optimal mix of the three types of energy vectors, a strong and healthy bioenergy market should have a place for both large- and small-scale applications, conventional along with novel solutions, centralised as well as decentralised schemes.

A viable approach should consist of three different, interacting and, as far as possible, co-ordinated strategic components or elements [Koukios]:

- A “defensive” element focusing on the support of traditional bioenergy uses in rural European areas that are threatened by extinction.
- An “aggressive” element centred around the effort of penetration of new bioenergy technologies and product vectors in existing and new markets.
- An “exploratory” element oriented towards future biomass applications though the encouragement and support of innovations.

It’s good to remember that, in Europe [ATLAS], the greatest part of biomass to electricity schemes was developed in pulp and paper industries and forest industries, where significant synergies and the necessity of waste management were critical success factors. Beyond these applications, biomass to electricity schemes have mainly been successfully deployed in Scandinavian countries (and partly Austria) where dedicated policies including tax and subsidy policies were implemented.

The following classification of characteristics of these three proposed strategic elements (table 27) represents an effort to construct roadmaps for biomass in the EU based on the analysis reported in this document.

Table 27 : Outline of a European market-oriented biomass strategy [4]

Strategy Element	Targets for Feedstocks	Targets for Technologies	Targets for Users and Systems
Defensive	• Sustainable forest and wood management • Rational use of waste and residues	Improvement of: • Wood combustion efficiency • Feedstock quality (e.g. pellets) • Landfill gas systems	• Existing bioheat markets • Co-generation • Solid biofuels - Standards • Local systems
Aggressive	• Systematic use of bio-resources • Introduction of energy crops	• Supporting advanced combustion • Promoting gasification • Promoting biogas • Develop transport fuel from cellulosics	• New bioheat and bioelectricity uses • Co-firing at coal plants • Transport fuel additives • Regional systems
Exploratory	• Complex local/regional biomass systems • New energy crops	• Demonstrate pyrolysis • Develop hydrogen from biomass sources	• Fuel cells • Complex systems • Transport biofuels • New engines

The U.S. DOE Biomass Power Program is working to address the issues of making biomass competitive by working with today's industry to increase its reliability and to develop advanced systems for increased efficiency and environmental performance. The pathways under discussion are included in the figure below.

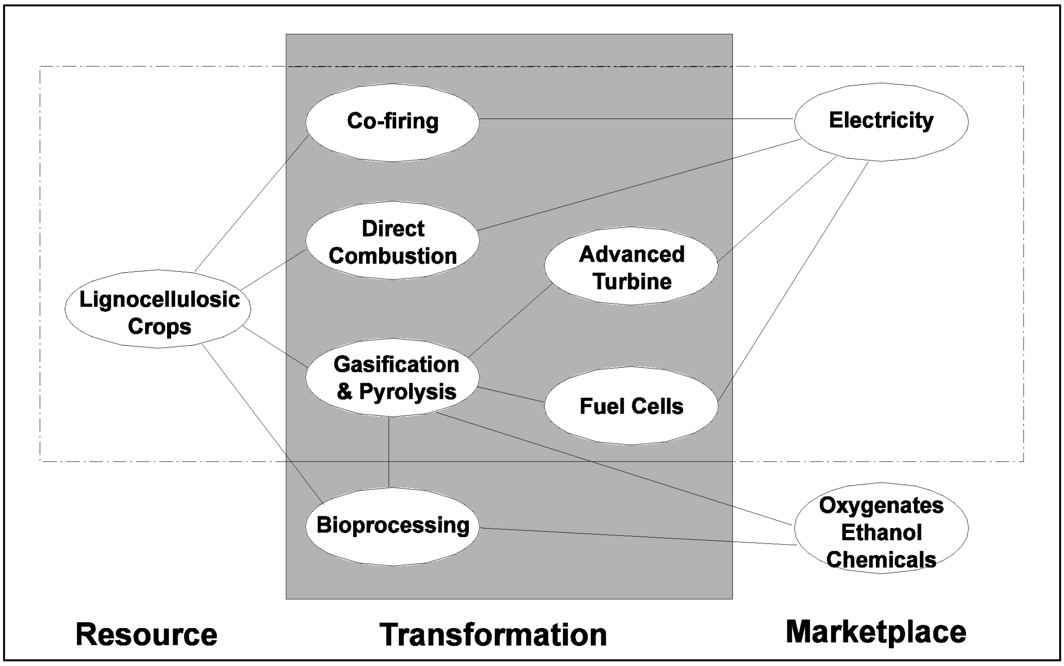


Figure 20 : Biomass energy market pathways. Source: Craig et al [NREL 1995]

There appear to be niches wherein biomass power systems are either competitive or desirable. The success of projects targeted at these niches are dependant upon numerous factors, but among the most important of these are [Craig / NREL 1995]:

- a reliable, cost-stable feedstock and
- reliable advanced technology.

The technical barriers and cost uncertainties associated with both of these are steadily falling. To maintain or accelerate the development and deployment pace in the timely fashion required to capture attractive domestic and international markets, it is necessary to pursue a tightly coupled and well integrated development, testing, and demonstration program. Such a program must incorporate results from all stages and sizes into all others. This will further allow biomass power systems to adequately and effectively leverage the technical developments taking place outside the Biomass Power program in power conversion technologies such as turbines and fuel cells. The aggregate of these factors will permit the industry to rapidly traverse the learning curve to reduce costs and uncertainty and create a vibrant biomass power industry [Koukios].

3 Geothermal electricity

Figure 21 : View of the two Carboli geothermal plants Creek in Italy. Source: Enel GreenPower / IGA

Figure 22 : Geothermal power plant at Wairakei, New Zealand. Source: IGA

Figure 23 : The Geysers geothermal power plant in California, USA. Source: IGA

3.1 Techno-economic development

The first attempt at generating electricity from geothermal steam was made at Larderello in 1904. Electricity generation at Larderello was a commercial success. The example set by Italy was followed by several countries. The first geothermal wells in Japan were drilled at Beppu in 1919 and in the USA at The Geysers, California, in 1921. In 1958, a small geothermal power plant began operating in New Zealand and in 1959 in Mexico, and in many other countries in the years to follow.

Obviously, geothermal technology is particularly related to the type of the natural energy source and resource. A geothermal system is made up of three main elements: a *heat source*, a *reservoir* and a *fluid*, which is the carrier that transfers the heat. The heat source can be either a very high temperature (> 600°C) magmatic intrusion that has reached relatively shallow depths (5-10 km) or, as in certain low temperature systems, the Earth's normal temperature, which increases with depth. The mechanism underlying geothermal systems is by and large governed by *fluid convection*. Of all the elements of a geothermal system, the heat source is the only one that needs to be natural. In the *Hot Dry Rock* (HDR) project, implemented in the USA in the early 1970s, both the fluid and the reservoir are artificial.

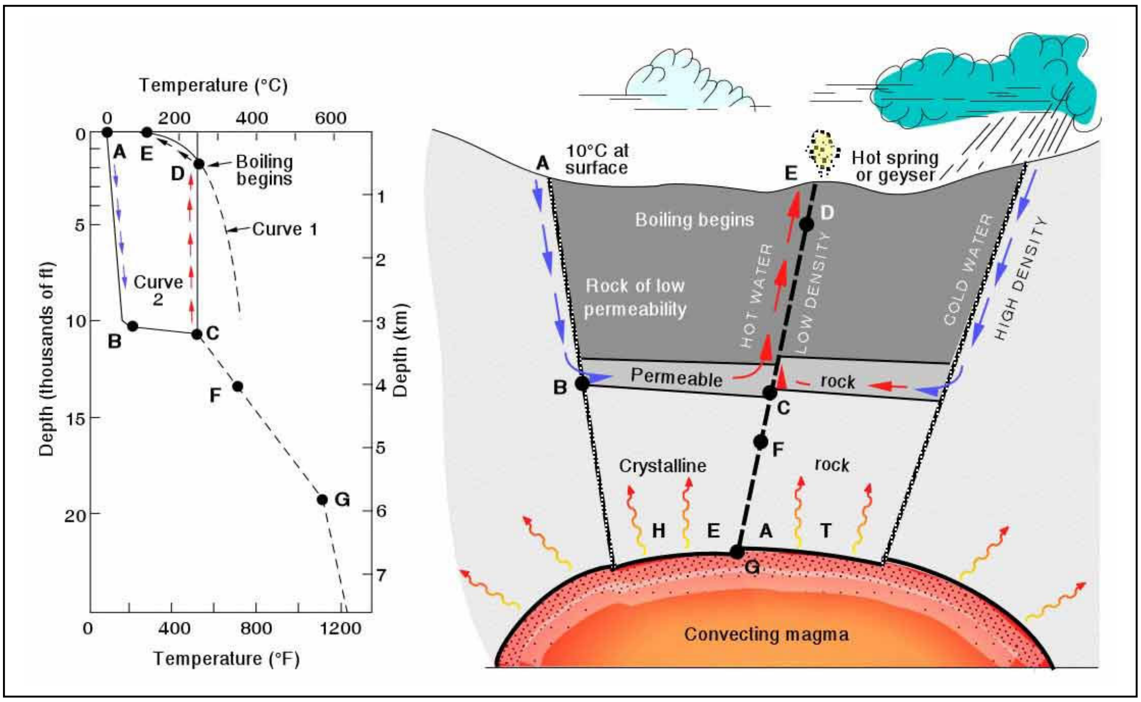


Figure 24: Model of a geothermal system. Curve 1 is the reference curve for the boiling point of pure water. Curve 2 shows the temperature profile along a typical circulation route from recharge at point A to discharge at point E. Source: White

Electricity generation mainly takes place in conventional steam turbines and binary plants, depending on the characteristics of the geothermal resource.

Conventional steam turbines require fluids at temperatures of at least 150°C and are available with either atmospheric (backpressure) or condensing exhausts. Atmospheric exhaust turbines are simpler and cheaper. The steam - directly from dry steam wells or, after separation, from wet wells - is passed through a turbine and exhausted to the atmosphere. With this type of unit, steam consumption from the same inlet pressure is almost double that of a condensing unit per kilowatt-hour produced. However, the atmospheric exhaust turbines are extremely useful as pilot plants, stand-by plants, in the case of small supplies from isolated wells, and for generating electricity from test wells during field development. They are also used when the steam has a high non-condensable gas content (> 12% in weight). The atmospheric exhaust units can be constructed and installed very quickly and put into operation in little more than 13-14 months from their order date. This type of machine is usually available in small sizes (2.5 - 5 MW_e).

The condensing units, having more auxiliary equipment, are more complex than the atmospheric exhaust units and the bigger sizes take up to twice as long to construct and install. The specific steam consumption of the condensing units is, however, about half of the atmospheric exhaust units. Condensing plants of 55 - 60 MW_e capacity are very common but plants of 110 MW_e have recently been constructed and installed (see figure below).

Generating electricity from low-to-medium temperature geothermal fluids and from the waste hot waters coming from the separators in water-dominated geothermal fields has made considerable progress with improvements made in binary fluid technology. The *binary plants* utilise a secondary working fluid, usually an organic fluid that has a low boiling point and high vapour pressure at low temperatures when compared to steam. The secondary fluid is operated through a conventional Rankine cycle: the geothermal fluid yields heat to the secondary fluid through heat exchangers, in which this fluid is heated and vaporises; the vapour produced drives a normal axial flow turbine, is then cooled and condensed, and the cycle begins again (see figure below).

By selecting suitable secondary fluids, binary systems can be designed to utilise geothermal fluids in the temperature range 85-175°C. The upper limit depends on the thermal stability of the organic binary fluid, and the lower limit on technical-economic factors: below this temperature the size of the heat exchangers required would render the project uneconomical. Not only the heat exchanger size is decisive, but also the fluid temperature. The efficiency of conversion from heat to electricity decreases strongly with fluid temperature: for 85 °C it is only 2 %, below 60 °C it is practically zero. Apart from low-to-medium temperature geothermal fluids and waste fluids, binary systems can also be utilised where flashing of the geothermal fluids should preferably be avoided (for example, to prevent well sealing). In this case, downhole pumps can be used to keep the fluids in a pressurised liquid state, and the energy can be extracted from the circulating fluid by means of binary units.

Binary plants are usually constructed in small modular units of a few hundred kW_e to a few MW_e capacity. These units can then be linked up to create power-plants of a few tens of megawatts. Their cost depends on a number of factors, but particularly on the temperature of the geothermal fluid produced, which influences the size of the turbine, heat exchangers and cooling system. The total size of the plant has little effect on the specific cost, as a series of standard modular units is joined together to obtain larger capacities.

After long trial and error, binary plant technology is emerging as a very cost-effective and reliable means of converting into electricity the energy available from water-dominated geothermal fields (below 175°C).

A very important pilot project for the geothermal heat mining has been active in Europe for a few years: it consists in the artificial fracturation of the deep rocks (granites), and the heat mining with a closed reinjection-production loop (it is denominated Hot Dry Rock – HDR or Enhanced Geothermal System – EGS). The activity is carried out in Soultz site, Alsatia, close to the France-Germany border.

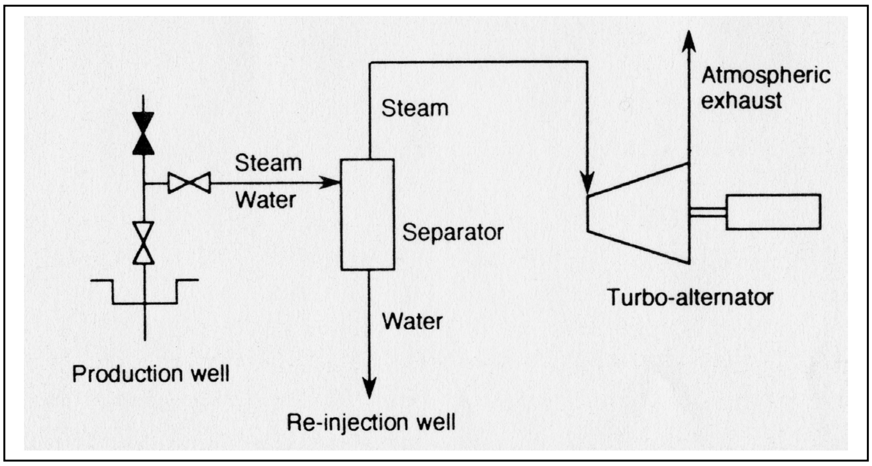


Figure 25 : Conventional steam turbines with atmospheric exhaust. Source: IGA / Bertani

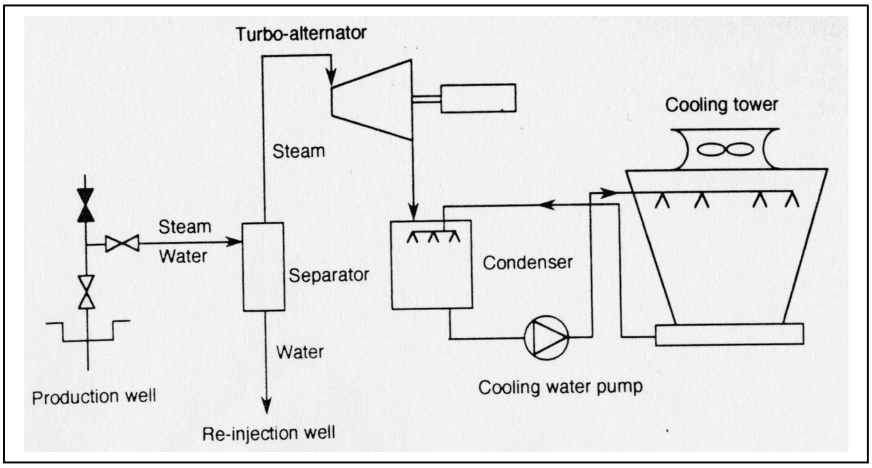


Figure 26 : Conventional steam turbines with condensing cycle. Source: IGA / Bertani

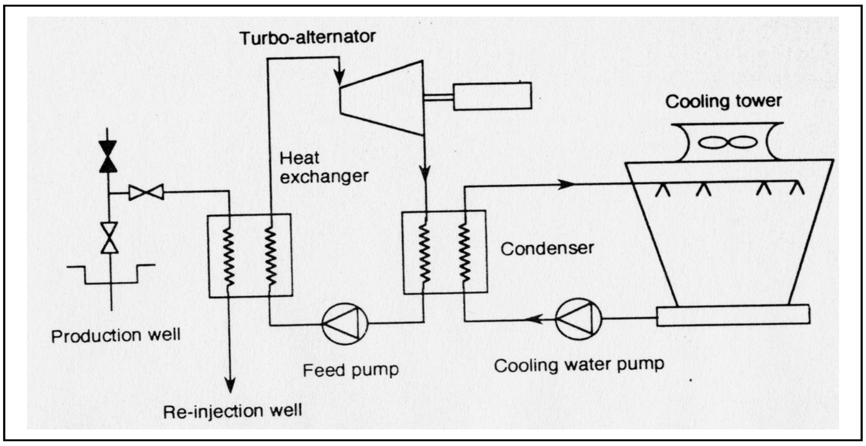


Figure 27 : Binary cycle simplified. Source: IGA / Bertani

3.2 Costs and cost reduction opportunities

Costs of a geothermal plant are heavily weighted toward early expenses, rather than fuel to keep them running. Well drilling and pipeline construction occur first, followed by resource analysis of the drilling information. Next is design of the actual plant. Power plant construction is usually completed concurrent with final field development. The initial cost for the field and power plant is around $2000 per installed kW in the U.S., probably $3000 to $5000/kWe for a small (<1MW$_e$) power plant, and $1500 to $2500/kWe for larger plants, depending on the resource temperature and chemistry. Operating and maintenance costs range from $0.015 to $0.045 per kWh, depending on the contract price for the electricity. Most geothermal power plants can run at greater than 90% availability (i.e. producing more than 90% of the time), but running at 97% or 98% can increase maintenance costs. Higher-priced electricity justifies running the plant 98% of the time because the resulting higher maintenance costs are recovered (http://www.eren.doe.gov/geothermal/geofaq.html)

There are some unique aspects of the geothermal project management (McClain, 2000):

- Exploration and leasing
- Project development and feasibility studies
- Well field development
- Project finance, construction, start-up operation
- Commercial operation
- Field & plant expansion

Exploration and leasing: This phase is normally broken up in the following activities: Reconnaissance assessment, leasing and land acquisition, exploratory drilling and well testing. In general, the first two activities are low-cost and low-risk phases ranging form 50000 to 500000 US$ in total. Exploratory drilling and reservoir assessment is a high risk phase: if the exploration did not succeed in finding a good resource, the entire project can be cancelled. Many different activities are normally associated with this phase: geological data, geophysical surveys, approval process for drilling, building road, mobilizing a drilling rig, well testing, physical and chemical data collection. The cost could be easily in the range from 0.75 to 2.5 million US$ per each exploration well, and the entire programme can reach the value of 3 – 6 million US$ for being completed.

Project Development and Feasibility Studies: If the previous phase is satisfactory, the development stage can start: it is an intermediate and critical step: it's necessary to achieve the compilation of a reservoir assessment report, the negotiation of a power sale contract, the approval of construction of wells, steam and water lines, power plant, coping with environmental constraints, and the finalization of design and cost/revenue estimation. Despite of its importance, the cost is not particularly high, ranging from 0.25 to 2.3 million USD, with highest expenses for pre-construction permits and environmental approval.

Well Field Development and Project Finance, Construction, Start-up Operation: This phase is rather complicated, with many parallel activities: drilling often overlaps with power plant construction. It's usually time-consuming: from a plant construction time is 12-16 months, while well drilling can last few years (depending on the number of parallel drilling rig in operation). A standard 50 MW project with 10 out of 12 production wells, two injection wells and two reserve wells, at an average cost of 2 million US$ per well (depending on depth), the overall well field development can reach 32 million US$. Power plant engineering, design, construction, start-up is rather complicated but not particularly geothermal related; the total investment cost for 50 MW can range from 3-10 to 50-150 million US$.

Commercial operations and Field & Plant expansion: The successful completion of the construction phase will change the management team from a drilling-construction oriented to power plant O&M and reservoir oriented. Geothermal plants have an availability factor of 98%, and can be operated full load 24 hours a day. with a capacity factor of 95-100%. The life estimation for a geothermal project is easily 10-20 years, and the project revenues can repay all the loans.

It is common to develop a project in stages, with multiple power plants being developed over time. A second unit in the same reservoir has several unique elements, like to verify that the new wells will not affect the productivity of the existing ones, and that no shut-down of the running plant should be planned, reducing the interference with the daily operation.

Conclusion: The overall cost for 50 MW project can be around 50-150 million US$. The resource assessment and exploration is a crucial point for the success of a geothermal project. It is important to develop the power plant in the same time of the well field, with an integrated programme of engineering, environmental and construction. The entire project is evolutionary in nature, with each phase of development being dependent upon the success of the prior one. Multidisciplinary teams are needed to manage a geothermal project from exploration through the operations phase, and these management teams need to be focused and staffed for the requirement of each phase.

Cost reduction opportunities arise in increasing the output of an existing project, via:

- Proper reservoir management (injection-reinjection-well stimulation), which can be responsible for increasing the sustainability of the resource over time;
- Expansion of the explored zone, which is - in general - less risky than a brand new area;
- Plant refurbishment, increasing the specific consumption, their efficiency and availability, with a better tuning on the thermodynamical characteristics of the given geothermal fluid for any site.

Other opportunities are related to exploration programmes. Before drawing up a geothermal exploration programme all existing geological, geophysical and geochemical data must be collected and integrated with any data available from previous studies on water, minerals and oil resources in the study area and adjacent areas. This information frequently plays an important role in defining the objectives of the geothermal exploration programme and could lead to a significant reduction in costs.

R&D is expected to bring new and improved processes and designs, like Hot Dry Rock (HDR) or Enhanced Geothermal System (EGS) being currently tested in Europe.

Table 28 : Estimates of the three main cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale). Each * is the approximate equivalence of 4% - 6% of cost reduction within a decade including expected technological learning and market growth. Source: NET Ltd, St.Ursen, Switzerland

	R&D	Manufacturing volume	Economy of scale
Geothermal	**	*	***

Table 29 : Summary of important cost figures. Source: compilation NET Ltd, St.Ursen, Switzerland

Cost figures	
Current investment costs in €$_{2000}$ per kWp	• low investment costs: 1200 • high investment costs: 5000
Potential investment costs in €$_{2000}$ per kWp in 2010	• low investment costs: 1000 • high investment costs: 3500
Current generation costs in €cents$_{2000}$ per kWh	• low generation costs: 5 • high generation costs: 14
Future generation costs in €cents$_{2000}$ per kWh in 2010	• low generation costs: 3.5 • high generation costs: 10

3.3 Potential

The presence of volcanoes, hot springs, and other thermal phenomena must have led our ancestors to surmise that parts of the interior of the Earth were hot. However, it was not until a period between the sixteenth and seventeenth century, when the first mines were excavated to several hundred metres below ground level, that man deduced from simple physical sensations that the Earth's temperature increased with depth.

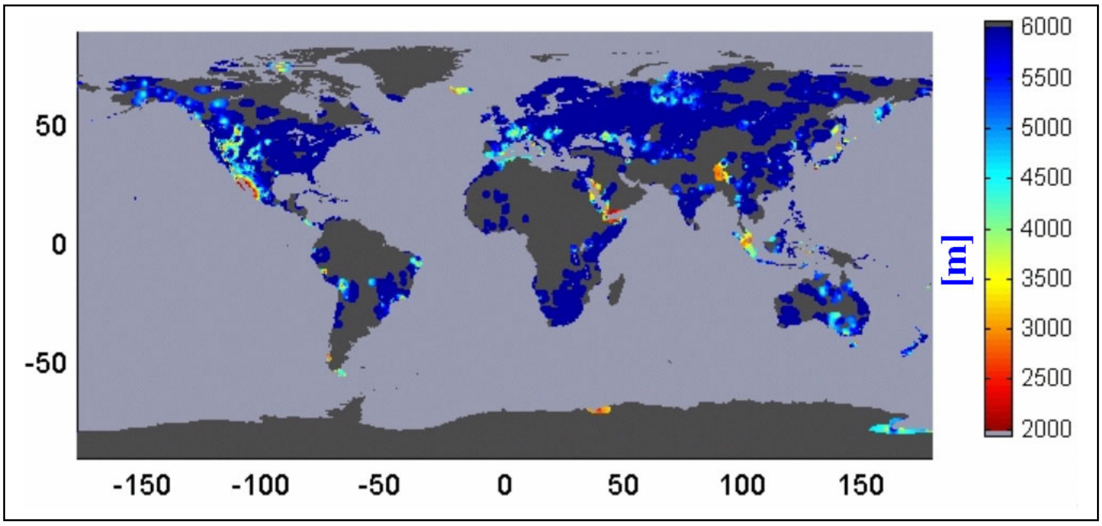


Figure 28 : Geothermal potential in the world taking into account temperature difference of 170 K and depths not > 6 km. Source: B. Lehner (USF) and G. Czisch (ISET)

All modern thermal models of the Earth must, in fact, take into account the heat continually generated by the decay of the long-lived radioactive isotopes of uranium (U^{238}, U^{235}), thorium (Th^{232}) and potassium (K^{40}), which are present in the Earth (Lubimova, 1968). Added to radiogenic heat, in uncertain proportions, are other potential sources of heat such as the primordial energy of planetary accretion. Realistic theories on these models were not available until the 1980s, when it was demonstrated that there was no equilibrium between the radiogenic heat generated in the Earth's interior and the heat dissipated into space from the Earth, and that our planet is slowly cooling down.

Estimates from more than twenty years ago gave the total heat content of the Earth, reckoned above an assumed average surface temperature of 15°C, in the order of 12.6 x 10^{24} MJ, and that of the crust in the order of 5.4 x 10^{21} MJ (Armstead, 1983). The thermal energy of the Earth is therefore immense but only a fraction can be utilised by man. So far, our utilisation of this energy has been limited to areas in which geological conditions permit a carrier (water in the liquid phase or steam) to "transfer" the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources, but innovative techniques in the near future may offer new perspectives in this sector.

The most common criterion for classifying geothermal resources is that based on the enthalpy of the geothermal fluids that act as the carrier transporting heat from the deep hot rocks to the surface. *Enthalpy*, which can be considered more or less proportional to temperature, is used to express the heat (thermal energy) content of the fluids, and gives a rough idea of their 'value'.

Table 30 : Classification of geothermal resources in °C. Source: Nicholson

Resources	°C
Low enthalpy	<150
Intermediate enthalpy	150
High enthalpy	>150

Table 31 : Potential areas for geothermal power generation in Europe. Source: classification proposed and developed by Barbier and Santoprete, 1993; Dickson and Fanelli, 1995; Cataldi, 1999; adopted by NET Ltd, St. Ursen, Switzerland

Classification	Areas	Surface in Europe in %	Remarks
Very Good	• French Antilles (Guadeloupe - Martinique) • Iceland, Azores (Portugal), Canaries (Spain), along the mid-Atlantic ridge • Far east of Russia (Kamchatcka, on the Pacific ocean “ring of fire”) • Pre-Apennine belt of Tuscany and Latium (geothermal fields of Larderello, Mt. Amiata and Latera) • Aeolian islands (Italy) and Aegean islands (Greece) • Western Anatolia (Turkey)	0.2%	suitable for electricity generation with the present technologies and the current economic scenario
Good	• Area on the border of the above mentioned regions • Central Massif in France • Rhine graben in Germany • Campidano graben (Sardinia, Italy) • Pannonian basin (Hungary, Romania) • Lesbos island (Greece) • (Eastern Siberia (Russia))	2.3%	suitable for electricity generation with the present technologies and the current economic scenario
Moderate		12.5%	
Poor		85%	

The electric production is possible only in the first two categories (2.5% of the European surface), with the present technologies and the current economic scenario.

Apart Italy, the second most promising country is Turkey: there are only 20 MWp of installed capacity, but there is the large potential of 200 - 300 MWp. Greece has a geothermal potential of approximately 200 MWp, scattered on many small islands, but the negative reaction of the local population is a major obstacle to the resource exploitation. Iceland is an important geothermal country, with 200 MWp of installed capacity and 4000 MWp of potential: it is much higher than the effective electricity needs of the country. In Russia, the Kamchatcka region and the Kuril Islands have 34 MW installed, with an important potential of about 400-500 MWp. Finally, France and Portugal in the Atlantic Ocean have small resources (Guadeloupe and Azores, 4.7 MWp and 16 MWp respectively), with few tens of MWp of potential (Popovski et al., 2000).

The geothermal resources suitable for electricity production are rather limited and not equally spread in Europe, while for the direct uses the prospects are much more favorable.

However, today only a small part of the whole geothermal potential has been explored and exploited. The prospects are very promising, and the opportunity of the heat mining in non-hydrothermal system artificially fractured via a closed loop can be very important in the long-term future.

As a conclusion, the geothermal electricity development in (geographic) Europe can be in the range of 1500 - 2000 MW for the year 2010 (exceeding the objective set of 1000 MWp in the EC's White Book), while for 2020 the installed capacity would be in the range from 2000 to 3000 MWp. A great share of this capacity will be installed in today's EU15.

Table 32 : Summary of important potential factors. Source: compilation NET Ltd, St.Ursen, Switzerland

Top potential factors	
Geofactor influencing energy input	• enthalpy (temperature gradient)
Limit (availability / capacity)	• site availability
Capacity installed in 1998 in kWh per year and capita in EU15 and Switzerland	• 11 kWh
Potential in kWh per year and capita in EU15 and Switzerland	• 20 - 25 kWh by 2010 • 50 - 100 kWh by 2020
Future potential beyond term year given	• moderate to good
Rule of thumb for conversion ratio* (installed power to electric output)	• 1 kWp --> 5500 kWh

* based on global capacity of around 8 GWp and electricity generation of 44 TWh

3.4 Markets

Electricity generation is the most important form of utilisation of high-temperature geothermal resources (> 150°C). The medium-to-low temperature resources (< 150°C) are suited to many different types of application.

The *low enthalpy* geothermal resource is widely used in Europe.

The *high enthalpy* reservoirs, suitable for electricity production, are present only in few countries: Italy, Turkey, and Greece. Politically included among the European countries, but geographically belonging to other geological entities, are the geothermal systems of Iceland, Russia, France and Portugal (Lund, 2001; Cataldi et al., 1999).

Table 33: Geothermal development in (geographic) Europe to the year 2020. Source: Cataldi

Country	Forecast on installed geothermal power installed in MWp in the year 2010	Forecast on installed geothermal power installed in MWp in the year 2020
France	30	50
Greece	10	30
Iceland	220	300
Italy	930	1000
Portugal	35	70
Russia	130	300
Turkey	70	200
Other	50	90
TOTAL	≈1500	≈2000

The global geothermal electrical market has a very important geo-referentiation, as clearly visible in the figure below. Geothermal power can play a fairly significant role in the energy balance of some areas and of the *developing countries* in particular.

Geothermal power generation is not only present in large scale applications. *Small mobile plants*, conventional or not, can help in meeting the energy requirements of isolated areas. The convenience of the small mobile plants is most evident for areas without ready access to conventional fuels, and for communities that would be too expensive to connect to the national electric grid, despite the presence of high voltage transmission lines in the vicinity. The expense involved in serving these small by-passed communities is prohibitive, since the step-down transformers needed to tap electricity from high voltage lines cost more than US$ 675000 each, installed, and the simplest form of local distribution of electricity, at 11 kV using wooden poles, costs a minimum of US$ 20000 per kilometre (Aumento and Antonelli). By comparison, the capital cost of a binary unit is now of the order of 1600-1700 US$/kW installed, excluding drilling costs. The demand for electric capacity per person at off-grid sites will range from 0.2 kW in less-developed areas to 1.0 kW or higher in developed areas. A 100 kW_e plant could serve 100 to 500 people. A 1000 kW_e plant would serve 1000 to 5000 people (Entingh et al., 1994).

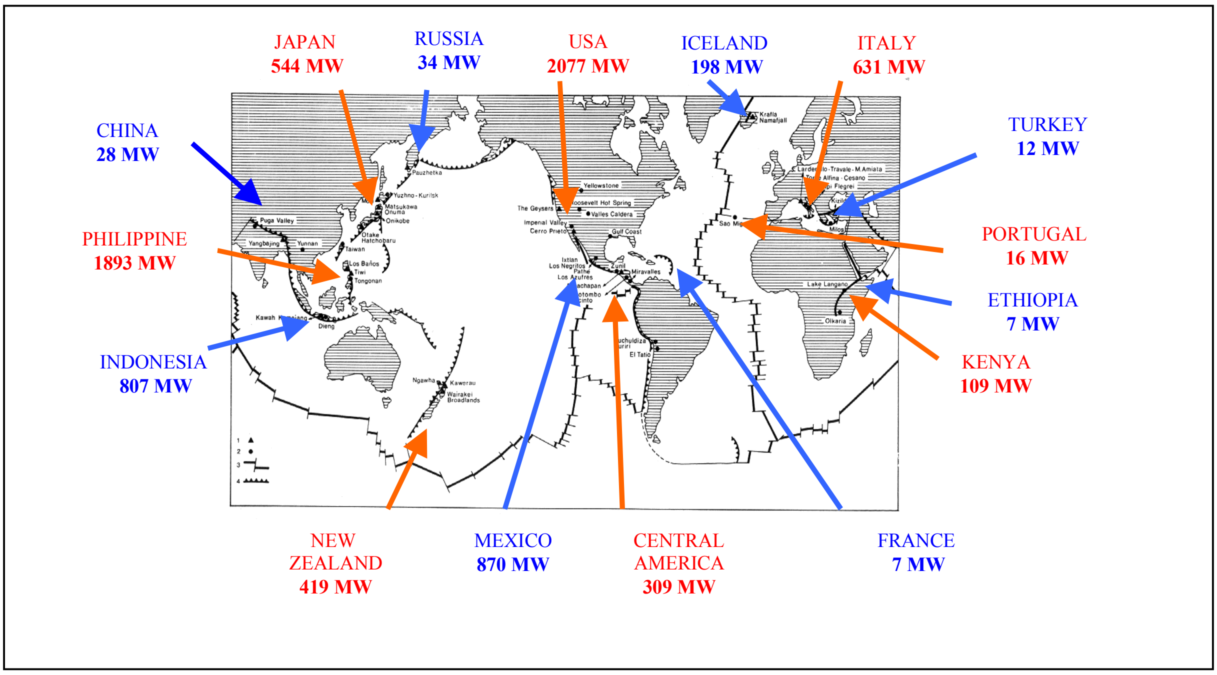


Figure 29 : World localisation of the geo-electricity market. Source: IGA / Bertani

3.5 Needs and measures

The following priorities should be addressed in the future European research and industrial developments (see table below).

Table 34 : Needs and measures for geothermal development. Source: IGA / Bertani, adopted by NET Ltd, St.Ursen, Switzerland

Priority	Needs	Measures
Short term	• Improving exploration techniques, highlighting the importance of geophysical methods, integrated modeling, slim hole drilling for reservoir characterization • Resource assessment: updating the present knowledge of the resource, new harmonized assessment techniques, computational methods and site selection tools; identification of constraints (land use, legislation, market availability) • Improvement of technical reliability and resource predictability • Capital cost reduction, via reducing drilling costs (hard rock drilling, high temperature tools, directional drilling in hostile environment) and combined cycles, with intense heat utilisation associated with electricity production • Cost reduction, specially via increasing lifetime and reliability, as well as reducing maintenance intervals, implying the reduction of Operation and Maintenance costs • Environmental impact mitigation, in order to increase the local acceptance of the populations	• Support in dissemination of information on geothermal energy use at various levels, from decision makers to potential consumers and the public of large • Identification of local markets, favoring the access to the grid connections and removing local restrictions (permitting, land availability) • Harmonisation of import/export rules, both for equipment and cross-border energy transfer • Harmonisation of Codes and Standards • Support and in particular the support within the 6^{th} framework programme of the EC • Adoption of policies, laws and regulations that promote investment in development of their indigenous geothermal resources • Favoring a positive public attitude toward the geothermal energy • Education and training, both for specialists and general public • Performance of assessments of their country's geothermal resource potential for use in electrical power generation, heating and cooling of homes and buildings, food processing, fish farming, refrigeration, and a myriad of other uses
Medium term	• Reservoir development techniques, with special attention on submersible pumps and scaling/corrosion control • New power cycle or optimisation of the existing ones, in order to improve efficiency and reliability, with special focus on small units for low temperature cycles	• A special focus on safety and reliability • Creation of a political and public environment and market conditions favorable for geothermal energy
Long term	• High temperature tracer technology • Hot Dry Rock / Enhanced Geothermal System technology: artificial fracturation, reservoir monitoring, circulation loop	• Support for export of European geothermal technology to other areas of the world • The governments of nations to make strong commitments to developing their indigenous geothermal resources for the benefit of their own people, humanity and the environment • The United Nations, the World Bank, and other institutions must include strong geothermal energy components in their programmes • Promotion and encouragement of expanded international cooperation in geothermal energy research, and in the development and demonstration of new and improved technologies

4 Small hydro power

Figure 30 : Small hydro power plant in Janesie, Slovakia. Source : Inforse-Europe

Figure 31 : Small Hydro canal during winter time in Switzerland. Source **:** Swiss small hydro power programme

Figure 32 : Small hydro scheme, Benatky ned Jizerou, Czech Republic. **Source** : DTI web

4.1 Techno-economic development

Hydro-electric facilities with a capacity of less than about 10 MW (1 MW = 1000 kW) are generally referred to as "small hydro", small hydro facilities with a capacity in the 100kW to 1MW range are referred to as "mini hydro" and small hydro facilities with a capacity under 100kW are finally referred to as "micro hydro". SHP (**S**mall **H**ydro **P**ower) technology is mature and proven [WEC 1996].

Early hydroelectric power plants were much more reliable and efficient than the fossil fuel fired plants of the day. This resulted in a proliferation of small to medium sized hydroelectric generating stations distributed wherever there was an adequate supply of moving water and a need for electricity. Originally, hydroelectric power stations were of a small size and were set up at waterfalls in the vicinity of towns because it was not possible at that time, to transmit electrical energy over great distances. The main reason why there has been large-scale use of hydroelectric power is because it can now be transmitted inexpensively over hundreds of kilometres to where it is required, making hydropower economically viable. Most subsequent hydroelectric development was focused on medium to large projects. The majority of these power plants involved large dams, which flooded vast areas of land to provide water storage and therefore a constant supply of electricity. With the expansion of centralised, fossil fuel generation and networked electricity distribution in many countries during the past century, many sites were abandoned. Even rural areas without mains electricity generally found it cheaper and easier to install diesel generators than to bother with the complications of installing hydroelectric system. The oil crisis of 1973 was a major catalyst in prompting developed and developing countries alike to look to their indigenous resources for electricity generation. The environmental impacts of large hydro projects are being identified as a cause for concern, it is becoming increasingly difficult for developers to build new dams because of opposition from environmentalists and people living on the land to be flooded. Environmental concerns have re-awakened interest in the technology, and many governments both inside and outside the EU are offering incentives to increase small-scale hydro deployment as it is increasingly proving an attractive option for supplying electricity to the regional grid.

The main requirement for hydropower is to create an artificial head of water so that water can be diverted through a pipe into a turbine from where it discharges, usually through a draft tube or diffuser back into the river at a lower level [EUREC]. The principal requirements are [ATLAS]:

- A suitable catchment area
- A hydraulic head
- A means of transporting water from the intake to the turbine (pipe or millrace)
- A turbine house containing the power generator equipment and valve gear needed to regulate the water supply
- A tailrace to return the water to its natural course
- A mechanical or electrical connection to the load to be supplied

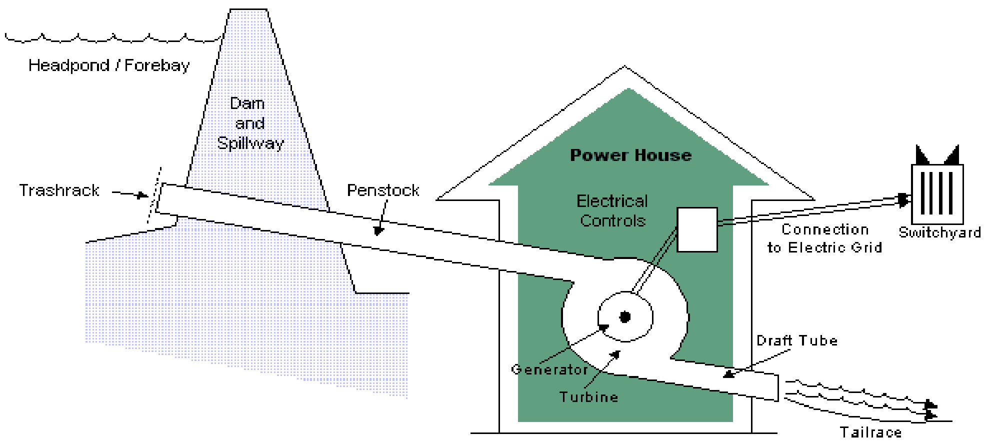


Figure 33: Parts of a small-hydro facility. Source : RETScreen International - Small Hydro Model [RETscreen]

Small hydropower (SHP) can generally be divided into three different categories depending on the type of head (high or low) and on the nature of the plant :

- **High head** power plants are the most common and generally exploit a dam to store water at an increased elevation. These schemes are commonly used in medium and high mountains sites.
- **Low head** hydroelectric plants are power plants, which generally utilize heads of only a few meters or less. Low head schemes are typically built in river valleys.
- **Marginal** hydropower systems are plants, which the hydropower potential is subordinate to other activity as can be irrigation or industrial process or drinking water supply or sewer for wastewater. This means that energy production is not the prime objective of the plant.

Since they first appeared, turbines manufactured in Europe have spread all over the world. Thanks to the inventions and the rapid growth of the energy demand at the end of the nineteenth century, Europe became the world leader in the manufacture and development of water turbines which gradually replaced the steam engines as the most important power source. During the twentieth century, the exploitation of water power was characterised by continuous technical development, in particular turbine efficiencies of some 95 to 96% were achieved. According to Hutton's and Moody's law the larger the turbine, the higher its efficiency; hence good quality designs of several hundreds of kW or greater tend to approach or even exceed 90% optimum efficiency. In contrast, the efficiency of a micro-hydro turbine of 10 kW is in the order of 60% to 80%. Figure below provides a guide to select the most appropriate turbine type.

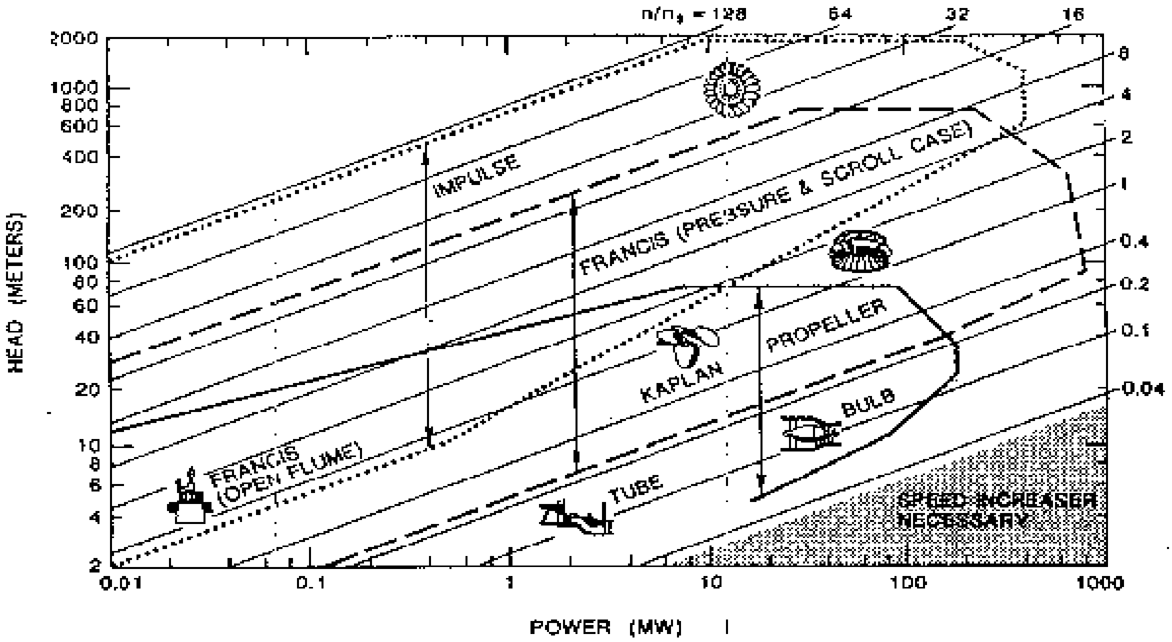


Figure 34 : Small hydro turbine selection chart [Gulliver, 1991]. Source : RETScreen International

To calculate the overall turbine generator efficiency, one must multiply the turbine efficiency by the generator efficiency. Turbine-generator efficiencies for small hydro system are usually ranging between 70% and 85 %. Very performing plants can reach an efficiency close to 90 % [MhyLab]. This implies that only marginal improvements may be anticipated with respect to efficiency. Significant reductions of the energy cost are no longer possible in improving the turbine design. On the other hand, the operation and maintenance (O&M) costs can be reduced in all new projects to their minimum, as the O&M equipment has been simplified by using computer techniques. SHP requires little maintenance over its useful lifetime, which can be well over 50 years. Normally, operation and routine maintenance of a small hydro plant can be handled easily by one part time operator [RETscreen].

4.2 Costs and cost reduction opportunities

Current costs

Investment costs for SHP plants are site-specific, depending on additional country-specific efforts as social barriers and planning issues; therefore the range of investment costs differs largely between and within the countries. REBUS model study [Voogt] and Elgreen model study [Huber] give wide ranges of costs for many European countries. The BlueAge study indicates investment and production SHP costs for 26 European countries.

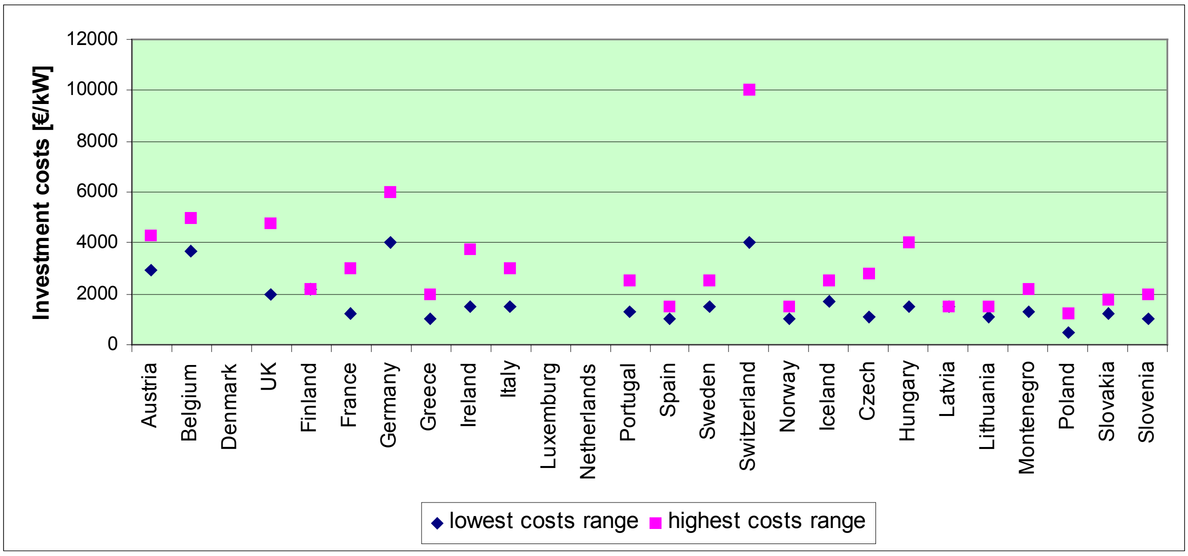


Figure 35 : Maximal and minimal investment costs [€/kW] of new SHP plants in European countries in 1999. Source : adapted from BlueAge [Lorenzoni], through NET Ltd., St. Ursen, Switzerland

Site and country specification of SHP costs are put in evidence in figure xy. From the BlueAge study it results that, in Europe, for what concerns new SHP plants, Switzerland has the highest investment costs (4000-10000 €/kW) and Poland the lowest (500-1200 €/kW).

Most new SHP installations appear to produce rather expensive electricity as the high up-front capital costs are usually written off over only 10 or 20 years (yet such systems commonly last without major replacement costs for 50 years or more). An old hydro site, where the capital investment has been written off, is cheap to run as the only costs relate to occasional maintenance and replacements.

The figure below shows a typical example of power unit costs and electricity costs in Western Europe for three different types of SHP plants. Costs are calculated for quite small SHP plants (which is the average European size): 1 to 2 MW for high and low head and a little less for the marginal SHP plant example.

The power unit cost is about the same for the three types of SHP plants : high head plants have the lowest power unit cost (1200 €/kW) and low head the highest (1260 €/kW). On the contrary, electricity cost is the lowest for low head and marginal SHP plants (respectively 0.068 €/kWh and 0.065 €/kWh compared to 0.085 €/kWh for high head SHP plants). In fact the energy unit costs depend mainly on the annual duration of production which is greatly associated to the available hydrology. Energy unit costs depend also on country electricity market regulation.

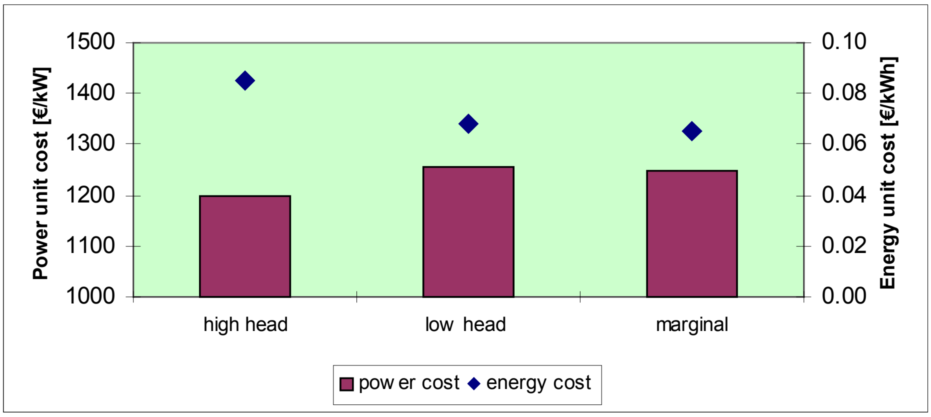


Figure 36: Example of power unit and electricity costs in Western Europe for three types of hydropower plant, with an installed capacity of 1 to 2 MW for high and low head, a little less for marginal SHP plants. Source: adapted from [INPG] and ATLAS study, through NET Ltd., St. Ursen, Switzerland

The geography of the sites (height of the water drop, site accessibility) where the plants are installed determines the technical choices and therefore the total level of investment costs. Among the different elements of the plant, turbines are the most important component. Because they are independent of the site location, the non-installed turbine costs are the only significant standard costs in SHP plants. The figure below shows average costs for SHP turbines issued from the most important European manufacturers. Turbine power costs grow exponentially with the diminishing of the turbine power size (the so-called scale effect, an inverse relationship between size and cost); a 10 kW turbine has a 1500 €/kWe cost, a 100 kW turbine a 600 €/kWe cost and a 1000 kW turbine a 150 €/kWe cost.

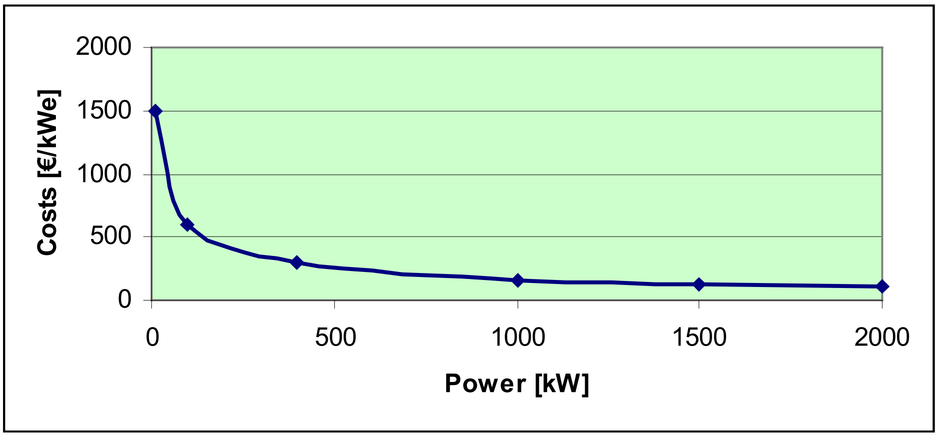


Figure 37 : Average cost (in €) of turbines for SHP plants depending on the power.
Source : adapted from EurObserver, through NET Ltd., St. Ursen, Switzerland

Cost reduction opportunities

The ongoing development research will concentrate on new materials such as composite materials. For small heads the development is concentrated on small units in multiple arrangements, using technique for variable speed and frequency conversion. Depending on various technical developments, cost reduction are primarily related to operational costs such as computerised systems, and this decreases the need for personnel resources. Minor cost reduction can be related to other technical development (such as higher efficiency, variable speed, etc) because new developments usually depend on long manufacturing series in order to give full economic benefit [Lorenzoni].

Since every component or aspect of a SHP plant has different impacts on capital and energy costs depending on the type of the plant (high head, low head and marginal), the potential for cost reduction is different for each SHP plant category (see figure below). Depending on various technical developments, cost reductions are primarily related to operational costs such as computerised systems, and the related decreased need for labour resources. Minor cost reductions can be related to other technical developments such as higher efficiency and variable speed, because new developments usually depend on manufacturing series in order to give full economic benefit.

Development work has to a great extent been aimed at improving the design and construction of SHP in order to reduce the costs of manufacturing of essential parts and to simplify the O&M [Lorenzoni].

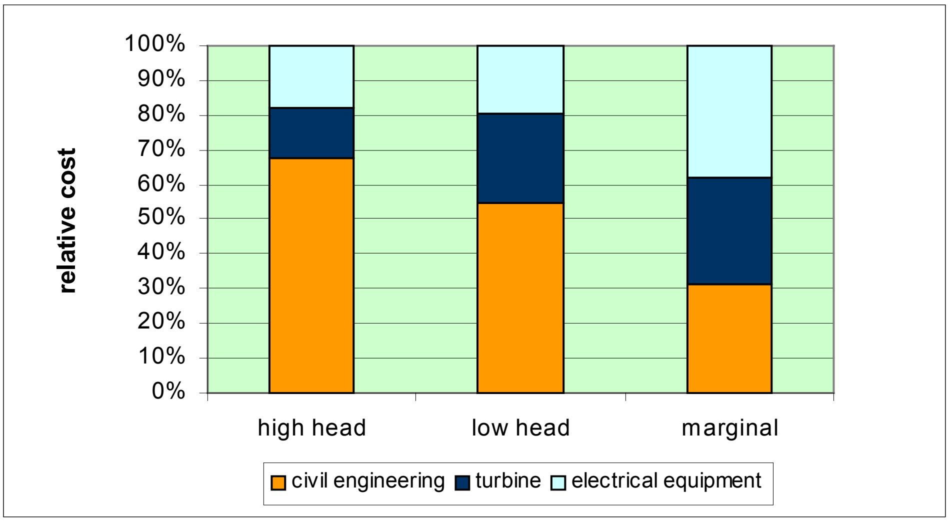


Figure 38 : Relative investment costs for three types of hydropower plant
Source: adapted from [INPG] and ATLAS study, through NET Ltd., St. Ursen, Switzerland

Generator

The present generator efficiency for new plants is close to 100% with common efficiency rates of 98 to 99%, which means that no improvements with respect to the efficiency can be achieved. For this domain, specific developments for small hydro with an effort of standardisation are crucial. The electrical generator represents a relatively low percentage of the total power plant cost; less than 5%. These costs can be easily controlled via standardisation of the equipment.

Turbine

During the twentieth century, turbine efficiency of some 95 to 96% were achieved. This implies that only marginal improvements may be anticipated with respect to efficiency. The efficiency of smaller turbines is lower than that of bigger ones and the efficiency figures have to be reduced due to scale effects. For mid size turbines some 1.5% could be a suitable cost reduction figure and for small turbines 3-4% [Lorenzoni]. For low head and for marginal hydropower plants, the relative importance of the turbine is greater than 25%. Thus for these plants, cost corresponding to efficiency improvement have to be taken into account in the global financial balance. For marginal SHP plants, as for example drinking water supply, turbine pumps working as generating electricity turbines are often a very good solution to diminish the corresponding cost.

Civil engineering

Since the civil engineering aspect represents a great share for low and high head SHP plant costs research for lowering cost of this element would permit to influence directly the cost-effectiveness of these types of plant. Traditional materials and methods are used for the building structures.

O&M

O&M costs can be reduced by using standard industrial components, standardised modular equipments and cubicles, modern monitoring technology via internet, highly automated monitoring devices, analysing the cause of an error and reporting via internet, which will allow to reduce lengthy visits to the plants. Remote control, web cams and microphones are further possibilities for cost-effective ways to monitor SHP plants [Joint ASEAN Mini Hydropower Programme]. It is important to well adapt the machine characteristics to the plant characteristics. If a good hydrologic database is available with the corresponding power load schedule of the plant, a global model based on simulation of all possible components (hydromechanics elements but also electromechanical and electric components) can be built. This global model permits to optimise all elements of the plants and the global performance and cost of the plant. Such kinds of computer aid design software are in development [INPG]. Different operation modes can be tested, such as variable or fixed speed, with different types of potential components, turbines multiplier, generators, transformer and civil engineering. The simulation on a typical hydrologic year allows for determining the best arrangement [INPG].

Expectations and forecasts

Costs are predicted to fall faster in low head and marginal plants. In fact, in these systems the electrical equipment represents a larger portion of the total plant costs compared to high head plants. Since the cost reduction potentials in this area are considerable, the total plant costs have as well a non-negligible capability to reduce costs. In comparison costs of high head plants are forecasted to decrease less, mainly because in such plants the civil engineering costs represent about 70% of the total plant costs (compared to 55% for low head plants and only 30% for marginal plants) and costs in this feature are expected to remain near stable.

The learning curve showed in the figure below consists in the range of generation costs as well as a schematic and differentiated progress ratio for the different SHP technology and cost bands. Typically, more expensive and more recent applications and systems tend to have a greater cost reduction potential thanks to greater learning capacities and potentials. Marginal plants have a greater cost reduction potential than low and high head plants because the contribution of classic components, which offer low cost reduction potential, is not the principal cost. SHP plants with significant electronic components or SHP plants which are computer driven have also a greater cost reduction potential with respect to more classical SHP plants. Typically marginal and low head SHP plants belong to the upper region of the figure xy and high head SHP plants to the lower one. It is however important to notice that these issues cannot be absolutely generalised as SHP plant costs depend on a lot of factors.

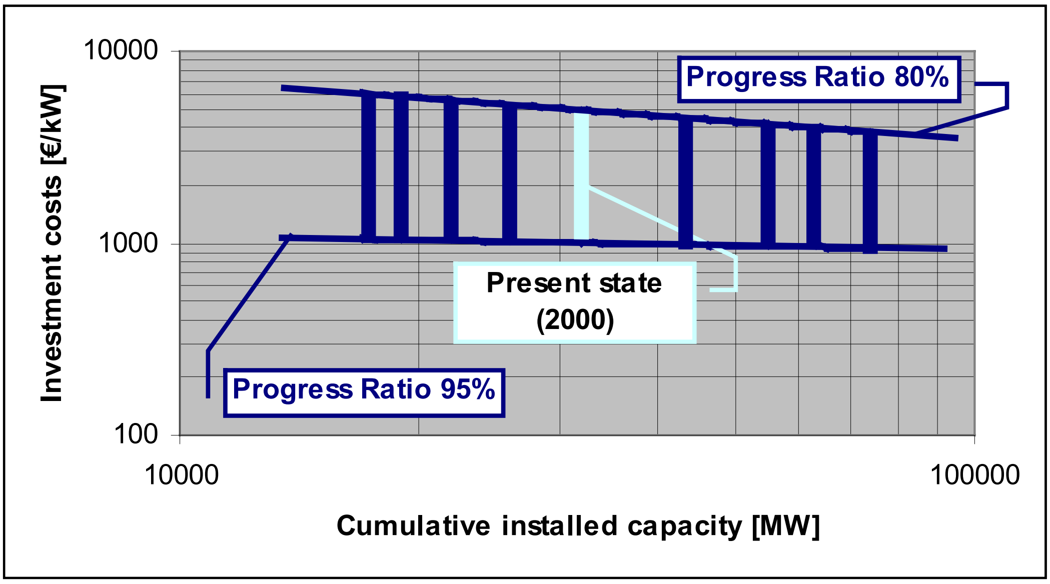


Figure 39: Experience curve for SHP plants in double-logarithmic diagram. Sticks represent the borders in between the investment costs are predicted to evolve by ATLAS study. The lines represent the outermost progress ratios. Source : compilation through NET Ltd., St. Ursen, Switzerland

Table 35 : Estimates of the three main cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale). Each * is the approximate equivalence of 4% - 6% of cost reduction within a decade including expected technological learning and market growth. Source: compilation NET Ltd, St. Ursen, Switzerland

	R&D	Manufacturing volume	Economy of scale
Small hydro	**	*	**

Table 36 : Summary of important cost figures for European countries.
Source: compilation NET Ltd, St. Ursen, Switzerland

Cost figures	
Current investment costs in Europe in €$_{2000}$ per kWp	• low investment costs: 1000 • high investment costs: 5000
Potential investment costs in Europe in €$_{2000}$ per kWp in 2010	• low investment costs: 950 • high investment costs: 4500
Current generation costs in Europe in €cents$_{2000}$ per kWh	• low generation costs: 3 • high generation costs: 15
Future generation costs in Europe in €cents$_{2000}$ per kWh in 2010	• low generation costs: 2 • high generation costs: 10

4.3 Potential

The amount of power that can be produced at a hydroelectric site is a function of the available head and flow. A "rule of thumb" relationship is that power is equal to seven times the product of the flow (Q) and gross head (H) at the site (P = 7QH). Producing one kW of power at a site with 100 m of head will require one tenth the flow of water than a site with 10 m of head would require [RETscreen]. The natural factors which influences the worldwide SHP potential are the quantity of flow and the head. The flow depends of the quantity of water available, which can roughly be related to the annual average precipitation, and the head, which depends basically on the topography. The potential is normally a function of the price of the electricity sold. The higher the price the higher the potential. The economic world hydro potential is around 7300 TWh a year. 32% has been developed, but only 5% (117 TWh) through small-scale sites.

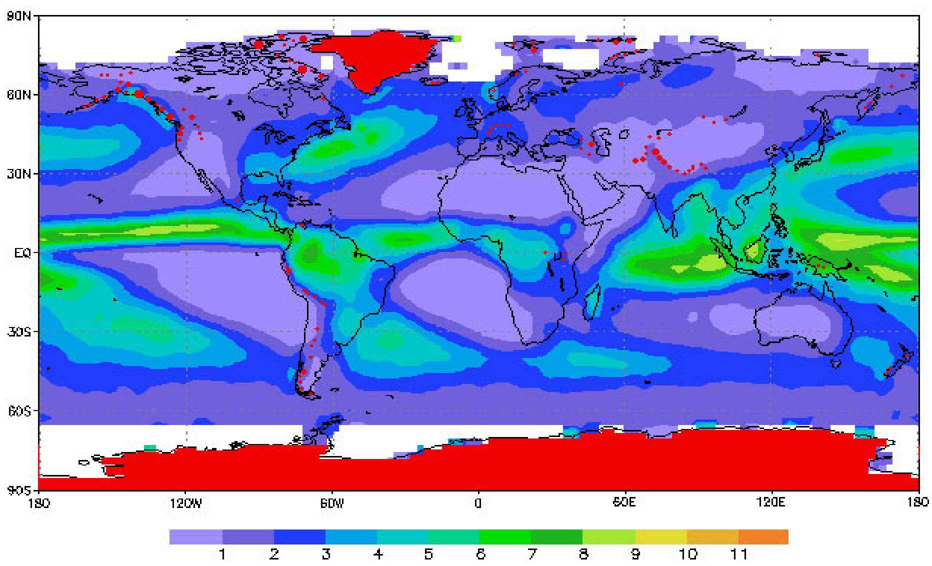


Figure 40: Annual average precipitation (mm/day) 1988-1996. **Source :** adapted from NOAA, through NET Ltd., St. Ursen, Switzerland

Europe, while still representing a major small-scale hydro market, is expected to reduce the building rates of new capacity and to concentrate on refurbishment and upgrading existing stations. In Europe the SHP plants situated in the EU are the oldest; almost 45% are over 60 years old and 68% over 40 years. The eastern European countries have the highest share of young plants, in fact 38% are less than 20 years old [Lorenzoni]. This explains why in the EU the greatest potential is represented on the refurbishments of old plants. There are exceptions to this, such as Spain, which is expected to install 1000 MW of new small hydro capacity by 2010. For comparison, China expects to install at least this amount every year [ATLAS].

In absolute capacity terms, Spain, Norway, Italy, Sweden, Germany, Switzerland, France and Austria are expected to be the main contributors in the mid-long term. These eight countries together account for 87% of the European installed SHP capacity in 2000 [ATLAS, Voogt]. The BlueAGE project in its final report [Lorenzoni] estimated that without any constraints (environmental, legal and economic) and with current technology, the contribution of SHP in Europe could be more than doubled (+ 14250 MW, + 9615 MW in the EU and + 4650 in non-member states). If these constraints, instead, are considered the potential is substantially reduced; under realistic restrictions the potential for new SHP capacity is estimated to be 6700 MW, which is rather less of what was estimated by the EU commission in the White Paper issued in 1997 [Lorenzoni].

It is estimated that less than 10% of the technical SHP potential in the southern developing countries has already been realized. In fact, if no constraints (environmental, legal and economic) are taken into account the SHP potential capacity in these countries is evaluated at around 150-200 GW. In Asia, because of the great contribution of India, Nepal and China, almost 15% of the technical SHP potential capacity (60-80 GW) has been developed, while in South America only 7% of the technical SHP potential capacity (40-50 GW) has been achieved. In the Pacific area and in Africa less than 5% of the technical potential capacity (5-10 GW respectively 40-60 GW) has been realized (see figure below).

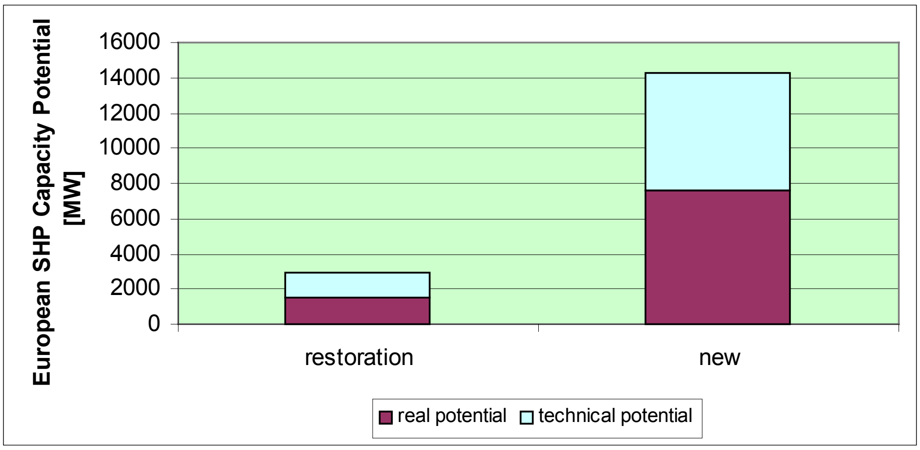


Figure 41: Technical and real European SHP capacity (which takes into account environmental, legal and economic constraints) potential for old sites and for new plants. Source : adapted from BlueAge [Lorenzoni], through NET Ltd., St. Ursen, Switzerland

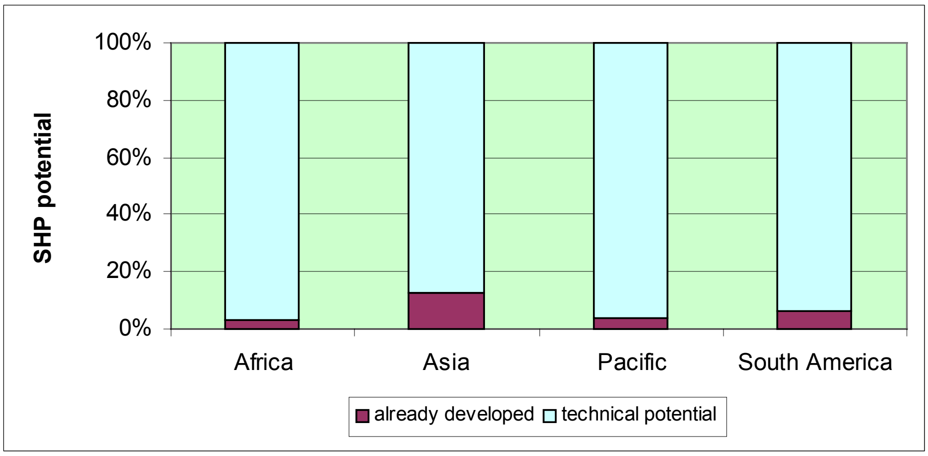


Figure 42: Technical and achieved SHP potential in developing world region. Source **:** adapted from [DOE], through NET Ltd., St. Ursen, Switzerland

The most common economic handicap that most SHP plants have to face is the size effect, an inverse relationship between size and cost. For example as the rated power of a piece of equipment, such as a turbine, decreases, its specific cost increases.

Table 37 : Summary of important potential factors. Source: compilation NET Ltd, St. Ursen, Switzerland

Top potential factors	
Geofactor influencing energy input	• Hydrology and topography
Limit (availability / capacity)	• Site availability
Capacity installed in 1998 in kWh per year and capita in EU15	• 103 kWh
Potential in kWh per year and capita in EU15	• 125 kWh by 2010 • 150 kWh by 2020
Future potential beyond term year given	• medium-high
Rule of thumb for conversion ratio* (installed power to electric output)	• 1 kWp --> 3138 kWh per year

4.4 Markets and market growth

By 2000 the worldwide installed capacity of SHP was 32 GW, mostly in Europe with 12.5 GW, China with 9.3 GW and North America with slightly more than 5 GW [ATLAS].

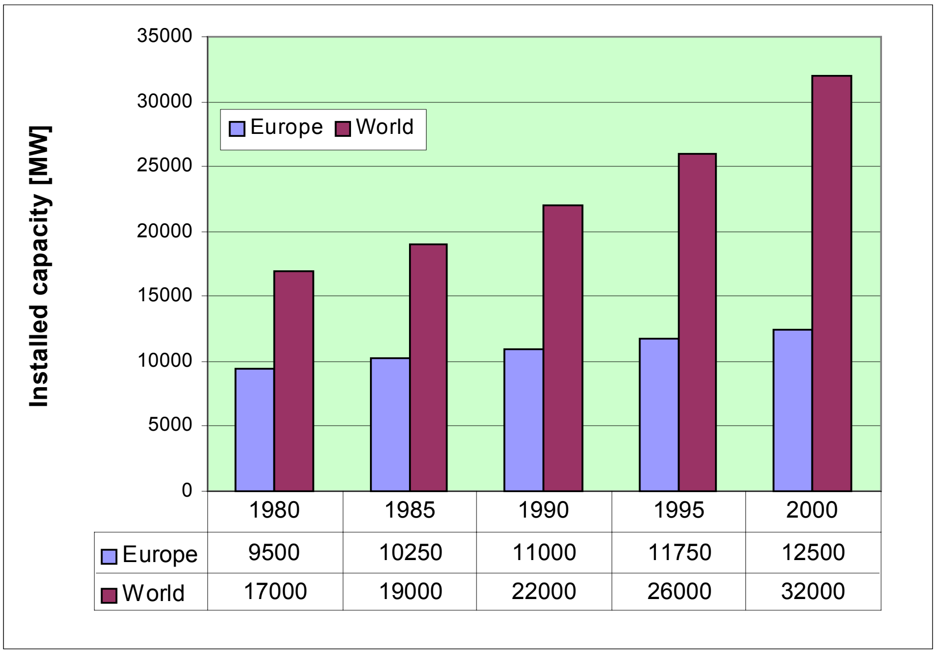


Figure 43: Small hydro power installed capacity in EU and worldwide between 1980 and 2000
Source : adapted from Atals project and WEC , through NET Ltd., St. Ursen, Switzerland

SHP is the foremost electricity-producing new renewable energy in terms of installed capacity and energy yield both in Europe and the World [ATLAS]. In Europe, where more than 17000 SHP plants supply 1.7% of the European electricity, the SHP production represent 9.7% of the total hydro power production [Lorenzoni]. As can be seen in table 38, Alpine and Scandinavian regions are leading the way almost because they own considerable natural potential due to the particular adapted topography.

Table 38 : SHP capacity and production in EU countries in 1999
Source : adapted from BlueAge [Lorenzoni], through NET Ltd., St. Ursen, Switzerland

Country	Production per year [GWh]	Installed capacity [MW]	Conversion ratio kWp --> kWh	Production per year and pro capita [kWh/year*inhab]
Austria	4246	848	5007	525
Sweden	4448	936	4752	503
Luxembourg	154	35	4400	358
Finland	1328	304	4368	258
Italy	8321	2210	3765	146
Spain	5231	1506	3473	133
France	7131	1997	3571	121
EU15	**30859**	**9833**	**3138**	**103**
Germany	6277	1418	4427	77
Portugal	566	247	2291	57
Ireland	112	55	2036	30
Belgium	204	59	3458	20
Greece	146	44	3318	14
Denmark	27	11	2455	5
UK	242	161	1503	4
Netherlands	1	2	500	0

The World Energy Council (WEC) assess that worldwide the installed capacity is estimated to grow with rates between 1% and 7%. Developing countries will experience the greater growth rate while Europe, North America and the Pacific area will grow with less important rates. Starting from the present situation (year 2000), different scenarios for each region can be proposed in according to the growth rate forecast. The largest increase is expected to be in China. Rapid expansion with important growth rates (5%) is also expected in other areas of Asia, Latin America, Middle East, North and Sub-Saharan Africa. Central and Eastern Europe are expected to increase their capacity with a lower growth rate (2%), almost through refurbishment and restoration of old sites. The world market for small hydro technology is worth well over 1000 million of € per year [WEC].

Table 39 : SHP installed capacity and corresponding growth rates worldwide by 2020 for a business as usual case scenario. **Source** : adapted from ATLAS project and WEC, through NET Ltd., St. Ursen, Switzerland

Region	**Installed capacity in MWp**					**Growth Rate**
	Present	**Business as usual**				
	2000	**2005**	**2010**	**2015**	**2020**	
North America	5154	5417	5693	5984	6289	**1%**
Latin America	2607	3327	4247	5420	6917	**5%**
Western Europe	9704	10714	11829	13060	14420	**2%**
Eastern Europe	3082	3403	3757	4148	4580	**2%**
Middle East + North Africa	108	138	176	225	287	**5%**
Sub-Saharan Africa	434	554	707	902	1152	**5%**
Pacific	137	151	167	184	204	**2%**
China	9331	11909	15199	19398	24758	**5%**
Rest of Asia	823	1050	1341	1711	2184	**5%**
Total	**31380**	**36663**	**43116**	**51032**	**60791**	**3.2%**

Europe holds a leading position in the world market of small hydro technology. Four major multinationals, all of which have significant European involvement, dominate the market for larger turbines. The market between 0.5 - 5 MW/site is more open to international trade involving smaller companies. Europe has a multi-disciplinary and highly skilled small hydro industry which offers the full range of products and services required to develop small hydro projects from initial feasibility and design through to construction, financing and operation [ATLAS].

The most recent years were characterized by a weakening of the SHP industry in those countries where the electricity deregulation started early (UK, Ireland, Sweden). On the other hand countries as Germany or Spain with a stable buy-back rate system (feed in) and long sighted systems which gives the investors good economy and stability to motivate them to invest in new plant, refurbish or reinstall into service older plants experienced a small increase in the SHP market [Lorenzoni].

Although EU equipment manufactures still hold a leading position in the world, this position is being threatened since members countries are not very motivated to invest in new SHP and to keep up existing SHP plants. This situation is caused by a decreasing economy for energy producers in the deregulated electricity market and the increasing obstacles created by environmental and legal constraints (the margins for producers are still good in a few countries like Germany and Spain and consequently the markets in these countries are better).

The non EU European market is still promising and offers good prospects for Eu manufacturers but financing the hydro-project is a serious problem as well as differences in business culture. Small companies are finding it difficult to deal with such problems. In the short term the European market will not allow European manufacturers to keep their competence and capacity. A change in the European situation may occur if a directive promoting electricity from RE sources is adopted. The current best market for European SHP manufacturers are related to the market for new equipment, for service, for renovation and modernisation.

Markets for new equipment are located where the demand for electricity is rapidly growing or where a change of electricity production system is necessary due to environmental reason or to fulfil the requirements of the Kyoto Protocol. Such a market in the EU includes countries whose electricity production is currently based on fossil fuel as Germany and Spain.

Outside the EU Eastern Europe, Southeast Asia, South America and some African countries represent the most promising regions. On the other hand market for the EU manufacturers concerning work on existing plants is still in the EU home market, where a considerable number of SHP plants are over 40 years old and thus need refurbishment or modernisation. However currently producers are reluctant to enter this kind of market because of low buy-back rates and uncertainty of future regulation [Lorenzoni].

Green power market

Many sites have the potential for hydropower production; however, development of many of these sites could lead to significant ecological issues. Past hydropower projects have disrupted fish runs, flooded large areas, and converted rapids into placid lakes. Nowadays, it appears that with some forethought and precautions, small-hydro power can be adapted to local environmental concerns and made to comply with new environmental policies. Green markets represent a great opportunity for further deployment of SHP, thus it is important to develop labelling instruments, which will allow SHP to be better accepted by the concerned population.

Refurbishment

Restoration of old sites means the replacement of existing equipment with more efficient one, which in general means also an increase in power production and/or reduced cost of maintenance.

Refurbishment, instead, means a more extensive overhaul of a power plant that can include change of equipment but it is not aimed at increasing power production, only to make it sustainable for a long

time. The restoration of old sites is one of the most promising and cost-effective ways to increase hydro generating capacity in Europe, as many thousands of old sites developed in the early part of the past century have been abandoned and may be readily restored with modern equipment at marginal cost [IEA web]. About 65% of SHP plants located in Western Europe and 50% of those installed in Eastern Europe are more than 40 years old. Proper maintenance and refurbishment of these plants, especially

those in the poorest conditions and with obsolete technologies, could contribute to the development of the SHP potential [Lorenzoni]. In Europe the greatest potential for upgrading old sites is located in the alpine countries (Italy, Switzerland, Austria, France and Germany).

Marginal Hydropower

In many areas, dams are built in rivers for the purpose of flood control, water regulation for navigation, irrigation, or drinking water supply. Potential exists to adapt these sites to multipurpose projects, for example installing a power plant to generate hydropower in conjunction with other purposes as outlined above. The additional costs of civil engineering for the power plant are often minimal and can expand the economic potential of the site. Given the obstacles in developed countries, many initiators, in their attempt to obtain a license to build up new sites, have met the use of supply and irrigation water for power is of interest for future expansions.

Developing countries

In developing countries, the growing demand for energy is often met by thermal power, which has growing consequences for the global environment. In rural areas of these countries, energy demand is often moderate and the need can often be met appropriately by small or micro hydro schemes. The plants are often operated in isolation or are connected to local grids. Small hydro is well adapted to this local demand. In remote areas, the main competitor to small-scale hydropower is presently diesel generation.

4.5 Needs and measures

Small hydroelectric plants are doubtless the most paradoxical RE source of the sector. In spite of a mature and well-established technology resulting from several decades of experience and a non-polluting character, small hydro plants are victims of important of constraints in the industrialized nations. Small hydro is one of the cheapest renewable energy sources available and its impact on the natural environment is minimal if sufficient precautions are taken.

Solutions have to be developed to overcome penalizing issues like size effect, which increases specific cost with regard to the size. R&D support for low cost, low head equipment is required to solve these problems. Further R&D will allow SHP to remain relevant in this changing atmosphere. R&D is needed in technical areas to reduce costs. Although small hydro technology is mature and well-established in the market, there is a case for further R&D work to improve equipment designs, investigate different materials, improve control systems and optimise generation as part of integrated water management systems.

To encourage the wider take-up of small hydro powe there may also be scope for non-technical requirements, which consist of the establishment of an institutional and economic framework. This includes the reduction of administrative delays during approval of small hydro power projects, the simplification of the procedures for gaining permission for water abstraction from rivers and, in order to avoid environmental opposition, the institution of a standard method to determine an acceptable minimum river flow. Financial organisations also need to be made conscious of the technology and its requirements, as well as improving procedures for the sale of electricity to the grids.

for gradually obtaining a more favourable economic and institutional infrastructure r, such as finding methods of finance and arrangements for electricity procurement more compatible with small hydro power and by streamlining and simplifying the procedures for gaining permission for water abstraction

Table 40 : Needs and measures for SHP
Source: adapted from IEA 2000, through NET Ltd., St. Ursen, Switzerland

	Needs and Measures		
	Technological R&D	**Non Technological R&D**	**Environmental aspect**
Near term	• Restoration of old sites • Electronical control and monitoring	• Use of existing civil works • Evaluation of the real environmental impact • Criteria for "green" label • Marketing (dissemination, awareness campaign, information)	• Fish ladders • Noise reduction
Mid term	• Standardisation • New material (plastic, anticorrosion) • Induction generator	• Reduction of administrative delays • Institution of a standard method to determine acceptable minimum river flow	• Powerhouse integration in the landscape • Residual flow • Reservoir management • Power plant design
Long term	• Submersible generators • Variable speed technique • Extra succion technique	• Establishment of a institutional and economic framework	• Fish guidance system • Hydropeaking

5 Solar photovoltaic electricity

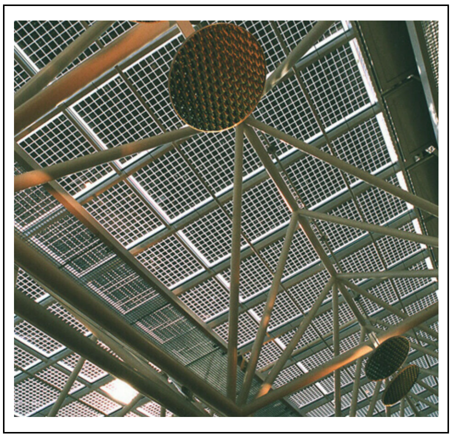


Figure 44 : Semi-transparent roof top PV installation in Zurich, Switzerland. Source: energieburo, Zurich, Switzerland

Figure 45 : Façade integrated PV installation in Berlin-Marzahn, Germany. Source: NET Ltd, St.Ursen Switzerland

Figure 46 : Noise barrier integrated PV installation in Zurich-Oerlikon. Source: TNC, Erlenbach, Switzerland

5.1 Techno-economic development

PV has diversified in technology and application - from space to terrestrial applications. Several technologies are promising and allow for considerable cost reductions. The history of PV shows however that these cost reductions have not become reality as fast as often anticipated. Nevertheless, PV is becoming cheaper and competitive in an ever growing number of applications so that it can exploit more and more of the tremendous potential.

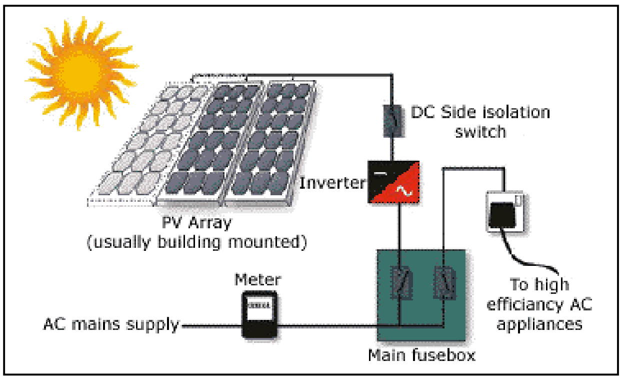


Figure 47 : Illustration of a grid-connected PV system with the components typically required. Source: http://www.pv-uk.org.uk

PV technology and application is characterised by its modularity. PV can be implemented on virtually any scale and size. The overall efficiency of systems available on the market usually varies between 6% and 14% depending mainly on the type of cell technology and type of application. The expected life time of PV systems is between 20 and 30 years. Some components, e.g. inverter or battery have to be replaced more regularly.

Solar cells

Cell efficiency and diversification continued to progress at a more or less steady pace. Generally, experts expect crystalline silicon to stay dominant in the next years and thin-film solar cells to be considerably less expensive in a medium to long-term perspective. Most significant patterns for cost, efficiency, sustainability and applicability are [Bossert]:

- Most thin-film technologies will have lower module costs per Wp than crystalline silicon.
- Crystalline silicon achieves good efficiency on a stabilised level whereas thin-film may achieve similar level in medium term, for certain thin-film technologies efficiency rate and stability is still a problem.
- Possible benefits are higher for thin-film but the technology risks are also higher (typical example are organic cells) than for crystalline silicon
- Energy payback time is lower for thin-film technologies.
- Toxicity of the materials used is most probably not a problem if processing is properly solved, recycling is an issue for any technology.
- Applicability / product diversity is probably higher for thin-film technologies although there is a large number of applications where crystalline silicon will be used for a long time.

Some key findings can be made with reference to the technological development and cost structure for cell and module manufacturing:

- Capital costs are quite high due to great initial investments and high start up costs.
- Semiconductor processing is crucial to achieve lower costs and prices.
- Material costs prevail in total costs when manufacturing costs have considerably decreased.
- Costs for other materials (substrates, encapsulants, pottants, mounts, electrical connections) dominate when semiconductor costs are optimised.
- Other costs for warranty, internal R&D, etc. are reduced when volumes increase and prices decrease.

- Prices / costs differ more per m^2 than per Wp. Cell technologies with high efficiency rates are relatively expensive per area unit. Cell technologies with less high efficiency rates are relatively little expensive per area unit. Thus, costs vary less per Wp for the different cell technologies. This is one basic feature for PV that indicates that different cell technologies can exist side by side as some applications request high efficiency on little area available and other applications need less expensive material on sufficient area available (e.g. façades).

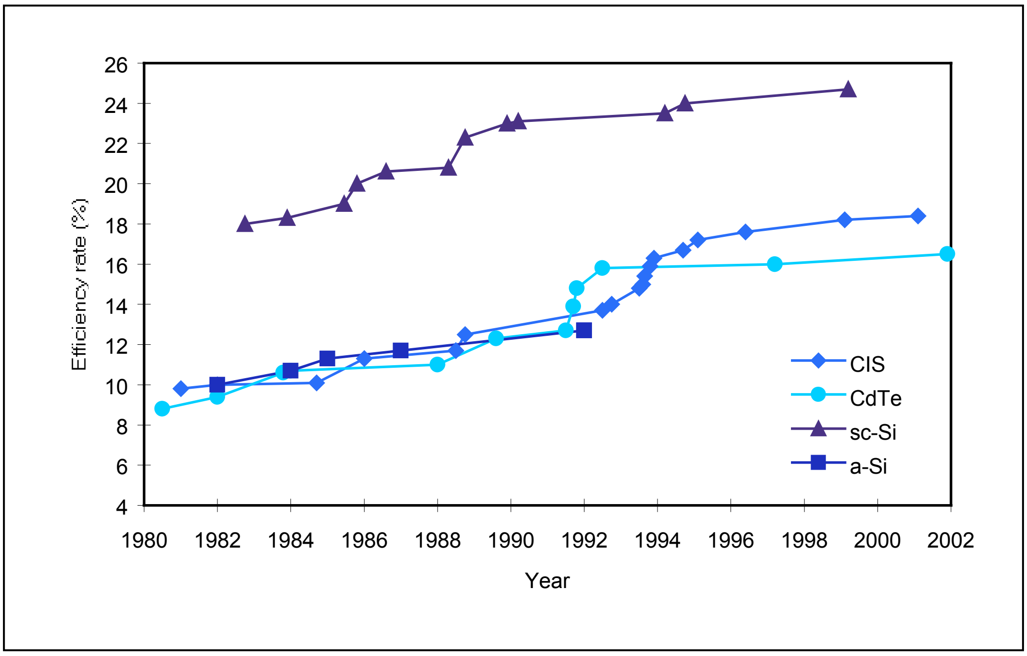


Figure 48 : Cell efficiency evolution since. Source: PV insider's report, PV News, IEA 2001

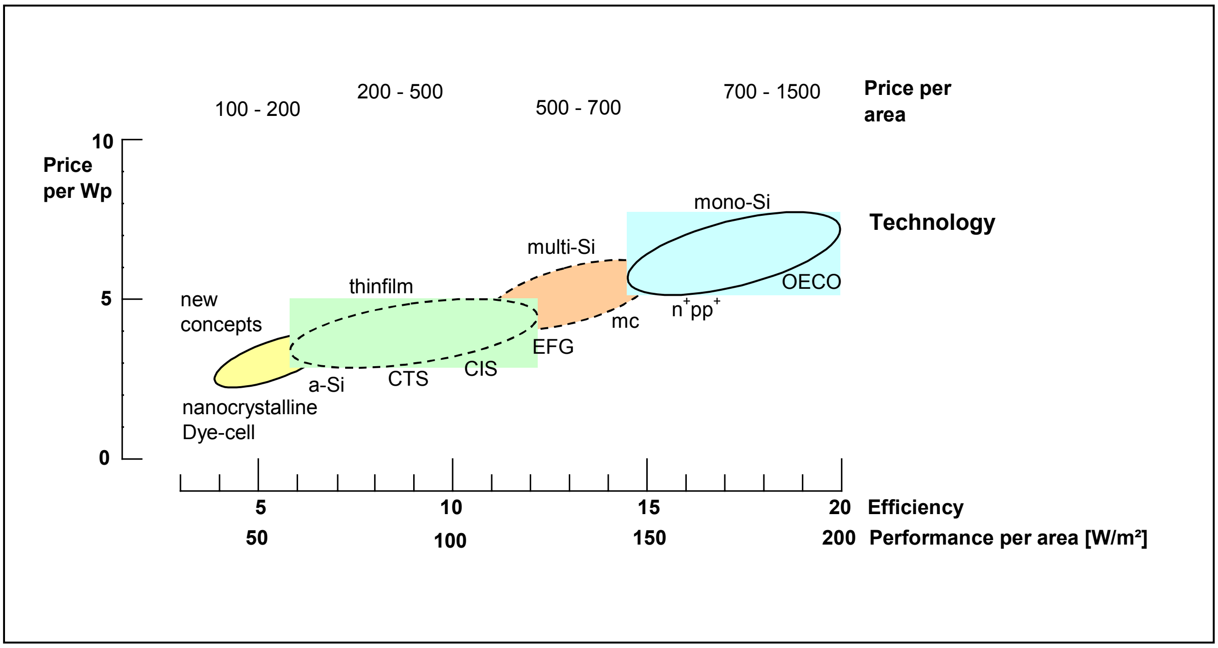
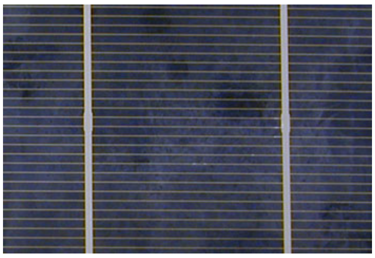


Figure 49 : Area related price (in € / m^2) and power output (in € / Wp) for various technologies. Source: RWE Solar GmbH, Alzenau

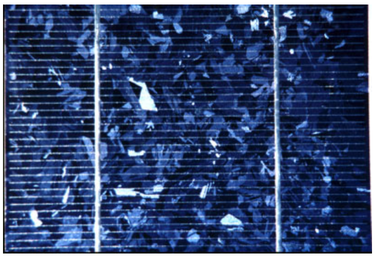
Solar modules

The state of the art and perspectives of different solar modules are given in the table below.

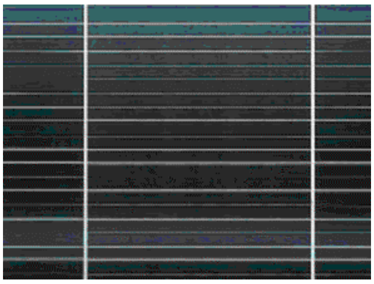
Table 41 : Overview over solar module types. Sources: Photon



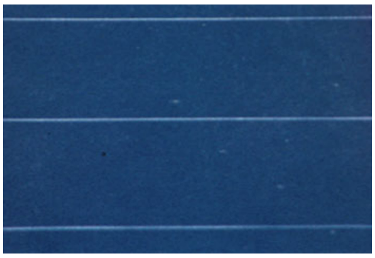
Solar cell type used	**Monocrystalline silicon**
Common module efficiency rate	10 – 15 %
Description	pure monocrystalline silicon
	single and continuous crystal lattice structure with almost no defects or impurities
Advantages	Highest stable efficiency rate
	Long experience
Disadvantages	Long, complicated, energy intensive and costly industrial process
	Crystal sawing
World market share	42%
Direct manufacturing cost in 2000*	$2.45/Wp



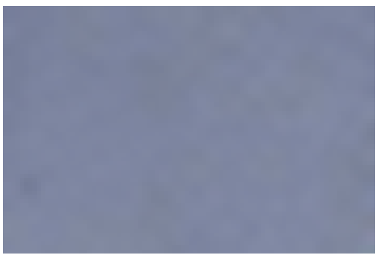
Solar cell type used	**Multicrystalline silicon**
Common module efficiency rate	9 – 13 %
Description	numerous grains of monocrystalline silicon
	molten polycrystalline silicon is cast into ingots
Advantages	Faster and more economic manufacturing process
	Good experience
Disadvantages	Energy intensive, less economic production compared to thin cell technology
	Crystal sawing
World market share	42%
Direct manufacturing cost in 2000*	$2.10/Wp



Solar cell type used	**EFG (Edge-defined Film-fed Growth) silicon**
Common module efficiency rate	10 – 13 %
Description	silicon crystalline growth not in blocks but in thin layers (octagon, sheet or ribbon form)
Advantages	Very fast and economic production process
	No sawing
Disadvantages	Uneven cell surface causing problems with further automatic processing
World market share	3 %
Direct manufacturing cost in 2000*	n.a.



Solar cell type used	**Amorphous silicon**
Common module efficiency rate	4 – 6 %
Description	silicon atoms in a thin homogenous layer rather than crystal structure
Advantages	developed technology and used in consumer applications
	Convey belt production possible.
	Cells can be thinner, much less silicon material used
	Deposits possible both on rigid or flexible substrates
	No crystal sawing
Disadvantages	Lower efficiency rate – especially due to degradation
World market share	12%
Direct manufacturing cost in 2000*	$2.70/Wp



Solar cell type used	**Other solar cell types (e.g. CIS, CdTe)**
Common module efficiency rate	7 – 10 %
Description	other materials such as copper indium diselenide (CIS) or cadmium telluride (CdTe) used
Advantages	Very fast and relatively inexpensive industrial process
	Thin cells
	Better efficiency rates than thin cells based on amorphous silicone
	No crystal sawing
Disadvantages	Partially production process still to be developed
	Partially rare or toxic material used
World market share	1%
Direct manufacturing cost in 2000*	$2.25 - 2.30/Wp

* Assessed for new process on (hypothetical) 10 MWp plant [Arthur D. Little]

Balance-of-system

All **system components** are being improved, hence the reliability of PV systems is corroborated. For instance, the efficiency rate of common inverters in the range of 1.5 - 3.3 kWp used to be between 85.5% to 90% in the years 1988 to 1990, today's efficiency is are clearly above 90% even for smaller units (100-200 Wp) and are often close to 95% for the most common models [Häberlin].

New and improved components help open up new markets. Inverters are nowadays available as serial products for smaller PV installations so that grid connection for BIPV (Building-Integrated Photovoltaics, a term for the design and integration of PV into the building envelope, typically replacing conventional building materials) systems is technically solved.

The Balance Of System (BOS, in a photovoltaic system, the term 'balance of system' refers to all of the system components except the PV modules) may count for about 40% of the grid-connected system costs [KPMG]. Prices of most system components follow the curve of module costs and make the whole system cheaper.

Storage issues of stand-alone systems are also of high technical reliability. Batteries are not really a new product but the charge / discharge behaviour of PV requests adapted battery system components to reach a maximum life time of the battery. A lot of problems encountered were due to dimensioning. Experience and software tools made available, PV stand-alone systems are reliable as any other common stand-alone system (e.g. diesel generator) and often prove to be the best and most economic solution, however storage remains an important issue.

5.2 Costs and cost reduction opportunities

Prices for entire systems [IEA 2001] vary widely and depend on a variety of factors including system size, location, customer type, grid connection and technical specification. Another factor that has been shown to have a significant effect on prices is the presence of a market stimulation measure, which can have dramatic effects on demand (and thus supply) of equipment in the target sector. Less expensive grid-connected systems cost about 5 to 7 € per Wp, stand-alone system costs are (much) higher but are comparatively competitive with other autonomous electricity supply systems.

Future and projected costs vary considerably but show corroborating common aspects. R&D and volume will contribute to realise significant cost reduction opportunities. Technology development will continue in time, e.g. better cell efficiency, improved and new processes and advance in volume, e.g. bigger manufacturing plants. Three major avenues [Zweibel] will result in the biggest cost savings:

- Process and device optimisation (e.g. cell efficiency)
- Minimisation of materials costs (e.g. material utilisation)
- Volume (e.g. up-scaling of purchases and manufacturing)

Cost reduction opportunities for module production can be found in up-scaling, cell efficiency increase, yield loss decrease and improved material utilisation. Values for reduction opportunities (within this decade) are given in % of current costs and are as follows [Arthur D. Little]:

- **Up-scaling** offers high cost reduction opportunities. A tenfold up-scaling from 10 MWp to 100 MWp allows for reducing current costs by a fourth (21% - 27%) thanks to volume purchase, balanced line, larger equipment and higher throughput.

- **Cell efficiency** is expected to augment the absolute rate by around 3% (2% - 4%) within the next decade thanks to better process control, material quality, contacting and layer integration. Higher cell efficiency induces cost reduction in the range from 14% up to 25% of the current costs. Cost reduction opportunities are higher for new thin film solar cells and lower for crystalline silicon technologies.

- **Yield** losses (including broken and out-of-spec product) are reduced. Cost reduction opportunities are rather modest for crystalline silicon (around 5%) and considerable for new thin-film technologies (19%).

- **Material utilisation** can be improved and allows for cost reductions of around 9% for crystalline silicon and around 5% for thin-film technologies.

Transferring the figures for cost reduction opportunities in PV modules shown [Arthur D. Little] to the three avenues, process and device optimisation will reduce costs by about 15% - 25% and more efficient material use will reduce the costs by another 15% - 25%. Mainly R&D is therefore expected to reduce costs by some 30% for crystalline silicon and by some 50% for thin-film technologies in the first decade of this millennium. Increasing mass production on its own will contribute to cost reductions, too. Up-scaling the manufacturing plants by a factor of 5 - 10 can lower the manufacturing costs by some 25%. MUSIC FM [Bruton] stipulates that the manufacturing costs are divided by 4 given the up-scaling by a factor of 25. This inherently and implicitly includes improvements within technology development. As far as simplifications are permitted, it can be stated that an up-scale of the manufacturing plant by a factor of 5 implies a cost reduction of some 20%.

To summarise, the following rough values can be assessed for cost reduction opportunities in the field of R&D, manufacturing volume and economy of scale with a time horizon of 2010:

- some 20% for up-scaling (manufacturing volume) and

- some 30% for R&D related issues and technological improvements in process, device and material use.

This may bring about a total price reduction of some 50% within a decade.

Apparently, economy of scale do exist for installations of some 15% for large scale installations compared to small scale installations. However for the very modular structure of PV systems, it makes the technology not cheaper as such but mainly the purchase price as also the planning and the implementation are lowered. The economy of scale is more or less “absorbed” by the other two cost reduction opportunities identified, i.e. up-scaling with respect to a greater number of identical components and technological improvements in process, device and material use with respect to bigger components. Of course, these cost reducing effects cannot be clearly separated and are subject to definitions. Here for PV, the effectiveness of the economy of scale is more or less restricted to single installations and projects.

Table 42 : Indicative figures on the economy of scale of building-integrated PV systems in Switzerland. Source: Swiss PV subsidy programme running from 1997 -2001 [Wolfer]

Installed capacity size	*Number of projects*	*Total installed capacity*	*Installation costs per kWp in € (1 € = CHF 1.50)*
< 2 kWp	80	105 kWp	10635
2 - 4 kWp	131	401 kWp	9245
4 - 10 kWp	83	508 kWp	8519
10 - 20 kWp	33	424 kWp	8959
20 - 50 kWp	26	774 kWp	8328
> 50 kWp	21	1952 kWp	7927

Table 43 : Estimates of the three main cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale). Each * is the approximate equivalence of 4% - 6% of cost reduction within a decade including expected technological learning and market growth. Source: NET Ltd, St.Ursen, Switzerland

	R&D	**Manufacturing volume**	**Economy of scale**
Solar photovoltaics	*****	****	*

Assuming that the learning curve sticks to the progress ratio of 80% (every doubling of the volume produced brings about a decrease of some 20%) and the market keeps on performing growth rates of 25%, the module production costs could fall below € 2 in 2010 and below € 1 in 2020 with system costs being below € 4 respectively € 2 (see also table and figure below). The annual shipments would be close to 2 GWp in 2010 and the total capacity installed around 14 GWp. Within another decade, both the annual shipments and the total capacity installed would be tenfold at the same growth rate.

The experience curve based analysis shows that there is a huge and fast cost reduction opportunity in relative terms but in absolute terms, PV power remains comparatively expensive in the next two decades.

Table 44 : Experience curve based forecasts of future capacities and costs taking three progress ratios (0.78, 0.80 and 0.82) and three growth rates (20%, 25% and 30%) in the years 2005, 2010 and 2020. Source: NET Ltd, St.Ursen, Switzerland

Year	Growth rate assu-med	Total installed capacity in MWp	Progress ratio 0.82 for modules	Progress ratio 0.80 for modules	Progress ratio 0.78 for modules	Progress ratio 0.82 for systems	Progress ratio 0.80 for systems	Progress ratio 0.78 for systems
2001	real	1730	3.80	3.80	3.80	6.80	6.80	6.80
2005	20%	4249	2.94	2.85	2.75	5.26	5.09	4.93
2005	25%	4548	2.88	2.78	2.69	5.16	4.98	4.81
2005	30%	4875	2.82	2.72	2.62	5.05	4.87	4.69
2010	20%	11489	2.21	2.07	1.93	3.95	3.70	3.45
2010	25%	14341	2.07	**1.92**	1.78	3.71	3.44	3.19
2010	30%	18003	1.94	1.79	1.64	3.48	3.20	2.94
2020	20%	74334	1.29	1.13	0.99	2.32	2.03	1.77
2020	25%	135430	1.09	**0.93**	0.80	1.95	1.67	1.42
2020	30%	247734	0.92	0.77	0.64	1.64	1.38	1.15

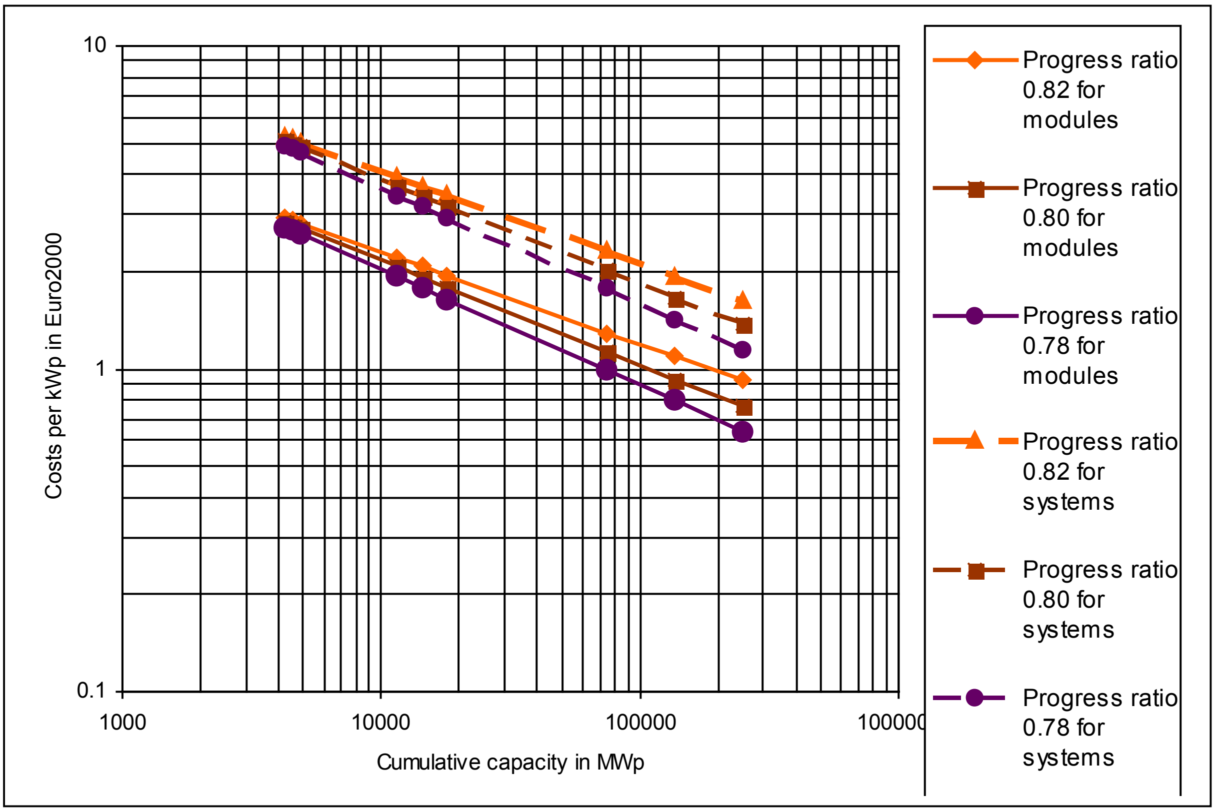


Figure 50 : Experience curve based forecasts of future capacities and costs taking three progress ratios (0.78, 0.80 and 0.82) and three growth rates (20%, 25% and 30%). The graph shows bundles of dots. The first bundle is for the year 2005, second for 2010 and third for 2020. Each first dot reflects the growth rate of 20%, each second dot reflects the growth rate of 25% and each third dot reflects the growth rate of 30%. Source: NET Ltd, St.Ursen, Switzerland

These figures have to be handled carefully. For instance, if the growth rate was down by 5% (thus 20%), the annual shipments and the total capacity installed in 2020 would be just half of the values for a growth rate of 25%. Additionally, if the progress ratio was higher by only 2% (thus 82%, i.e. every doubling of the volume produced brings about a decrease of some 18%), the module and systems costs would decrease much less and are around 15% higher in 2010 and 30% higher than in the scenario “25% growth rate and 80% progress ratio”.

To forecast future costs is a hazardous issue. Nevertheless, a best guess based on the experience curve and the current developments leads to the conclusion that kWh costs the year 2010 could be in the range of 20 - 30 € cents in areas / on surfaces with high irradiation and 35 - 60 € cents in areas / on surfaces with medium and low irradiation in and the costs could be divided by 2 from 2010 to 2020. Some important cost figures are given in the table below.

Table 45: Summary of important cost figures. Source: compilation NET Ltd, St.Ursen, Switzerland

Cost figures	
Current investment costs in €$_{2000}$ per kWp	• low investment costs: 5000 • high investment costs: 7000
Potential investment costs in €$_{2000}$ per kWp in 2010	• low investment costs: 2500 • high investment costs: 4000
Current generation costs in €cents$_{2000}$ per kWh	• low generation costs: 35 • high generation costs: 120
Future generation costs in €cents$_{2000}$ per kWh in 2010	• low generation costs: 20 • high generation costs: 60

5.3 Potential

The potential for photovoltaic applications is tremendous as the solar irradiation is ubiquitious. Available areas and applications are abundant, i.e. the building stock in industrialised countries offers enough suitable surfaces to generate solar electricity equivalent to 15% up to 50% of the current electricity consumption. This is already more than the existing grid can most probably bear. Most renewable electricity sources have opportunities in areas without existing grid connection so it is for PV. PV is supposed to play an important role (Solar Home Systems, micro grids) to provide two billion people with power in the decades to come.

Models seem to have a problem with PV potential and costs. The potential being obviously great and the price being obviously much higher than the bulk power price do not help models - be it a simple or a sophisticated one - make sensible results. As shown in the section about the mid-term potential and costs, results (and the underlying assumptions) vary a lot and are sometimes even contradictory. The fundamental problem is that models hardly differ and assess neither the competitive niche markets including purely economically competitive applications and / or highly differentiated tariff systems nor the (other than economic) value enhanced markets.

Another specificity of PV is that the costs depend very much on the “sky”. Grid-connected PV systems are modular and there is only little economy of scale and technology-related system cost differences. The system price in a mature PV market is more or less the same disregarding the site. However, the electric output strongly depends on the “sky”, that is co-relates to the solar irradiation. The kWh costs are very much related to how much solar irradiation a region receives and how the PV array is oriented.

The electricity costs depend on the globlal irradiation. Roughly speaking, the ratio “solar irradiation - electric output” is proportional (other factors like operation temperature, dirt, reflexivity, share of diffuse light, etc. influence this relationship).

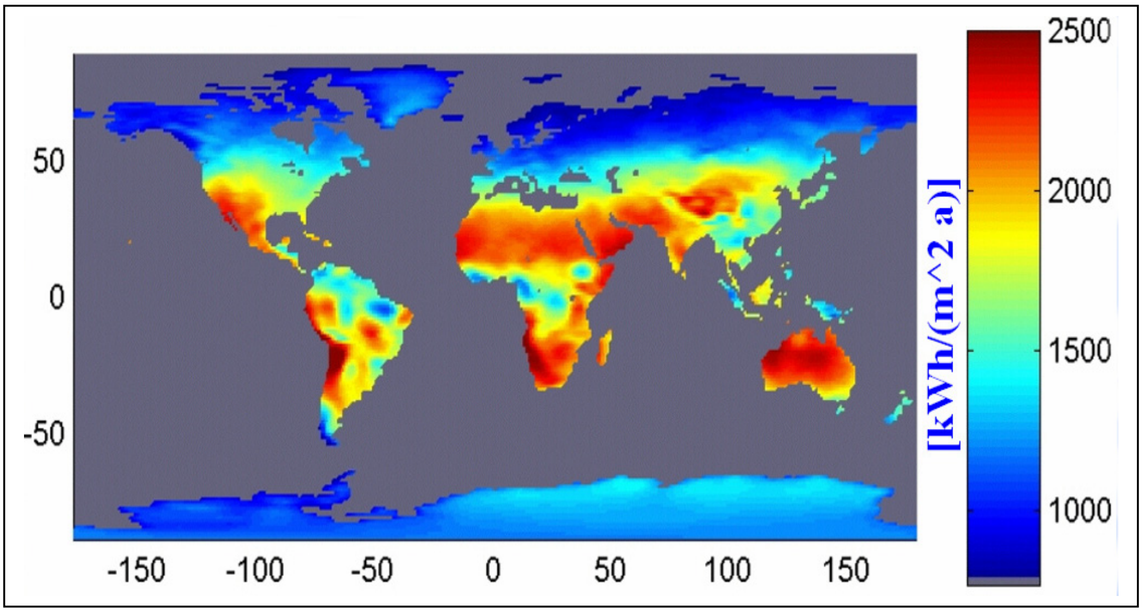


Figure 51 : Global horizontal irradiation (1983-1992). Source: G. Czisch

In Europe, the areas with favourable meteorology-based cost conditions can be easily detected. Portugal, Spain, Greece, Italy and partly France show the lowest kWh costs. Highest costs can be derived for the Northern European countries where the costs are about 30% up to 40% higher than in the South. Costs are a bit lower in central western European countries. The potential can show an inverse picture with Northern Europe on top and Southern Europe at the bottom as - assuming such a potential definition - in some Northern European countries more building area is available per capita compensating this way the lower irradiation per area unit.

Table 46 : Summary of important potential factors. Source: compilation NET Ltd, St.Ursen, Switzerland

Top potential factors	
Geofactor influencing energy input	• global irradiation
Limit (availability / capacity)	• grid (load) capacity
Capacity installed in 1998 in kWh per year and capita in EU15 and Switzerland	• 0 kWh
Potential in kWh per year and capita in EU15 and Switzerland	• 10 kWh by 2010 • 100 kWh by 2020
Future potential beyond term year given	• very high
Rule of thumb for conversion ratio* (installed power to electric output)	• 1 kWp --> 1200 kWh per year

* Assumptions: solar irradiation 1200 kWh / m^2 and year, system efficiency 10%

5.4 Markets and market growth

There are several specific characteristics with PV. One important feature is that PV as a technology is neither globally cost-effective nor globally incompetitive. Some market segments are fully cost-effective and some are not. To quote a few: many stand alone applications offer best value, be it for electricity generation in remote or off-grid areas or be it for solar powered parking metres. Furthermore, grid connected solar power can be bought by virtually any customer willing to pay an extra price for green electricity if solar electricity doesn't encounter any prohibitive transmission constraints.

On the other side, PV is not competitive with bulk base load electricity production. Needs identified and measures suggested shall hence take into account that a part of the PV market is completely competitive and do not need any financial support and that other less competitive applications do need additional support to reach more ambitious goals.

PV is unlikely to be a significant contributor to the energy balance in the short term, unless the price can be brought down quickly. Cost reductions happen and are quite impressive as every doubling of the volume produced brings about a cost decrease of some 20%.

The current market growth is over 30% per annum thanks to the high demand especially in some industrial countries where attractive market incentives support PV applications. This high demand is currently slowing down a bit the cost decrease but doubtlessly will increase the manufacturing volume and subsequently costs are supposed to drop.

As long as the market growth stays sustained like that, the objectives set by the PV industry, NGOs and progressive policy makers can be reached. Most forecasts actually consider a fairly strong growth until 2010 and a lower growth rate after that.

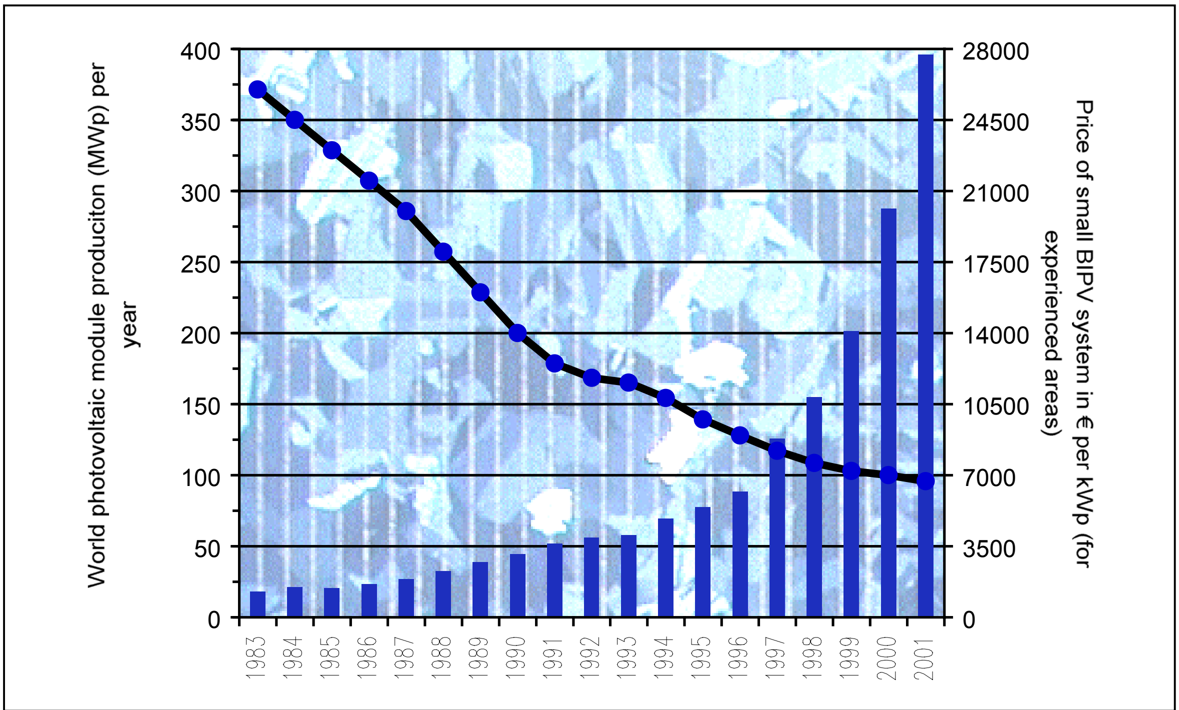


Figure 52 : Annual world PV module production (in columns) and costs (dots on the line) in recent years. Source: compilation NET Ltd, St. Ursen, Switzerland, recent module production data from PV News February 2002

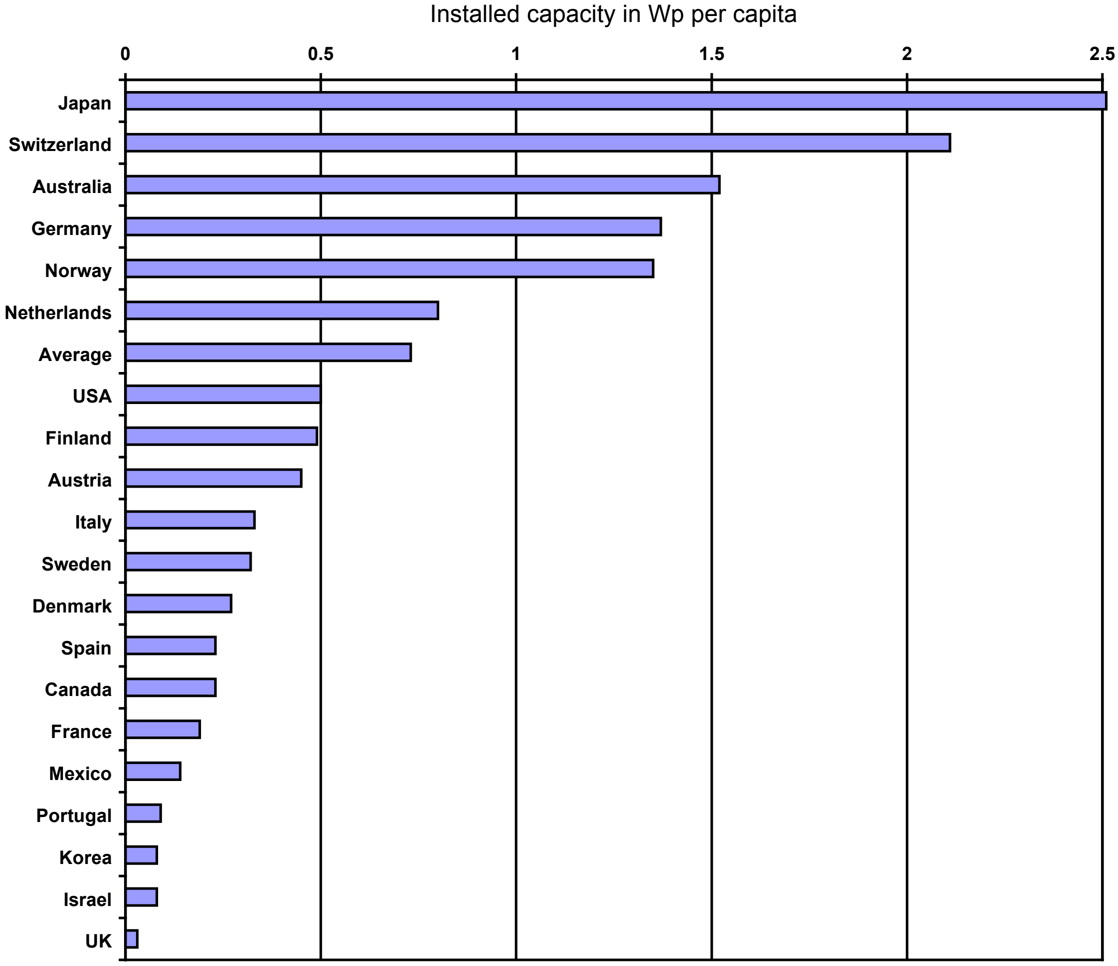


Figure 53 : Installed capacity in Wp per capita in IEA PVPS countries in 2000. Source: IEA2001

Originally derived from the diffusion model [IEA 1996, Sellers] and today's common place is the insight that PV has to go the commercialisation path that is to be market-driven. "Value-enhanced" markets form stepping stones to bulk power formerly viewed as the "pot of gold at the end of the rainbow". Whether the ultimate goal is cheap bulk power or not, doesn't really matter. What's more is to recognise the promising segments and issues. Some of the "promising segments" are outlined below.

Decentralised grid-connected photovoltaic systems (mainly BIPV)

are becoming more important, especially in Europe and Japan. As a matter of fact, the biggest potential application for photovoltaics in Europe and Japan is as embedded generators installed in the built environment and connected to the local electricity network.

Photovoltaic systems are the only RES-E technology which can be integrated into buildings and other infrastructure in various ways, e.g. photovoltaics can simply be mounted on using frames or incorporated into the actual building fabric. For these systems some advantages can be perceived:

- The built environment can be used in a multifunctional way by producing energy.
- Distribution losses are reduced because the system is installed at the point of use.
- No extra land is required for the PV system.
- Costs for mounting systems can be reduced if the system is incorporated in an existing structure.
- Costs are saved because energy storage is not required, hence improving the system efficiency (compared to off-grid systems).

Important programmes support the deployment of BIPV like 100 000 roofs programme and favourable feed-in tariff rates in Germany, 70000 roofs programme in Japan, Tetti fotovoltaici (2500 installations) in Italy and the one million solar roofs initiative in the USA.

Costs of building-integrated systems can be looked at from two points of view. First, BIPV as grid-connected system competes with other electricity production on the base of price per kWh. Second, BIPV as building element competes with other building materials on the base of price per m^2. BIPV building materials can already compete with prestigious costly façade elements like marble.

Generally, BIPV electricity is still relatively expensive. From a progressive point of view [Hoffmann], solar electricity may start to compete with a) utility peak power as early as from 2007 on and b) in areas like Southern Europe where solar irradiation is high. Building-integrated PV is about to make the step to be a construction material turning the building skin multifunctional by adding a solar power station.

Central grid-connected PV systems

Grid connection issues (with the exception of multifunctional building elements) for BIPV are also of value for central solar power stations. Particularly price per kWh is crucial. In areas with high solar irradiation, daily and summer peaks, PV can offer good opportunities not only on the price level but also for improved stability of the grid. This segment will have a vigorous growth when specific target costs are reached and the availability of suitable area is not a problem.

Stand-alone PV systems (mainly industrial)

are becoming more versatile. PV systems can supply energy for a great variety of remote areas as well as modern infrastructure related applications. Besides purely economic advantages, further good reasons can be found for such installations [Bank Sarasin]:

- Provide electricity for (low) power loads in virtually any place
- Reliability and long life time
- Highly mobile and flexible energy supply
- Often most appropriate technology to meet the electricity demand
- Almost emission free operation (no noise, no air pollution)

Stand alone systems can offer good value as:

- Telecommunication and signal
- PV-diesel hybrid
- Stand-alone systems in residential First World and also in
- Hybrid version (e.g. hydro, diesel).

PV can compete in terms of price per Wp. This does not only include electricity but energy services.

Developing countries

Issues for stand-alone systems are also of value for developing countries. PV can considerably contribute in rural electrification, especially in the segments from solar home systems to micro-grids. PV can be implemented in the context of more general programmes for poverty alleviation and agricultural developments by power supply, water pumping, cooling, etc.

Developing countries offer a large potential for PV mainly within the frame of rural electrification. Around 2 billion people are without access to electricity. The World Bank discussion paper No 388 [Taylor] hints at a PV leitmotiv on the way from technology to markets, that is the international and national challenge to foster further technological advancement and scale economies in PV production by fostering increases in PV demand, through development of those applications at or closest to commercial viability as much as possible. Cost reductions achieved through up-scaling and further development allow for market expansion. This way it is going to be a virtuous circle helping to get out of the chicken and egg of market development where buyers are waiting for the prices to fall and the producers are waiting for the demand to increase [KPMG]. The World Bank discussion paper [Taylor] suggests that, in the near term, priority should be given to the development of the more isolated niche markets, combined with step-by-step implementation of a more long-term strategy to acquire, develop and expand advanced PV production technology. Supplying power to isolated users show excellent near term commercial potential [Taylor].

Consumer applications

There is a wide range of solar powered consumer applications from calculators to mobile telephones. PV offers solutions at lowest costs and highest comfort. Generally, any market segment can be expected to experience significant growth in market size in the years and decades to come. Based on BIPV programmes in several countries in the industrialised world, decentralised grid-connected PV systems are supposed to become popular and drive the production of modules and BOS and bring costs down. This makes PV even more interesting in areas where the “hunger for electricity” asks for global sustainable and just solutions.

Liberalisation of electricity markets and greenpower marketing

New market opportunities are opened up thanks to the liberalisation of the electricity markets and greenpower marketing:

Liberalisation of electricity markets will bring highly differentiated tariff structures with it. Within that market structure, there will be places with features that make PV particularly competitive - be it for a generally high irradiation and / or be it for an optimal supply - demand match.

There are not only applications but also different target audience groups. Progressive institutions and private persons as well as public entities can play a leading role by using / producing solar electricity. The positive features that go along with solar electricity make PV a “green”, progressive and prestigious energy technology thus create a higher willingness to pay.

5.5 Needs and measures

RTD needs are manifold and measures have to deal with a diversification of dopants, substrates, thicknesses and ways of cell processing. Attention must be paid to raising cell efficiency, processing etc. in order to lower the total product costs. Some priority can be given to thin film technologies, both to basic research and to production processes and plants in order to reduce costs - without neglecting other technologies and aspects.

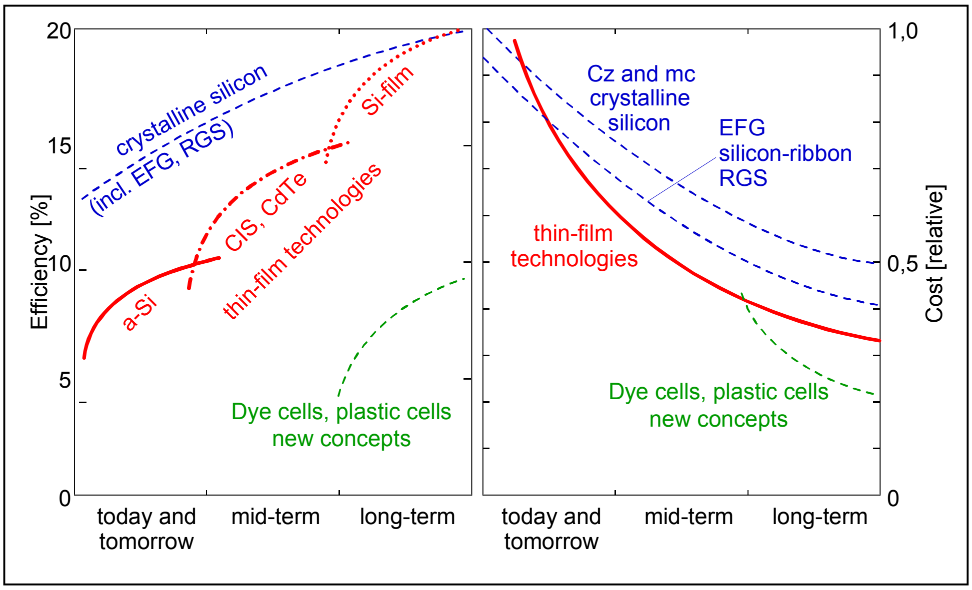


Figure 54 : Technology road map. Source: RWE Solar GmbH, Alzenau

Specifically, there is a clear need to identify market relevant products and measures should support to develop such products. Needs and measures are not only of technical nature but a wide range of non-technical issues, e.g. environmental aspects, marketing and finance, have to be addressed.

In general, the different measures to be taken shall be intelligently combined and steadily continued. An overview of measures in order to meet the needs are given for technology, environmental issues and marketing & finance in the table below.

Table 47 : Overview over measures in R&D for technology, environmental aspects and marketing & finance. Source: NET Ltd, St. Ursen, Switzerland

Measures and activities relating to	Technology	Environmental aspects	Marketing & finance
	• Product design (mainly BOS) • System engineering and design • Grid interconnection and islanding • Operational experience • Performance indicators • Quality assurance and safety • Pre-standardisation (pre-packaging, Do-It-Yourself, etc.) • Manufacturing improvements • Raw material supply	• Energy payback • Emissions • Materials issues • Production • Environmental indicators • Labelling of products	• Market indicators (size, growth, cost, industry, production capacity, etc.) • Potential • Financing • Value • Legislation • Information • Education
short –term (< 5yr.)	• Autonomous systems • BIPV	• Solar cells and modules • Support structures • Storage equipment	• Product-market combinations • Market analysis • Added value • Business models
medium-term (5 yr. < x < 10 yr.)	• Hybrid systems • Distributed generation • Grid-support • Network modelling	• Energy and material fluxes • Dynamic modelling • Recycling	• Market modelling • Economic modelling and impact
long-term (> 10 yr.)	• Large-scale (hybrid) systems • Storage issues • Grid interaction in distributed generation	• Disposal • Urban environment • Biosphere	• PV contribution to the energy supply system • Impact of distributed generation

6 Solar thermal electricity / Concentrating solar power

Figure 55 : SEGS plant in Mojave Desert, California. Source : EREN DOE

Figure 56 : 8.5m SBP Dish Distal II system at PSA. Source **:** EREN DOE

Figure 57 : Solar Two in Mojave Desert, California. Source : EREN DOE

6.1 Techno-economic development

At present **C**oncentrating **S**olar **P**ower (CSP) technology (which earlier was called Solar Thermal Electricity) is exploited through three different systems: parabolic trough, dish/engine system and power tower. All the CSP technologies rely on four basic key elements : concentrator, receiver, transport-storage and power conversion. The concentrator captures and concentrates solar direct radiation which is then delivered to the receiver. The receiver absorbs the concentrated sunlight, transferring its heat energy to the power-conversion system; in some CSP plants, a portion of the thermal energy is stored for later use.

The first parabolic system, which is commonly identified as “solar farm” uses mirrored troughs to collect sunlight, while the second parabolic system, generally known as dish system, collects sunlight through a dish-shaped solar collector. The third system, identified as power tower employs heliostats to reflect and concentrate sunlight onto a central tower-mounted receiver.

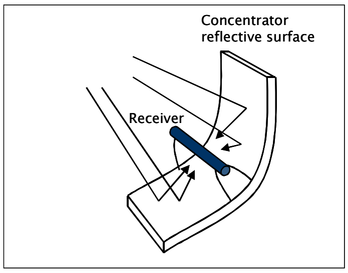


Figure 58 : Trough system

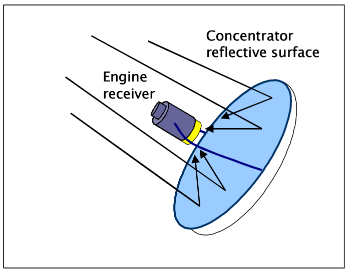


Figure 59 : Dish/engine system

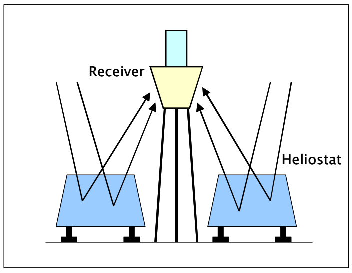


Figure 60 : Power Tower system

Source : all figures adapted from SunLab 1997 through NET Ltd., St. Ursen, Switzerland

Parabolic trough plants are the most mature CSP technology available today and the technology is most likely to be used for near term deployments. Power towers, with low cost and efficient thermal storage, promise to offer dispatchable, high annual capacity factor, solar-only plants in the mid-long term. The modularity of dish systems will allow them to be used in smaller high-value applications. Power towers and parabolic dishes offer the opportunity to achieve higher solar-to-electric efficiencies and lower costs than parabolic trough plants, but uncertainty remains as to whether these technologies can achieve the necessary capital cost reductions and available improvements. Parabolic dish systems are the most efficient of all solar technologies, with currently about 25% solar to electricity efficiency. The 4-95 Stirling PCU holds the world's efficiency record for converting solar energy into grid-quality electricity with 30% at 1000 watts per square meter [Western’s Energy Services].

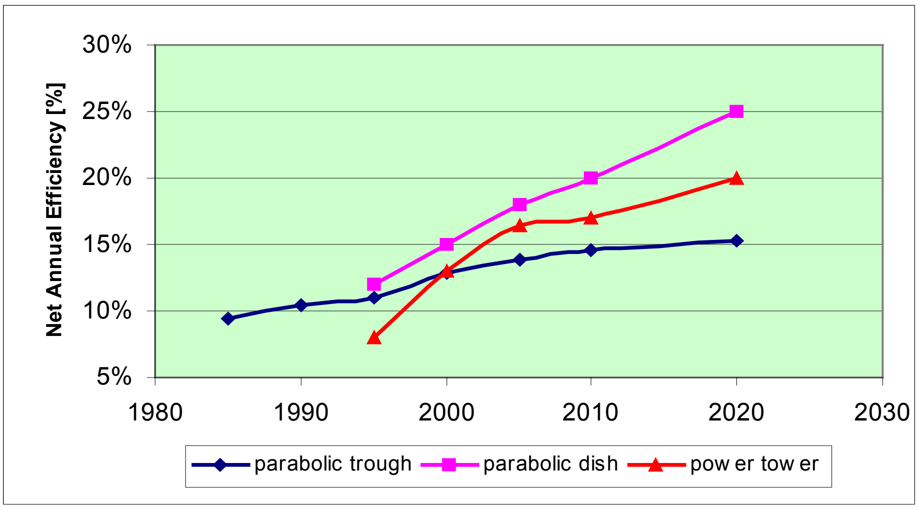


Figure 61 : Past, present and predicted net annual efficiency rates for different CSP technology
Source: Adapted from GEF through NET Ltd., St. Ursen, Switzerland

Hybridisation

Because of their thermal nature, each of the CSP system technologies can be "hybridised", or operated with conventional fossil fuels as well as solar energy. Hybridisation has the potential to dramatically augment the value of CSP technology by increasing its availability and dispatchability, decreasing its cost by making more effective use of power generation equipment and reducing technological risk by allowing conventional fuel use when needed [SolarPaces]. The decision on type of hybridisation has been primarily an economic decision. However it is clear from the SEGS (Solar Electric Generating Systems, SEGS is the generic term relating to parabolic trough employing a Rankine cycle with approximately 75% solar and 25% fossil fuel input) experience that hybridisation of the plants has been essential on the operational success of the project.

Thermal storage

In the same way as hybridisation, thermal storage does improve the dispatchability and marketability of solar thermal power plants, allowing them to produce electricity on demand, independent of solar collection. Storage not only allows high value dispatch of power, but decreases costs by permitting use of smaller turbines.

The most advanced thermal storage techniques have being applied to power tower technology. The lessons learnt from Solar Two are being applied to the first commercial molten-salt power, Solar Tres (SIII) for deployment in Spain. Design innovations influence all SIII system elements and result in two insulated tanks (hot and cold) storing 6250 tonnes of molten nitrate salt with capacity for 24 hours a day of full electrical energy production (with 16 hours of storage). The thermal storage raises annual plant capacity factor from 20%-22% for SII to over 60% for SIII [PSA].

Up to now there is no thermal storage option for current trough technology, SEGS plants meet dispatchability needs with natural gas fired boilers. A molten salt similar to the one used in Solar Two, but for lower temperatures, also deserves evaluation. In such a system heat is collected by the synthetic oil (pumped through the collector field) and then transferred to the salt via an oil-to-salt heat exchanger.

Dish system technology does not include any thermal storage capacity, however other options as battery storage are possible even if very expensive. Dish system indeed is ideal for grid connection electricity supply.

Table 48 : Thermal storage characteristics for each CSP plant
Source**:** Adapted from Sunlab through NET Ltd., St. Ursen, Switzerland

	Installed cost of energy storage for a 200 MW plant	Lifetime of storage system	Round-trip storage efficiency
	($/kWh$_t$)	(Years)	(%)
Parabolic Trough Synthetic-Oil	200	30	95
Parabolic Dish Battery Storage Grid Connected	500 to 800	5 to 10	76
Power Tower Molten Salt	30	30	99

6.2 Costs and cost reduction opportunities

The costs of electricity from CSP system depend on a multitude of factors. These factors include capital and O&M cost, system performance and, of course, the location. However, it is important to note that the technology cost and the eventual cost of electricity generated will be significantly influenced by factors external to the technology itself as the economy of scale. In order to reduce the technology costs to compete with current fossil fuel technologies, it will be necessary to scale-up projects to larger plant sizes and to develop solar power parks where multiple projects are built at the same site in a time phased succession [GEF].

The scale-up of the recently demonstrated power tower technologies are advances that should allow the continued drop of solar electricity costs into competitive ranges. Power costs from initial advanced technology plants will be higher than today's plants because they will be smaller and less mature than today's SEGS technology. However, as the advanced technology is scaled up and matures, electricity costs should be significantly lower than today's plants [SolarPACES].

There is a big potential for cost reduction in the development of advanced trough technology. The ISCCS (Integrated Solar Combined Cycle System) is a new design concept that integrates a parabolic trough plant with a gas turbine combined cycle. The ISCCS, which has generated much interest because it offers an innovative way to reduce costs and improves the overall solar to electricity efficiency, has the potential to reduce solar power costs by 22% [NREL]. The DISS (Direct Solar generation in parabolic trough collectors) is a programme to develop a new generation of CSP plants with parabolic trough collectors and direct steam generation at the solar field, which will eliminate the use of oil as heat carrier and thus the need of a heat exchanger. The implementation of all the improvements pursued in the DISS projects could achieve a 26% reduction (15% increase in performance and 15% investment cost reduction) in the cost of electricity generated with this type of solar thermal power [SunLab].

The dish/engine technology will be improved by volumetric receivers, which exploit a characteristic of solar energy by avoiding the inherent heat transfer problems associated with conduction of high-temperature heat through a pressure vessel. Volumetric receivers avoid this by transmitting solar flux through a fused silica quartz window as light and can potentially work at significant higher temperatures, with vastly extended heat transfer areas, and reduced engine dead volumes, while utilizing a small fraction of the expensive high temperature alloys required in current Stirling engine. Scooping studies suggest that the annual solar-to-electric conversion in excess of 30% could be practically achieved with potentially lower cost "volumetric Stirling" designs. Similar performance enhancements can also be obtained by the use of high temperature ceramic components [Heller]. Others improvement for the dish /engine technology are foreseen with the Biodish project, which has the goal to develop a hybrid receiver for dish/Stirling systems that allows the use of solar energy as well as biogas as a renewable energy source. This enables the supply of electricity not only during sunshine hours but also during cloudy periods and nights. Since the gas burner is also suited for the use of natural gas, the system will have the full flexibility to be adapted to the requirements at different remote areas. The receiver is built from SiC ceramic and designed to transfer the heat from solar (mirror oriented site) and from the gas burner (at the opposite site) into the engines helium cycle. The burner control is designed to also work on part load to stabilize the electricity output [PSA].

Power Tower technology will concentrate its effort on the scaling up of the nitrate salt and TSA/Phoebus systems. 100 – 200 MWe is the target size. In addition to these two systems, a 20 MW Solgas plant, using a combined cycle plant with a solar power tower back up for generation of saturated steam, is planned for Southern Spain. Israel is developing high temperature, high pressure, windowed receivers for solar-driven gas turbine plants, and is conducting a feasibility study of a power tower to supply energy to chemical industry [GEF].

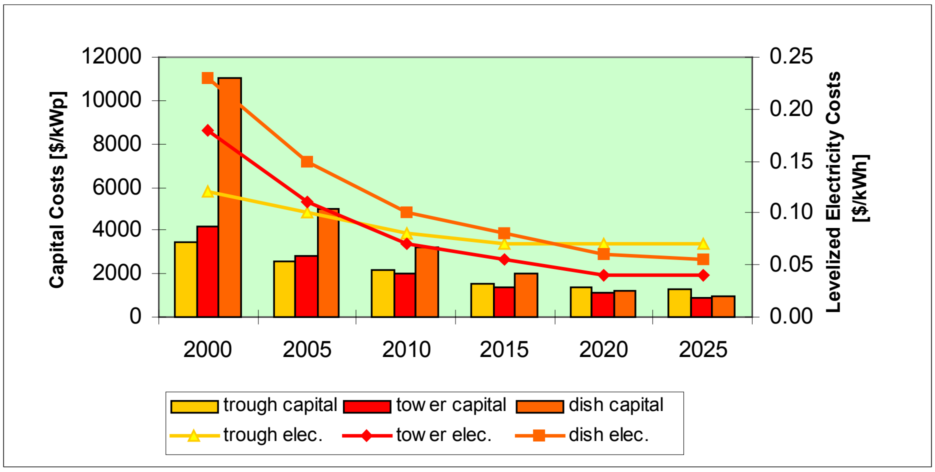


Figure 62: CSP capital and electricity generation costs
Source: Adapted from SolarPACES and SunLab, through NET Ltd., St. Ursen, Switzerland

Table 49 : Planned and predicted levelized electricity cost, system capital cost, O&M cost and surface cost for each CSP technology by 2005, 2010 and 2020. Source: adapted from SolarPACES, GEF and Sunlab, through NET Ltd., St. Ursen, Switzerland

	Parabolic trough			Dish system			Power tower		
	2005	**2010**	**2020**	**2005**	**2010**	**2020**	**2005**	**2010**	**2020**
$/kWh	0.10	0.08	0.07	0.15	0.10	0.055	0.11	0.07	0.04
$/Wp	2.6	2.2	1.4	5.0	3.2	1.2	2.8	2.1	1.1
O&M [¢/kWh]	1.0	0.5	0.4	4.0	1.5	0.9	1.2	0.4	0.3
$/m2	630	315	275	3000	1500	320	475	265	200

Because CSP employs conventional technology and materials (glass, concrete, steel and standard utility scale turbines), production capacity can be rapidly scaled up to several hundred megawatts/year, using existing industrial infrastructure. To ensure the success of initial new plants and thus enable large-scale construction of additional plants, the industry requires continuing access to the research base on which these plants will be designed and future costs reduced [SolarPACES].

In centralised large scale solar thermal power plants one of the easiest ways to reduce the cost of solar electricity from CSP technology is increasing the plant size. Studies have shown that doubling the size of a trough solar field reduces the capital cost by approximately 12%-14% [Morse]. Cost reduction typically comes from three areas. First the increased manufacturing volume for larger plants drives the costs per square meter down. Second a power plant that is twice the size will not cost twice as much as to build one. Third the O&M costs for larger plants will typically be less on a per kilowatt basis [Frier]. Power plant maintenance costs will be reduced with larger plants but solar field maintenance costs will scale more with solar field size [World Bank]. The O&M costs for the 30 MW complex of SEGS III to VII are currently running between 3 and 3.5 $ cents per kWh [SunLab]. SunLab estimates that O&M costs for a new design of a 30 MW plant would be a third lower at 1.9 cents/kWh and O&M costs for one 200 MW plant would be somewhat higher than 1 cent per kWh [SolarPACES].

Mass production represents a big potential for cost reduction, SunLab estimates that it could bring cost down between 15% and 30% of the actual state. On the other hand, technology development is estimated to be less important with a 10% cost reduction potential.

As for parabolic trough, further improvement of power tower performance will be reached through scaling up the size of the plants. The improved economy of scale will significantly reduce the cost of the heliostats on a $/m^2 basis. More improvements will be achieved due to developments in receiver efficiency and through improvements in heliostats manufacturing techniques. Finally developments in the thermal storage technology with the perfection of organic heat transfer fluid, as for parabolic trough, will contribute to improving the solar to electric efficiency [GEF].

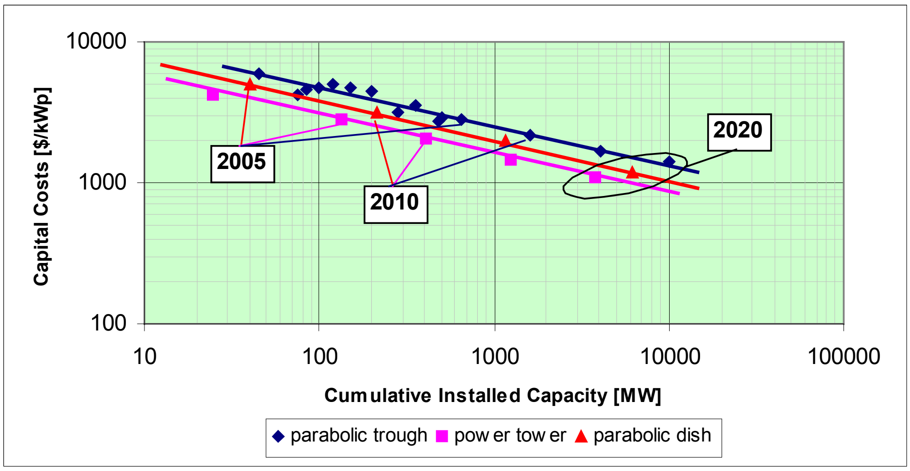


Figure 63: Past and predicted experience curves for CSP technologies. Source : compilation NET Ltd., St. Ursen, Switzerland

Table 50 : Summary of important cost figures. Source: compilation NET Ltd, St. Ursen, Switzerland

Cost figures	
Current investment costs in €$_{2000}$ per kWp	• low investment costs: 3000 • high investment costs: 6000
Potential investment costs in €$_{2000}$ per kWp in 2010	• low investment costs: 2000 • high investment costs: 3500
Current generation costs in €cents$_{2000}$ per kWh	• low generation costs: 12 • high generation costs: 20
Future generation costs in €cents$_{2000}$ per kWh in 2010	• low generation costs: 7 • high generation costs: 12

Table 51 : Estimates of the three main cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale). Each * is the approximate equivalence of 4% - 6% of cost reduction within a decade including expected technological learning and market growth. Source: NET Ltd, St. Ursen, Switzerland

CSP technology	**R&D**	**Manufacturing volume**	**Economy of scale**
Parabolic trough	**	***	****
Dish/engine system	***	****	**
Power tower	**	***	****

6.3 Potential

CSP can only focus on the direct solar radiation and cannot concentrate diffuse sky radiation. As a result, solar thermal power plants will only perform well in very sunny locations, specifically in arid and semi-arid regions of the world [SolarPACES]. CSP technology can deliver acceptable productions regarding costs typically when radiation levels exceed 1700 kWh/m^2-yr. Appropriate regions include the southern European countries, North and Southern Africa, the Middle East, western India, western Australia, the Andean Plateau, north-eastern Brazil, northern Mexico and the Southwest United States [EUREC]. Although the tropics have high solar radiation, the high diffuse solar radiation and long rainy seasons make these regions less desirable for CSP technology [SolarPACES].

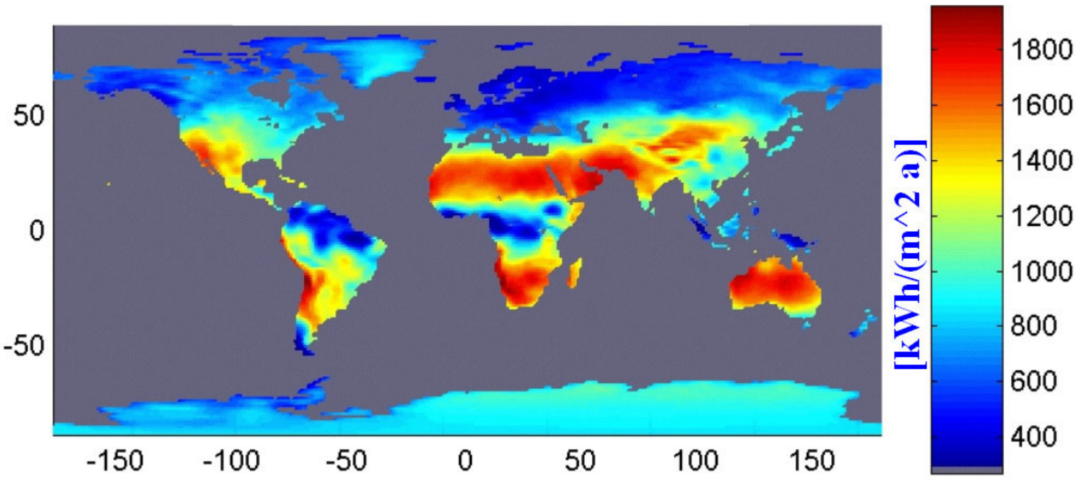


Figure 64 : World direct horizontal radiation [kWh/m^2-yr] 1983-1992
Source: ECMWF, NCEP, G. Czisch, Iset/IPP, 2000

There is a huge as yet untapped market for supplying power to the 40% of the world population that does not yet have a reliable supply of electricity. Most of these people live in remote villages, many of which lie in the Sunbelt. The developing worldwide markets potential size is immense. The IEA projects an increasing demand for electrical power worldwide, which will result in more than a doubling of the existing wide-ranging installed capacity. More than half of this in developing countries and a large part in areas with good solar resources, limited fossil fuel supplies, and no power distribution network.

Since dish systems can operate independently of power grids in remote sunny location, they are the most appropriate CSP technology for distributed applications as water pumping or village electrification. Because of the estimated market growth and due to the hybridisation capabilities, high efficiency and conventional construction, dish/engine systems are expected to compete soon in the distributed markets. Important potential markets in developing countries exist, also for parabolic trough and power tower. In fact, principally due to reduced O&M charges, in developing countries costs appear to be slightly lower than the USA/EU values for the same capacity compared and for the same kind of plants [SolarPACES].

Table 52 : Summary of important potential factors. Source: compilation NET Ltd, St. Ursen, Switzerland

Top potential factors	
Geofactor influencing energy input	• direct irradiation
Limit (availability / capacity)	• area availability /grid capacity
Capacity installed in 1998 in kWh per year and capita in EU15	• 0 kWh
Potential in kWh per year and capita in EU15	• 5 kWh by 2010 • 50 kWh by 2020
Future potential beyond term year given	• high
Rule of thumb for conversion ratio* (installed power to electric output)	• 1 kWp --> 1900 kWh per year

* Assumptions: solar irradiation 1700 kWh / m^2 and year, system efficiency 15%

6.4 Markets

In general, it is clear that parabolic trough plants are the most mature CSP technology available today and the technology most likely to be used for near-term deployments. Although this technology is the cheapest solar technology, there are still significant areas for improvement and cost cutting.

Power towers, with low cost and efficient thermal storage, promise to offer dispatchable, high capacity factor, solar-only plants in the near future and are very close to commercialisation. Power towers may well be competing with trough plants in the mid-term.

The nature of parabolic dish system will allow them to be used in smaller high-value and off-grid remote applications for deployment in the medium to long-term, further development and field testing will be needed with significant potential for cost cutting through economies in the manufacturing. The modularity of dish engine systems allows them to be deployed individually for remote applications, or grouped together for small-grid or end-of-line utility application, in fact the system can readily be expanded with additional modules to accommodate future load growth. Solar dish/engine systems are being developed for use in emerging global markets for distributed generation, green power, remote power, and grid-connected applications. Individual units ranging in size from 9 to 25 kW can operate independently of power grids in remote sunny locations to pump water or to provide electricity for people living in remote areas.

CSP is most likely some 20 years behind wind power in market development. At the end of the past century operating CSP capacity was about 400 MWe with an output of nearly 1 TWh. No new commercial plants have been built since 1991, number of projects are under deployment and it is plausible that, with an expected growth rate of 20%, 2500 MW of installed capacity will be reached by 2010 in comparison wind technology reached this capacity in 1990. Because CSP costs are dropping rapidly towards levels similar to those obtained by wind, CSP may grow in a manner rather similar to wind technology. The World Energy Council and the SunLab expect a global growth rate close to 25% from 2010 to 2020; the CSP installed capacity will then be approximately 20 GW by 2020 [SunLab]. Market projections partly agree with the projections of the World Energy Council and SunLab, and estimate that installed capacity will range from 1.8 to 8.3 GW by 2010 and from 10 to 45 GW by 2020, which would mean an annual growth rate ranging between 20 and 35%.

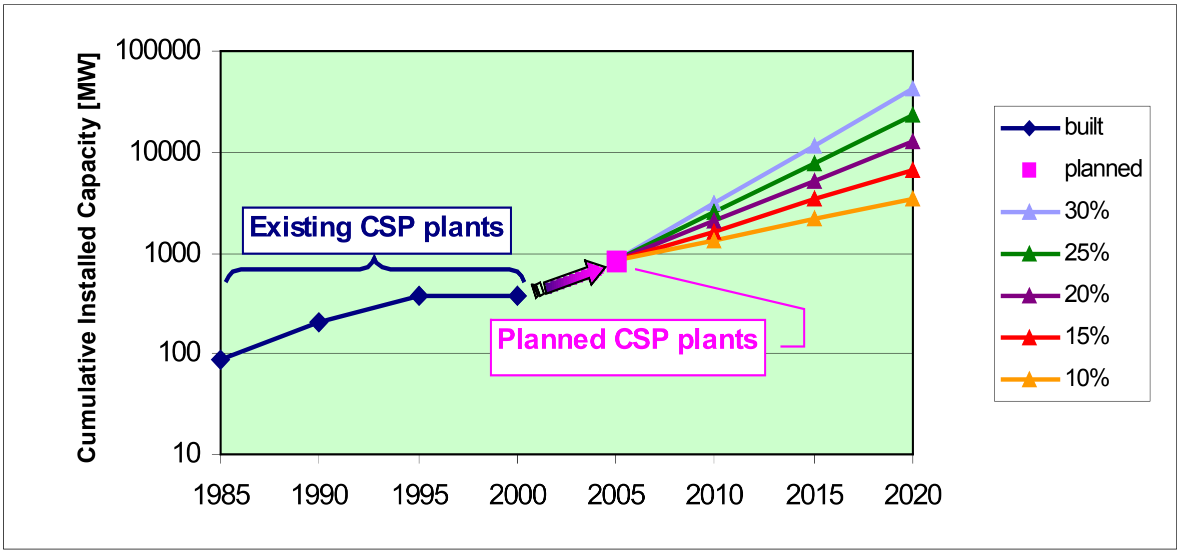


Figure 65: Past, present and predicted CSP installed capacity for different growth rates. Source: Data for existing and planned plants from World Bank, figure compilation NET Ltd., St. Ursen. Switzerland

In the near to mid term, SunLab and SolarPACES estimate that CSP technologies will be able to meet the requirements of two major electric power markets: large-scale dispatchable markets as grid-connected peaking or base-load power and rapidly expanding distributed markets including both on-grid and remote/off-grid applications. CSP technologies are very close to meet requirements of high value and niche markets, where the cost of energy is higher due to high fuel prices (e.g. island systems) or as a result of a green power generation emphasizing.

6.5 Needs and measures

The technical potential of CSP technologies has been demonstrated in particular for the parabolic trough technology, which is waiting for a chance to be developed. Power tower technology requires the development of low cost heliostats and the development of further commercial plants. Parabolic dishes require the development of at least one commercial engine and the maturity of a low cost concentrator.

In order to further reduce costs, CSP technology needs to be constantly improved. Costs can be reduced also by non technical measures by reducing debt service costs through grants, low interest loans and tax credits. Suggestions for needs and measures to bring CSP costs down are given by SunLab and SolarPACES roadmaps. Non technical R&D are mainly applicable only for centralised CSP plants since they need more important incentives than distributed power plant as dish/engine systems.

Table 53 : Needs and measures for CSP technology for the near, mid and long term
Source: adapted from SolarPACES and SunLab, through NET Ltd., St. Ursen, Switzerland

<table>
<tr><th></th><th colspan="3">Technical R&D</th><th>Non technical R&D</th></tr>
<tr><th></th><th>Trough</th><th>Power Tower</th><th>Dish</th><th>Trough
Power Tower
(Dish)</th></tr>
<tr><td>Near term (2005)</td><td>• increasing plant size (100 MW)
• Increasing collector area
• plant design (ISCCS)
• thermal storage (two tank molten salt, thermocline)</td><td>• increasing plant size (30MW)
• increasing heliostat size (150 m^2)
• thermal storage (thermocline)
• high-flux molten salt receiver technology</td><td>• increasing plant size (25 kW)
• use of production-level engine</td><td>• low cost financing
• grants</td></tr>
<tr><td>Mid term (2010)</td><td>• increasing plant size (200 MW)
• increasing collector area
• plant design optimisation
• advanced trough collector design
• advanced reflector design
• thermal Storage (molten salt as HTF)
• reduction of parasitcs loads</td><td>• increasing plant size (100 MW)
• increasing heliostat size (170 m^2)
• thermal storage (advanced organic salt)
• heliostats field improvements (optical, structure, control)
• volumetric receiver</td><td>• increasing plant size (50 kW)
• improvements in mirrors and supports structures
• heat pipe receiver
• control systems (fully automatic operation)</td><td>• green market development
• solar tax equity
• system analysis tools
• high resolution satellite insulation data</td></tr>
<tr><td>Long term (2020)</td><td>• increasing plant size (350 MW)
• plant design (DSG)
• thermal storage (advanced organic salt as HTF)</td><td>• increasing plant size (100 MW)
• thermal storage (high temperature phase change, hydrogen)</td><td>• improvements in volumetric receiver
• improvements in mirror and engine technology
• reducing of parasitic loads</td><td>• solar power parks
• solar investment funds</td></tr>
</table>

7 Wind energy

Figure 66 : Wind farm consisting of 35 machines of 1.5 MW each and a rotor diameter of 66 m at Holtriem, Germany. Source: Enercon / EUREC

Figure 67 : Danish offshore wind farm at Tunø Knob, consisting of 10 machines of 500 kW each and a rotor diameter of 39 m. Source: Elsam / EUREC

Figure 68 : Single grid connected 400 kW wind turbine with a rotor diameter of 31 m owned and operated by a farmer at Sint Maartensbrug, the Netherlands. Source: Beurskens / EUREC

7.1 Techno-economic development

Wind turbine systems exist in a range of capacities. A typology is given for turbine size and application categories in the table below.

Table 54 : Wind turbine categories for different applications. Source: EUREC

	Type of application	Type of wind turbine
A	Onshore and offshore grid connected wind farms in size varying from about 10 MW to several 100 MW.	Installed power > 1.5 MW
B	Decentralised and single operating machines connected to the grid.	0.5 MW< installed power < 1.5 MW
C	Decentralised units for both grid connected operation and for hybrid and stand-alone operation.	Installed power < 0.5 MW

The commercial and technological development is very much related to the turbine size (see figure below). From the very beginning of the modern wind energy technology development, starting in the mid 1970s, we can notice a gradual and consequent growth of the unit size of commercial machines. From 10 m diameter in the mid 1970s to 80 m and more at present.

Table 55 : Average capacity of wind generators in kWp for three leading countries. Source: EurObserv'Er

Year	Germany	Spain	United States
1995	473	297	327
1996	530	420	511
1997	623	422	707
1998	783	504	723
1999	919	589	720
2000	1101	648	761
2001	1281	723	881

With the rotor diameter as criterion, the development of turbine technology can be classified in four phases (EUREC):

Phase 1, before 1985: < 15 m diameter
This was truly the pioneering phase of almost home made turbines, designed by very simple design rules. International standards, quality control, detailed load cases, grid quality requirements were yet non-existing. Wind turbine research was focused mainly on theoretical problems and on technology concepts (large turbines, flexible concepts, vertical axis turbines).

Phase 2, 1985-1989: 15 < Ø < 30 m:
In this phase the technology matured towards some successful concepts, of which small series were produced. Research resulted in first design codes and national standards. The basis for all current design codes is laid in this period.

Phase 3, 1989-1994: 30 < Ø < 50 m:
In this phase codes as well as standards were established and validated in several international benchmarks. Industry was able to set up mass production of the successful 500/600 kW class of turbines. In all fields of technology this was the period of the complaint of many turbine manufacturers that the research community produced more results than industry could absorb.

Phase 4: 1994-now: Ø > 50 m
The acceleration from 1 MW to 2 MW, with preparations going on for 3, 4, 5 and 6 MW turbines characterise this phase. This acceleration is entirely market driven, and not guided by European research programmes as was the case with the 500 kW to 1 MW turbines. The research focuses on a number of weak spots in the design knowledge (many related to stall) and transfers this knowledge to engineering rules with limited validity due to a lack of experimental data. The design codes remain essentially unchanged in this phase. R&D on new topics like short term wind forecasting has started and provides results (codes for short term wind power prediction).

The rated power per turbine is still on the rise (EurObserv'Er [31]): from a technological point of view, the next generation of turbines will have a power capacity of between 3 and 5 MWp. Some manufacturers have already announced commercial prototypes. This is the case of the German company Enercon which should be the first industry to develop an offshore wind turbine of 4.5 MWp (Enercon model E112). Vestas has presented its next turbine, the model V90-3 MW, which will be mass produced by the year 2003. Enron is working on an offshore/onshore wind turbine prototype of a class higher than 3 MWp (Enron Wind 3.2 and Enron Wind 3.6). This prototype was installed in spring 2002.

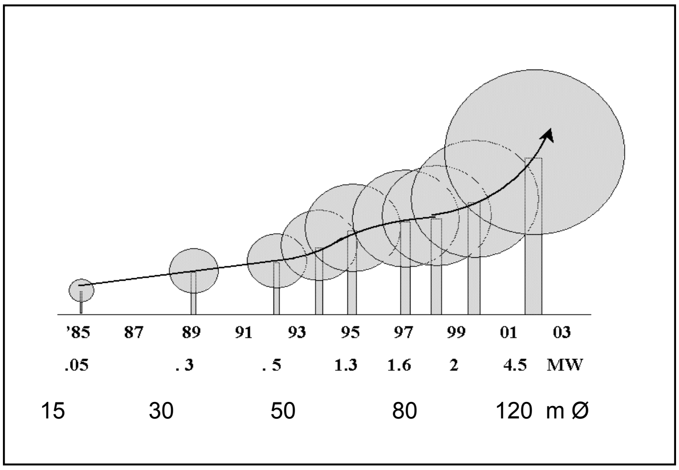


Figure 69 : Turbine sizes at market introduction. Source: Van Kuik, G.A.M.

The technical developments can be summarised as follows (EUREC):

- Increase in scale, diameters from 10 meter to 120 meter
- Increase in capacity from 0.03 MW to 5 MW
- From fixed blade to variable pitch
- From classical drive trains to direct drives
- Variable speed conversion systems
- Develop of power electronics
- Decrease in weight relative to capacity
- Introduction of offshore technology (foundations, operation and maintenance)

From stall to pitch regulation
Many turbine manufacturers are moving to pitch regulation and variable speed technology, a new development is the so called active stall. Both Bonus and NEG-Micon use active stall for its >1 MW turbines, although NEG-Micon uses stall for their 1.5 MW turbine.

Use of direct drive in large turbines
Optimisation of drive-train – direct drive by use of multipole synchronous or permanent magnet generator or traditional drive-train-gearbox, couplings and asynchronous generator. Control of blades (pitch/adjustment) and control of rotor revolution speed enables the designer to reduce torque peaks in the transmission; hence, lower component prices may be realised.

Use of materials
Decrease in weight relative to the capacity of the turbine is desirable because a decrease in the amount of material means decreasing costs. A considerable decrease in weight of turbines is being obtained through a better understanding of how loads affect the turbine and thereby the possibility to calculate closer to the physical limits of materials.

Better and new materials e.g. higher strength to mass ratio, for the blade (advanced composites) can reduce the weight of the rotor (a compromise between strength / stiffness and dampening properties). Glass fibre blades are already in use. New developments are towards using fibre-reinforced materials such as with carbon fibre. Weight reductions of nearly 50% compared to standard rotors are considered feasible (typically from 5500 kg to 2500 kg).

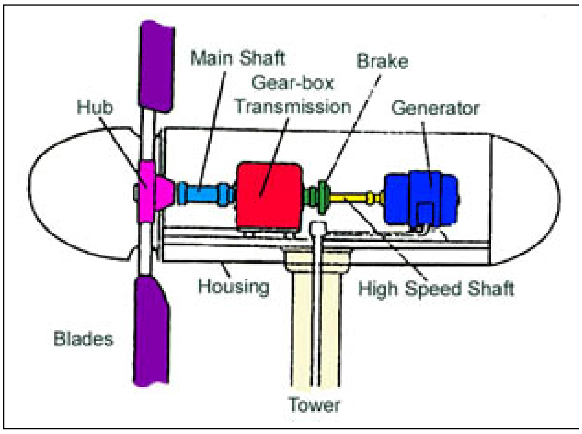


Figure 70 : Components of a large scale wind generator. Source: Australian Greenhouse Office [27]

Technical design lifetime

Technical design lifetime for modern machines is typically 20 years. However, this does not exclude the need to replace certain components after a shorter interval. Because of the rapid development towards large machines, uncertainty about the reliability of components of machines increases again and maintenance costs tend to increase slightly. This is expected to be a temporary phenomenon. Consumables such as oil for gearboxes, brakes, clutches, etc. are often replaced with intervals of 1 to 3 years. Parts of the yaw system are replaced in intervals of 5 years. Depending on the operational strategy and design, components exposed to fatigue loads such as main bearings, bearings in gearbox and generator are foreseen to be replaced halfway the design lifetime. Sometimes the reason for early replacement is due to design errors, often caused by the need to reduce costs by ignoring safety margins.

7.2 Costs and cost reduction opportunities

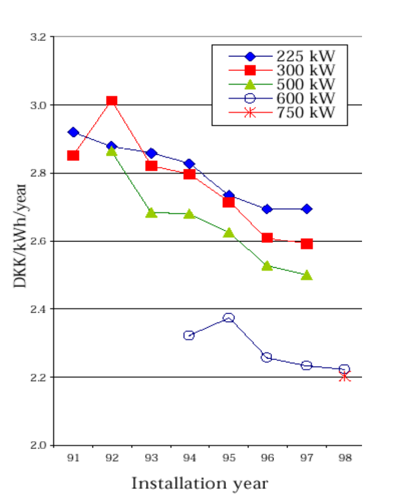
The cost reduction realised in the past can be attributed to improvements in technology and siting:

- about three quarters due to design improvements and more efficient manufacturing
- about one quarter due to improved siting

Upscaling the turbine size plays - from a historical and prospective point of view - a central role to (further) reduce costs.

The effects of the scale on the relative cost of the machines are illustrated in the figures below showing the specific investment costs as a function of capacity.

Another effect of economy of scale is wind farm operation. Project preparation costs in Denmark with 600 kW machines amount to the average value of 1.25 times the ex-factory cost [Energistirelsen; Miljø- og Energiministeriet]. Project preparation costs per machine can be reduced considerably by wind farm operation. More and more wind turbines are placed in clusters, so called wind farms, which are operated as single energy generating units. Unit size has evolved from a few MWp in the early 1980s to a few hundreds of MWp at present.



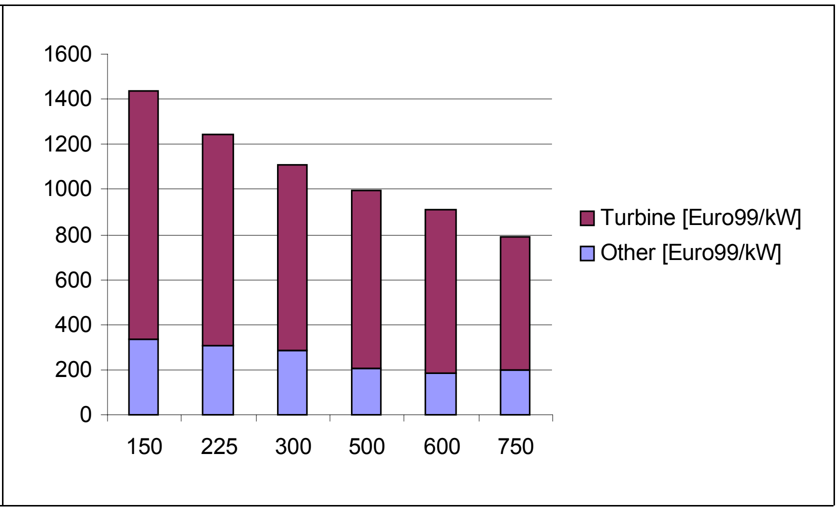


Figure 71 and 72 : Specific investment defined as ex-works Danish turbine price divided by annual production; roughness class 1; list prices of leading manufacturers (DKK_{1999}). On the right side, specific investment cost of Danish wind turbines as a function of capacity in kWp. Source: Wind power in Denmark [DEA]

Investigating and using good sites and increasing the tower height also helps reduce generation costs.

Technological improvements strongly related to R&D can contribute to reduce costs in manufacturing. Ex factory cost reductions of 15 to 20 % are being expected in a long term from the combination of the following features in advanced wind turbine concepts [Hagg, Rasmussen]:

- Reduction of loads by means of less conservative design and by means of the use of flexible turbine components, such as flexible blades, flexible hubs, variable speed generator systems. This leads to lower weights and in the final end to lower machine costs.
- Reduction of the number of components.
- Use of improved materials featuring higher strength to mass ratios and better internal damping.

An indication of improved efficiency (and better siting and higher hub heights) is also reflected in the development of the energy output per m^2 swept rotor area (see figure below).

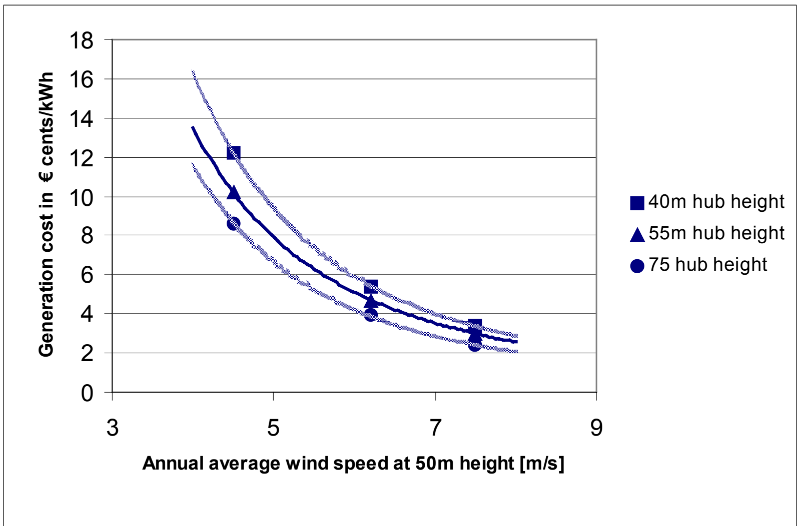


Figure 73: Generating costs of wind energy as a function of local average wind speed. The calculations have been carried out for three sizes of wind turbines. The ranges of inaccuracy are due to varying wind speeds at different hub heights. To take into account various dimensions, outputs were calculated at 40 m hub height (typically 500 kW machines), 55 m hub height (typically 1 MW machines) and 75 m (typically 2 MW machines) for a roughness class 2 terrain according to Troen, Petersen. Source: EUREC

Mass production / increasing the volume plays a minor role in further cost reductions due to “large and heavy” and relatively inexpensive components whose production structure tends to be decentralised as transportation costs can quickly balance lower costs achieved by mass production at a central manufacturing site. On the other hand, the concentration phenomenon is driven by economies of scale in turbine manufacturing and by the demand side being increasingly dominated by larger players.

Globally, there is a perspective for further cost reduction of 15% on the short term and close to 50% by the year 2020 [BTM]. The economy of scale - due to larger turbine sizes and wind farm operation- contributes up to half of the cost reduction potential. About a third can be achieved through R&D related improvements by means of combining new features in advanced wind turbine concepts, also contributing to bring down O&M costs by some 20%. A comparatively moderate contribution to cost reduction is attributed to increasing of the manufacturing volume.

The cost estimates show much agreement: in 2010 specific investment cost is predicted to be between €715/kW and €675/kW as shown in the figure above.

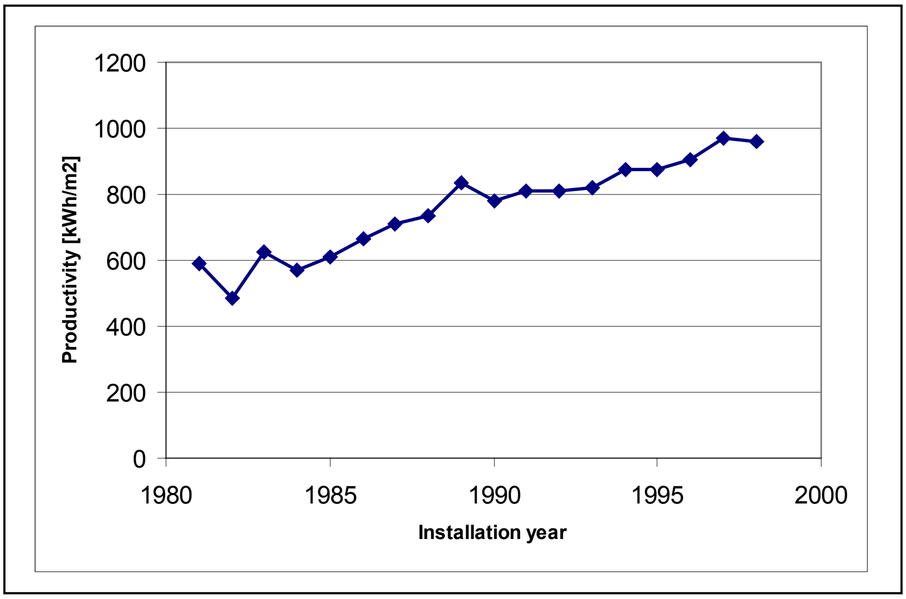


Figure 74 : Development of the energy output per m^2 swept rotor area of all Danish wind turbines. Source: Energistirelsen; Miljø- og Energiministeriet

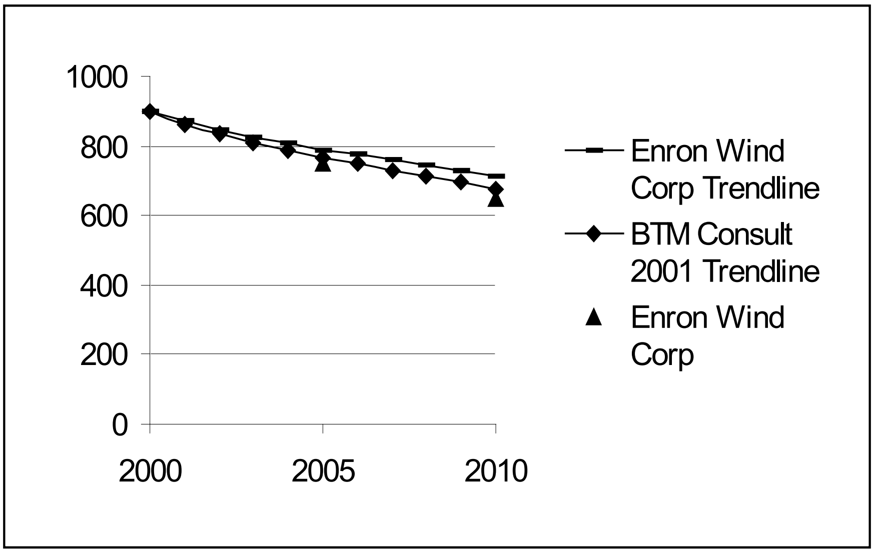


Figure 75: Specific investment cost of wind turbines, 2000-2010 (€$_{2000}$/kW). Source: EUREC

The cost reduction opportunities and forecasts can be plausibility checked with the wind energy experiences available in various regions. According to the market structure and maturity, the experience curves can look different. This is the case for wind energy (OECD / IEA / Wene C.O.):

- Progress ratio of 68% for electricity from wind energy in USA 1985 - 1994
- Progress ratio of 82% for electricity from wind energy in EU 1980 - 1995
- Progress ratio of 92% for electricity from wind energy in Germany 1990 - 1998

Globally, the cost developments between 1980 and 2000 indicate a progress ratio of approximately 0.90 with considerable variations in time and space. To estimate the cost reduction towards 2010, the following assumptions can be made:

- A progress ratio of 0.90 for the wind turbine, exclusive of the tower.
- A progress ratio of 0.96 for the tower.
- A progress ratio of 0.98 for the cost of civil works, infrastructure & grid connection.

In the future the progress ratio will most likely be higher, which means that the volume doubling will be likely to lead to lower cost reductions in the next decades compared to the previous decades.

Table 56 : Experience curve based forecasts of future capacities and costs taking three progress ratios (0.90, 0.925 and 0.95) and three growth rates (20%, 25% and 30%) in the years 2005, 2010 and 2020. Source: NET Ltd, St.Ursen, Switzerland. Data for built capacity until 2001 from EurObserv'Er / Systèmes solaires

Year	Growth rate assumed	Total installed capacity in MWp	Progress ratio 0.90 - costs per kWp	Progress ratio 0.925- costs per kWp	Progress ratio 0.95- costs per kWp	Costs per kWp
1985	real	1097				1700
1990	real	2023				1450
1995	real	4821				1200
2000	real	17696				950
2001	real	24554	900	900	900	900
2005	20%	77659	755	790	826	
2005	25%	86444	743	781	820	
2005	30%	96387	731	771	813	
2010	20%	230313	640	**699**	762	
2010	25%	301526	614	678	747	
2010	30%	396258	589	658	732	
2020	20%	1555366	479	564	662	
2020	25%	2961004	434	525	631	
2020	30%	5643631	393	488	**602**	

Looking at the past and forecast experience curve (see figure below and table above), further cost reductions are „strongly influenced by the progress ratio“, i.e. the inherent learning capacity of wind energy technology. Taking an overall progress ratio of 0.925 and a conservative growth rate of 20% until 2010, the specific investment kWp cost would be just below € 700. Taking a more conservative progress ratio of 0.95 and a more sustained growth rate of 30% until 2010, the specific investment kWp cost would be € 732. The very same conditions would bring kWp costs down to € 600 by 2020. Again, with a lower growth rate of 20% and a more advanced progress ratio of 0.925, the specific investment kWp costs would be lower, i.e. € 564.

The effect of offshore wind energy technology cannot be fully appreciated. Much higher capacities and larger turbines bring about considerable economies of scale but civil works and grid connection issues are mostly more costly than onshore. Higher installation costs may be offset by better wind conditions offshore. Again, on the other hand, in certain areas, best onshore sites are being used up.

It can be concluded that figures are quite coherent and future cost reduction opportunities mainly depend on steady technological progress but also on a sustained market growth to keep the promise blowing in the wind.

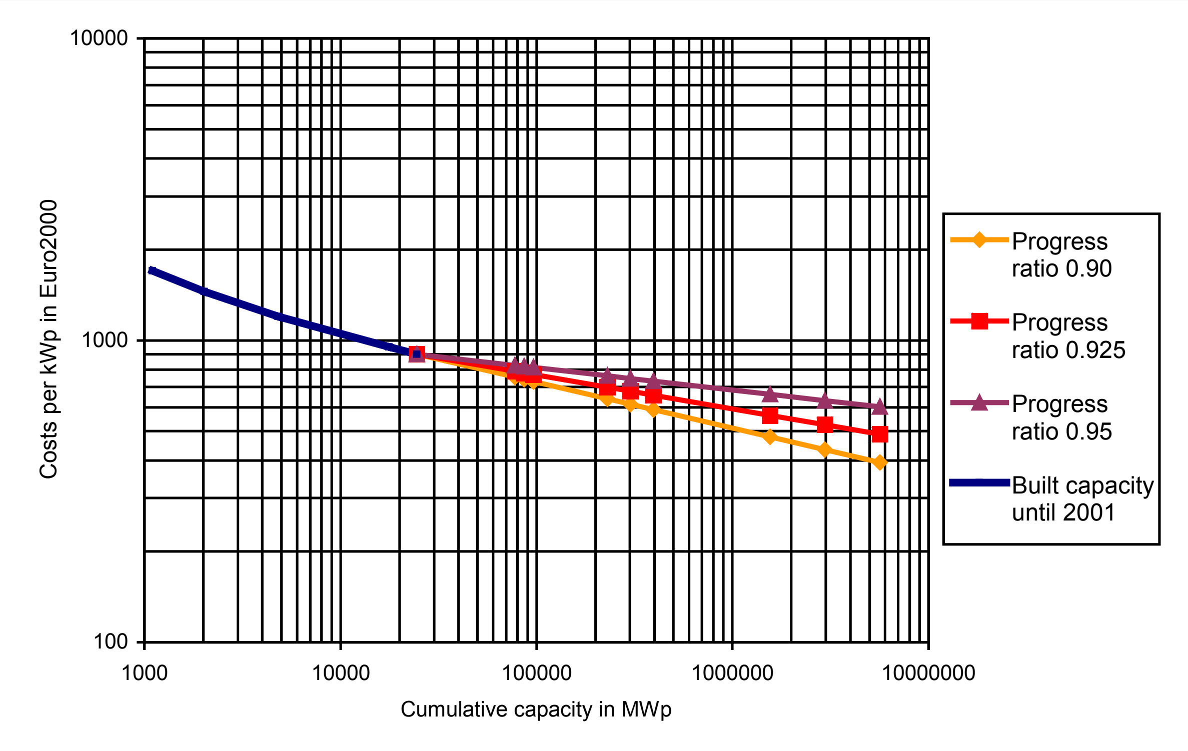


Figure 76 : Experience curve based forecasts of future capacities and costs taking three progress ratios (0.90, 0.925 and 0.95) and three growth rates (20%, 25% and 30%). The graphs shows bundles of dots. The first bundle is for the year 2005, second for 2010 and third for 2020. Each first dot reflects the growth rate of 20%, each second dot reflects the growth rate of 25% and each third dot reflects the growth rate of 30%. Source: NET Ltd, St.Ursen, Switzerland. Data for built capacity until 2001 from EurObserv'Er / Systèmes solaires

Table 57 : Estimates of the three main cost reduction opportunities (progress through R&D, economy of (manufacturing) volume and economy of scale). Each * is the approximate equivalence of 4% - 6% of cost reduction within a decade including expected technological learning and market growth. Source: NET Ltd, St.Ursen, Switzerland

	R&D	Manufacturing volume	Economy of scale
Wind onshore	**	*	***
Wind offshore	***	*	***

Table 58 : Summary of important cost figures. Source: compilation NET Ltd, St.Ursen, Switzerland

Cost figures	
Current investment costs in €$_{2000}$ per kWp	• low investment costs: 900 • high investment costs: 2000
Potential investment costs in €$_{2000}$ per kWp in 2010	• low investment costs: 700 • high investment costs: 1400
Current generation costs in €cents$_{2000}$ per kWh	• low generation costs: 5 • high generation costs: 15
Future generation costs in €cents$_{2000}$ per kWh in 2010	• low generation costs: 3.5 • high generation costs: 12

7.3 Potential

The potential of wind energy is enormous. Suitable areas / sites are characterised by higher average wind speed. Basically, for identical systems given, their annual electricity generation (costs) mainly depend on the average wind speed. The “good” areas can be clearly depicted in the map shown below. Favourable wind conditions can be mainly found in coastal areas as well as partly in mountainous areas.

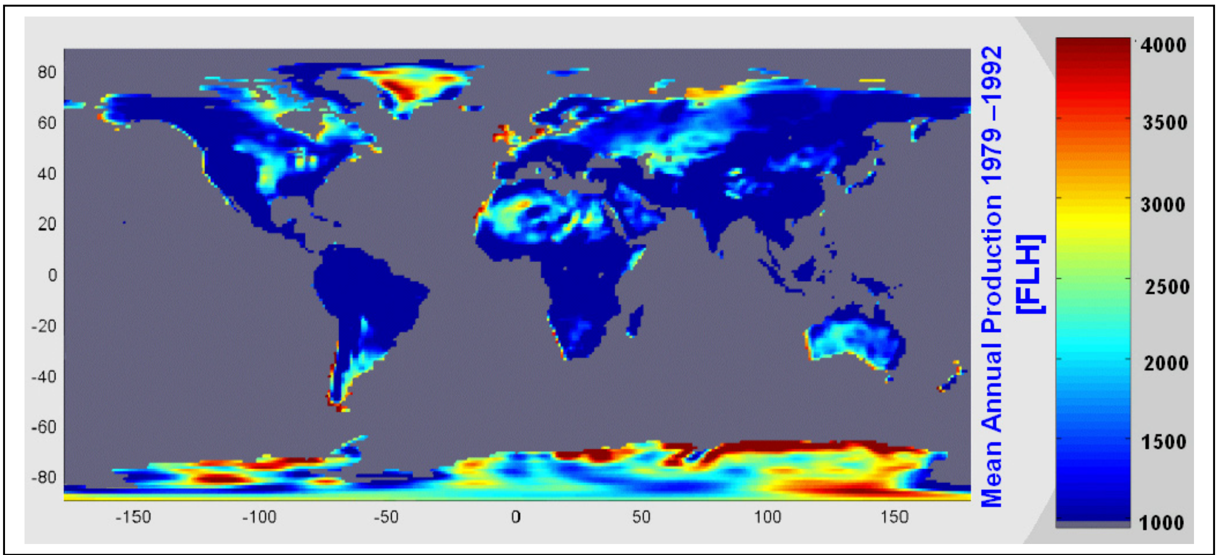


Figure 77: Mean annual production of 1.5 MW variable speed wind turbines (HH = 80 m) in full load hours. Source: G. Czisch

The future global progress ratio is likely to be around 90% to 95%. The vigorous market growth (rates) will imply several doublings of the volume thus bring costs considerably further down. The Enron Wind Corp estimates an installed capacity of 53 460 MW in 2005 and 133 220 MW in 2010. BTM Consult ApS estimates the world’s wind turbine capacity to be 58 210 MW in 2005 and 144 000 MW in 2010. More speculative is the estimate for the capacity installed in 2020. Enron’s estimate for the cumulative installed onshore capacity is 400 GW.

Table 59 : Summary of important potential factors. Source: compilation NET Ltd, St.Ursen, Switzerland

Top potential factors	
Geofactor influencing energy input	• wind speed ($E = 3.2\ V^3$) *[1]
Limit (availability / capacity)	• site availability • grid (load) capacity
Capacity installed in 1998 in kWh per year and capita in EU15 and Switzerland	• 32 kWh
Potential in kWh per year and capita in EU15 and Switzerland	• 250 kWh by 2010
Future potential beyond term year given	• high
Rule of thumb for conversion ratio*[2] (installed power to electric output)	• 1 kWp --> 1500 kWh - 2300 kWh per year

*[1] E = Energy [J], V = average annual wind speed (m/s) at hub height

*[2] European average based on 26.8 TWh production and 17.5 GWp capacity in 2001 (Systèmes Solaires) for the lower value and IEA data for the higher value based on production of 57 TWh and capacity of 24.3 GWp

In the past, the European Wind Energy Association EWEA was forced to adjust its targets to higher figures twice because of the spectacular growth of sales of wind turbines among others in the European Union. Its present targets are as follows:

- 8 000 MW by 2000 (at the beginning of 2000 the actual figure was approximately 13 600 MW (!))
- 60 000 MW by 2010 of which 5000 MW is to be installed offshore and
- 150 000 MW by 2020.

7.4 Markets and market growth

The market growth has been very much sustained in the wind energy sector (see figure below) and the installed capacity is particularly high in some European countries (see map below). To keep it sustained, two main drivers can be used: a) application-driven market growth and b) price-driven market growth. Obviously, their effects cannot be actually separated in reality.

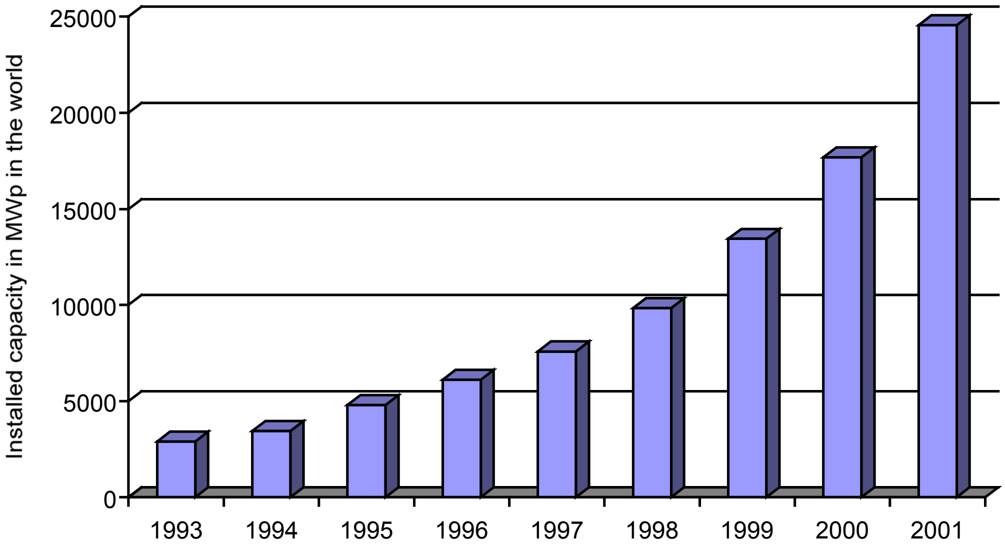


Figure 78: Installed capacity (in MWp) of wind energy in the world. Source: EurObserv'Er

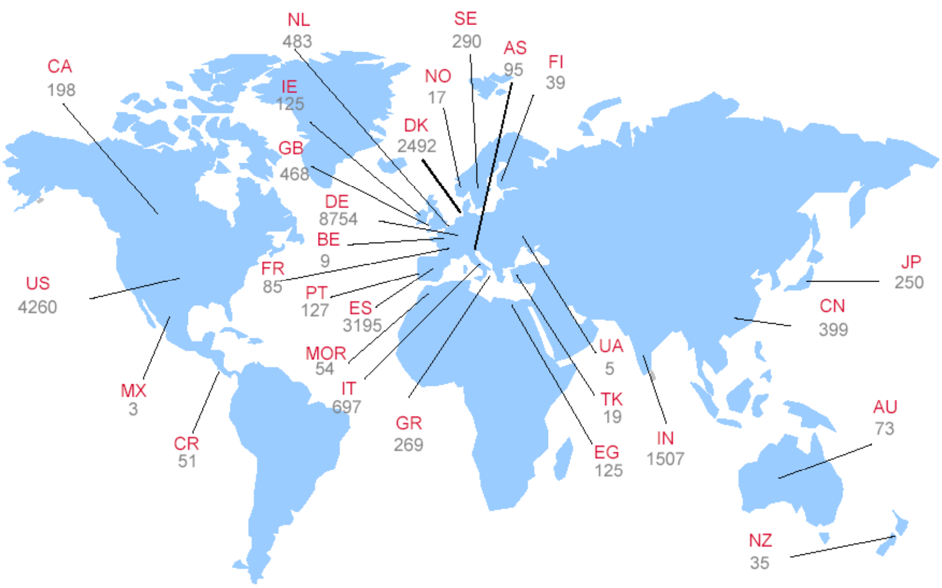


Figure 79: Installed wind energy capacity in MWp according to IEA data. Source: IEA / Goldman

Application-driven market growth

Wind energy has become very popular and is applied for both very specific energy services and bulk power production. Provided that the wind (speed) and site conditions do allow for wind energy generation, virtually any type of application - from autonomous energy supply to grid-connected wind farms - can be done by wind energy.

The market share of the *decentralised and single operating machines connected to the grid* in 1999 was still the largest: in 1999 about 70% of the total number of machines sold.

The market share of onshore and offshore grid connected *wind farms* in size varying from about 10 MW to several 100 MW is growing rapidly.

Renovation: As the decentralised and single operating machines connected to the grid (and also the machines of 100 kW to 500 kW from decentralised units for both grid connected operation and for hybrid and stand-alone operation are the oldest ones in operation especially in the pioneer countries like USA, Germany and Denmark, tear and wear and fatigue induced failures appear more frequent as the end of the projected lifetime comes in sight. This leads to increased maintenance costs in the overall statistics. Questions of replacing these machines by larger state-of-the-art machines or refurbishing the old ones are being addressed by project owner/operators.

Independent island renewable energy systems and developing countries: Many experiments were carried out and over 10 research institutions had more or less comprehensive development programmes. Looking back from the present situation, one can conclude that virtually all development efforts on autonomous systems had limited success. The need for independent island renewable energy systems has not changed since. Analysing and understanding the reasons why this happened could provide us with the conditions for a real successful revival of the development and market implementation of autonomous systems. The generally accepted notion that the market did not develop is that the actual stakeholders (technology developers, manufacturers) were not familiar with the demand side of the market for energy supply to remote places. Other reasons are to be found in former component costs: especially those components that in the past appeared to be too expensive or too unreliable, such as wind turbines, electronic components and control strategies have improved dramatically since. This leads to the conclusion that a revival of the development of autonomous systems is very well possible.

Small stand-alone turbines: Small battery charging wind turbines, (25 to 150 watts; i.e. rotor diameters from 0.5 meter to 1.5 meters), are by far the most successful in commercial terms. These systems are used for battery charging, water pumping, heating, etc. (<10 kW).

Price-driven market growth

The demand side of the market mainly drives the trend towards larger machines. The most important arguments for larger machines are:

- utilising economy of scale,
- less visual impact on the landscape per unit of installed power and the
- expectation that the multi MW machines are needed for exploiting the off-shore potential.

Wind power has been entering larger and broader markets in recent years. The vigorous growth of wind energy clearly deals with the relatively competitive green (bulk) power price. However, the relatively low technology costs and subsequently relatively competitve prices are most probably not the main reasons for the growth experienced but the prerequisite for it. A crucial factor are feed-in tariffs and subsequently a crucial role is played by the (electricity price) policy.

Referring to the recent up’s and down’s, stop&go’s in the wind energy market and referring to the present successes in Denmark, Germany and Spain, some professional associations claim that the most effective incentive for market development is fixing a minimum feed-in tariff for a sufficiently long period, e.g. 10 years. It is evident that in countries like Denmark, Germany and Spain fixed tariff systems indeed have been very successful.

7.5 Needs and measures

In order to meet the ambitious goals set by the wind policy makers and industry, a number of conditions have to be fulfilled. The following aspects can be considered to constitute the complex determining the success factors (EUREC).

- **Cost reduction** of wind energy.

- **Improving the value of the wind electricity.** In the first instance, value is determined by the avoided fuel cost of fossil-fuelled plants. Equally relevant are cost components which seldom are made explicit in the electricity market, such as the environmental advantages, capacity credit (to be improved by utilising methods to forecast the output of wind farms a fewer hours in advance), demand for green electricity by customers.

- Finding **new sites**: a) offshore: in densely populated coastal countries, b) onshore: funnels, hills, mountains in mountainous land locked countries.

- **System development**. On one hand, national grids have to be able to absorb large amounts of varying electricity output and on the other hand, wind energy plants need to meet specific requirements such as the amount of reactive power produced, harmonic distortion, predictability and controllability of the output.

- **Reduction of uncertainties** in predicting the technical and economic feasibility of projects. This means improved resource assessments, wind speed measurements, maintainability of machines, reliability, lifetime design methods.

- **Reducing environmental and negative social impacts** such as visual impact on the landscape, effects on birds and their habitats, acoustic noise emissions, etc.

- **Education and human resource development.** EWEA and Greenpeace expect a work force for 1.7 million jobs if the 10% target for 2020 is to be met. People have to be educated and trained in both technical and non technical capabilities. Training precedes actual employment!

- **Implementing national and international environmental and energy policies.** A large number of instruments have been implemented in the past by mostly national states. Some schemes proved to be very efficient and some were not. The proper integration of financial and other legal measures, in relation to the maturity of the technology appeared to be a necessary condition. On the international stage, a number of agreements are being developed to protect the environment and in which renewable energy plays a crucial role: Joint Implementation (JI) and Clean Development Mechanism (CDM).

The first two mentioned factors, of course, are closely linked together. The bigger the difference between the cost of wind energy and its value, the bigger the driving force behind the economic development of the wind energy technology.

The educational establishments such as universities and polytechnic schools, the R&D communities in the institutes and in industry have to provide the know how and capabilities to further specify the success factors, to develop and apply them.

The aspects discussed are to be linked to strategic goals in order to be effective. The strategic goals encompass the future wind energy generating capacities in different markets, industrial and employment goals. The table below links the success aspects to these strategic goals. The number of bullets indicates the relative importance of the aspect concerned in order to meet the strategic goal. The importance of course depends on the maturity of the technology, the stage of development and know how. The last column indicates the relative state of know how and practical experience with the various aspects. The fewer bullets appear the more R&D is required.

EWEA's wind energy targets form a sub group of the European Union's target of covering 10% of Europe's energy demand by means of renewable energy. To emphasise the importance of renewables for the developing economies, a rather arbitrary target is added for these countries. This target again is a sub group of EWEA and Greenpeace's recommendation of covering 10% of the world electricity demand by means of wind energy by the year 2020.

Table 60 : The relations between strategic goals and aspects of implementation success factors for wind energy systems. Source: EUREC

Strategic goals Success factors	10% renewable energy in Europe	30% new RE capacity in developing countries	Maintaining industrial capacity and employment
Cost reduction of wind energy	••	•••	•••••
Increasing the value of wind energy	•••	•••	•••
Finding new sites	••••	••	•
System development	••••	••••	•••
Reduction of uncertainties	••	•••••	•••••
Reduction of environmental effects and negative social impacts	•••	-	•
Education and human resource development	••	••	•••••
Development of policy and instruments	•••••	•••••	•••••

As the demand for wind energy systems developed very fast, manufacturers were not in the position to fully incorporate R&D results in their designs in order to optimise the systems. This implies that lessons from „learning curves" from other technologies have not yet been fully implemented. The use of R&D results is however needed in order to be able to utilise the cost reduction potential to its full extent. Reducing R&D budgets at the very moment wind energy technology appears to become successful in the market place would be therefore short-sighted.

On the contrary, R&D efforts should be intensified but targeted on the problems that are likely to hamper (the speed of) the large scale implementation of wind energy in the future.

Different aspects of the success factors in R&D are linked to different categories of applications through actions required. These actions constitute R&D priorities to further stimulate the use of wind energy systems. In table 10 the structure is illustrated and the necessary R&D activities have been listed.

Table 61 : Summary of R&D activities in relation to success factors and applications of wind energy systems. Source: EUREC

	Large scale wind farms on/offshore: P> 1.5 MW	Distributed systems on land: 0.5 MW<P<1.5 MW	Decentralised systems: P<0.5 MW
Cost reduction of wind energy	• Design improvement • Manufacturing technology • Transport and installation techniques • Reliability design for offshore	• Design improvement • Manufacturing technology	• Testing and evaluation prototypes
Increasing the value of wind energy	• Output forecasting methods • Controllability of large wind farms	• Output forecasting methods	
Finding new sites	• Offshore resource assessment • Resource assessment in mountainous areas • Resource assessment in cold climates • Design conditions and methods adapted to extreme external conditions	• Resource assessment in mountainous areas • Resource assessment in cold climates • Design conditions and methods adapted to extreme external conditions	• Resource assessment in mountainous areas • Resource assessment in cold climates • Design conditions and methods adapted to extreme external conditions • Market surveys
System development	• Optimisation of power electronic converters • Control strategies (for output and power quality control and to stabilise mechanical constructions) • Grid connection	• Optimisation of power electronic converters • Control systems (for output and power quality control) for weak grids	• Energy storage systems • Energy management systems • Standardisation and modularization • Updating system design methods and verification by means of experiments
Reduction of uncertainties	• Reliability design methods • More accurate resource assessment methods and output prediction calculation methods • Methods for fine tuning of power curves to local climatical circumstances • Development of fast aerodynamic diagnosis methods	• More accurate resource assessment methods and output prediction calculation methods • Methods for fine tuning of power curves to local climatical circumstances • Development of fast aerodynamic diagnosis methods	• System reliability
Reduction of environmental effects and negative social impacts	• Development of low noise blades • Monitoring effects on birds habitats • Minimise visual impact • Develop and test participation models for the public	• Development of low noise blades • Monitoring effects on birds habitats • Minimise visual impact • Develop and test participation models for the public	• Design systems with minimum electrical storage by means of batteries
Education and HRD	• Joint international R&D programmes in universities • Develop training schemes for lower and medium level technical skills • Establish specialised profesorates at universities • Develop educational material for primary schools	• Joint international R&D programmes in universities • Develop training schemes for lower and medium level technical skills • Establish specialised profesorates at universities • Develop educational material for primary schools	• Joint international R&D programmes in universities • Develop training schemes for lower and medium level technical skills
Development of policy and instruments	• Obligatory national targets for wind energy • Co-ordination by EC (European Directive) • Evaluate market stimulation programmes and design more effective instruments • Create open European market	• Obligatory national targets for wind energy • Co-ordination by EC (European Directive) • Evaluate market stimulation programmes and design more effective instruments • Create open European market	• Incorporate technology introduction in national rural devt. programmes and programmes of multi national organisations (World Bank, UNDP, etc.)

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