1. Photovoltaic Energy

L.Oikkonen, J.Paatero,T.Carlsson,P. Lund
Advanced Energy Systems
Helsinki University of Technology
Finland

Introduction

The sun is one of the prerequisites of life on Earth, providing light and maintaining the essential energy cycles. As a ubiquitous source of energy, sunlight can be used in electricity production as well. Solar cells or photovoltaics (PVs) are semiconductor devices that convert sunlight into electricity. Most photovoltaic cells available today are made from silicon. As the research on solar cells has progressed, several alternative cell solutions have been discovered. The focus of this text is on the current state of photovoltaic technology and markets.

1.1 General issues on photovoltaic technologies

Photovoltaic technology uses sunlight to generate electricity. The basic energy producing unit is the photovoltaic cell. It is made of semiconductor material which is sensitive to sunlight and it usually has an area of 1–100 cm^2. Individual cells are usually connected together to a module with typical areas of 0.5–2 m^2, and modules are combined in an array to create a PV system which produces the needed output voltage and current.

1.1.1 Peculiarities

Sunlight is a renewable energy source that could theoretically be exploited to supply energy abundantly for an indefinite time into the future. Completely free of cost, sunlight is widely available on Earth regardless of geographical location. On the other hand, the intermittency of sunlight causes the operation of photovoltaics to rely directly on the time of day and weather. On a cloudy day or at night, the power supply is diminished or cut off unless some other source of electricity is used. Additionally, the power density of sunlight is low (1 kW/m^2 in clear conditions), so large-scale PV electricity production requires either a large area covered with PV modules or mirrors for concentrating sunlight on a smaller area.

The power generated by a PV module depends on the module technology and on the intensity of sunlight. The power a module produces at a given moment is proportional to the perpendicular sunlight intensity on the module surface. Power is therefore reduced if conditions are cloudy or if the angle of incidence of sunlight is large. In general, the average power production of a PV system can be reliably estimated on a monthly basis from previously measured meteorological data. Shorter time intervals introduce uncertainty, but weather forecasts can well be used to predict power production one day in advance.

As a semiconductor device the PV module is quiet, static, and solid-state. It requires little maintenance in order to operate: the conversion of sunlight into electricity is a very reliable process that does not produce any emissions. In addition, the module does not include any moving parts that could wear out or break down. However, the encapsulation of the PV module is critical to ensure that the electrically active parts of the module are not harmed by the surrounding environment. In normal operation the system feeding the PV electricity to the network is more susceptible to damage than the module itself. (EPIA and Greenpeace, 2004;Kurokawa, 2003;Ross and Royer, 1999)

PV arrays can be built ranging from a few milliwatts up to several megawatts due to their modular design. Existing arrays can always be expanded to meet growing electricity demand, although the electronics in the system may need updating. Easily adaptable and lightweight, the PV panels can be installed virtually anywhere on Earth without concerns for fuel transportation logistics. Furthermore, PV modules can produce electricity at the point of consumption, which reduces transmission losses and can improves service reliability. (EPIA and Greenpeace, 2004;Kurokawa, 2003;PV-TRAC, 2005)

PV technology also offers an option for energy diversification. It can be used to complement other energy sources, both traditional and renewable. In particular, photovoltaic electricity is well suited for providing additional electricity during peak demand, which in some regions coincides with the sunniest hours of the day due to air conditioning. (Kurokawa, 2003;PV-TRAC, 2005)

At present, the major drawback of photovoltaic electricity is its high price. When a lot of power is needed, photovoltaics is seldom cost-effective. However, in small-scale consumption such as in residential buildings, the competitiveness of PV electricity is improving. While the initial investment into a PV system demands capital, operation and maintenance require next to nothing. (Ross and Royer, 1999)

1.1.2 Environmental aspects

Photovoltaic technology provides clean energy: sunlight acts as the fuel and there are no harmful emissions or polluting gases released during operation. In particular, PV systems do not produce any CO_2 emissions when operating, so they can be used to cut greenhouse gas emissions. Apart from operation, PV systems nevertheless carry the environmental weight of other stages in their life cycle. (Alsema and Nieuwlaar, 1997;Battisti and Corrado, 2005;EPIA and Greenpeace, 2004)

The life cycle of photovoltaic systems consists of the manufacturing, operating, decommissioning and recycling of the system. The life cycle of the module can extend at its best over 40 years (Realini, 2003), whereas the other components of the system last substantially less and thus require replacement. Presently the components do not have a large impact on the energy requirements of a grid-connected PV system compared to the energy-intensive module production. (Alsema and Nieuwlaar, 1997)

Most of PV’s ecological footprint originates from the manufacturing process, which can be traced in detail. Manufacturing consumes a relatively large amount of energy and bulk materials as well as some scarce or toxic substances. The energy used in PV production is taken from the grid, so the overall emissions of photovoltaic electricity are mostly inherited from the grid electricity generated by fossil fuels. (Alsema and Nieuwlaar, 1997;IEA, 2003)

One of the main environmental concerns with photovoltaic modules is the hazardous substances involved in the production of the modules, including large volumes of acid and alkaline etchants as well as smaller amounts of toxic lead (EPIA, 2004). In addition, certain PV technologies have specific needs: for example, some thin-film technologies require cadmium and selenium for production. However, the hazardous substances used in PV technology are deposited in a very stable and fixed way in the solar cell and therefore pose hardly any threat to the environment (Ross and Royer, 1999). The risks concerning the toxic materials used in photovoltaics should not be exaggerated as long as their disposal is properly attended to. (Alsema *et al*, 1997;Fthenakis, 2004)

Photovoltaics can also be evaluated in terms of energy pay-back time. Energy pay-back time illustrates the time taken for power generation to compensate for the energy used in production. For photovoltaic modules it is typically 2 to 4 years, which amounts to approximately 10% of their expected lifetime (EPIA and Greenpeace, 2004). The pay-back times decrease when the cells become more efficient, so considerable reductions up to less than one year or 3% is anticipated in the future (PV-TRAC, 2005).

In improving the cost-effectiveness of photovoltaics, most of their environmental impacts are bound to go down as well: the impacts are mainly associated with material use or processes that will have to be eliminated or optimized. Since new advances are constantly reported, the performance and cost limits have evidently not been met, and there are still plenty of improvements to be performed before optimal production is reached. (Ross and Royer, 1999;Sørensen, 2000) As the environmental impact of the module production decreases, the role of the other components will become more important in terms of the energy efficiency of the whole PV system. (Alsema and Nieuwlaar, 1997)

1.2 Description of photovoltaic technologies

PV technology involves solar cell modules as well as all the equipment needed to convert the generated DC electricity into alternating current, the mounting structure etc. Together, they form the actual PV system that produces usable electricity. In improving the PV system it is therefore essential to consider it as a whole. The ultimate challenge is to form a system producing a maximal amount of electricity at the lowest possible cost. PV technologies are classified by the different materials and methods which can be used to produce functioning PV modules. These range from crystalline silicon technology which has been developed for 50 years to organic solar cell concepts which have only recently discovered.

Extensive research on photovoltaics has brought forth several types of solar cells made from different materials. The most widely used are the crystalline silicon solar cells that lead the market with a share of 94% in 2003. Thin-film technologies occupy the remaining 6%. Figure 1 illustrates the relative market shares of solar cell technologies sold in 2003.

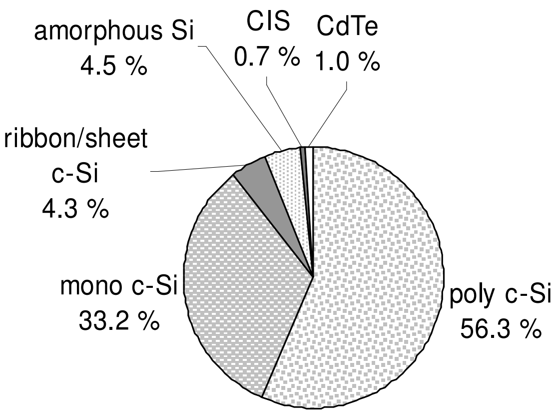

Figure 1. Market shares of different cell technologies sold in 2003 (EPIA and Greenpeace, 2004)

Solar cell technologies already introduced to the market continue to be developed further along with innovative new technologies such as third generation photovoltaics and organic cells. The central focus in research is to reduce PV costs by using less material, energy, and labor. But at the same time, the cell efficiencies must be kept up. Commercial cell efficiencies today range between some 6 and 17%, with the module efficiencies lagging a few percents behind as presented in Table 1. Theoretical limits show that there is still scope for substantial progress. The progress in solar cell efficiencies up until now is shown in detail in Figure 2.

Table 1. Efficiencies of commercial modules and maximum recorded module and cell efficiencies.

(Chopra *et al*, 2004;Frankl *et al*, 2004;Green *et al*, 2005)

Type	Typical range of module efficiency [%]	Maximum Recorded Module Efficiency [%]	Maximum Recorded Cell Efficiency [%]
Single crystalline silicon	12-15	22.7	24.7
Multicrystalline silicon	11-14	15.3	20.3
Amorphous silicon	5-9	10	12.7
CdTe thin-film	5-9	10.7	16.5
CIGS thin-film	9-11	13.4	18.4

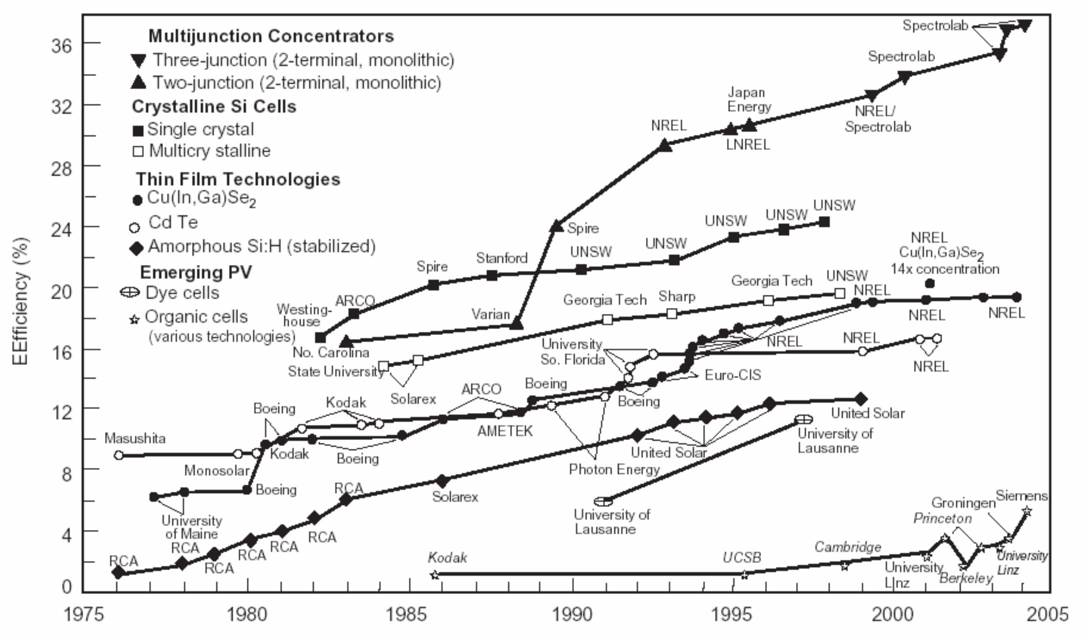

Figure 2. Progress in solar cell efficiencies for various research or laboratory devices (Surek, 2005)

1.2.1 Crystalline silicon

Crystalline silicon is the leading material for commercial photovoltaic cells. It is recognized for its familiarity, proven reliability, and material availability. Crystalline silicon was the first PV technology developed in the 1950s and its head start has contributed to its current success. Crystalline silicon solar cells exist in different forms such as monocrystalline, multicrystalline, ribbon and sheet silicon. (EPIA and Greenpeace, 2004;PV-TRAC, 2005;U.S. Department of Energy: Energy efficiency and renewable energy, 2005)

Silicon-based solar cell technology has gained much from the advances of the microelectronics industry (PV-TRAC, 2005) as both of them involve essentially the same silicon technology. In fact, the PV industry has been able to use reject materials from the microelectronics industry that were available at low cost (Kurokawa, 2003). However, as the PV industry grows the availability of suitable silicon feedstock may become a limiting factor (IEA, 2005;Kurokawa, 2003;U.S. Department of Energy: Energy efficiency and renewable energy, 2005).

The primary crystalline silicon technologies are based on wafers, which are silicon sheets averaging one third of a millimeter in thickness. The production of wafers consumes both material and energy since the silicon has to be purified and the wafer has to be sliced from an ingot or grown ribbons of silicon. Although large scale production of crystalline silicon cells is common, the manufacturing has not yet been optimally automated. (EPIA and Greenpeace, 2004;EPIA, 2004;PV-TRAC, 2005)

Wafer-based crystalline silicon cells differ in their material requirements (Phylipsen and Alsema, 1995). Monocrystalline silicon cells necessitate high-quality silicon but have the highest efficiency figures as well, in the range of 14-17% (Ross and Royer, 1999). Multicrystalline cells are made of lower quality material and achieve efficiencies of 12-14% (Ross and Royer, 1999). In laboratory conditions, cell efficiencies reaching 24.7% (Green *et al*, 2005) have been obtained with monocrystalline silicon. However, the high cell efficiencies counterbalance the relatively high cost of the silicon wafer.

To avoid the expensive and energy-intensive wafer slicing phase in manufacturing, the possibility of producing silicon directly in the form of sheets or ribbons has been investigated. For this reason, research has led to mainly two ribbon growth processes: the edge-defined film-fed growth (EFG) method and the dendritic web approach. The EFG has been developed the furthest and it is now in high volume commercial production whereas the other approaches are still under active development. (Burnham *et al*, 1993;Gordon, 2001;Green, 2000;Green, 2003)

1.2.2 Thin films

Thin-film solar cells may in the long run have the greatest potential for cost reduction among the different photovoltaic technologies. They consume far less material than wafer-based silicon solar cells and offer interesting possibilities for large-scale PV manufacture and use. Also, their smooth visual appearance is an advantage considering applications in building integration. (EPIA, 2004;Kurokawa, 2003;van der Zwaan and Rabl, 2003)

Thin-film modules are made by depositing micrometer thick layers of photosensitive materials on low cost substrates such as glass, plastic or stainless steel. The production phase is already showing improvements that will eventually be reflected in lower manufacturing costs. Firstly, the cells and the production as a whole use materials more efficiently than the crystalline silicon technology, which result in savings on the material costs. Secondly, the production shows potential for higher automation if a certain production volume is reached. Fewer processing steps and a simpler manufacturing technology facilitate the production of large-area modules. (EPIA and Greenpeace, 2004;EPIA, 2004;Surek, 2005;U.S. Department of Energy: Energy efficiency and renewable energy, 2005;van der Zwaan and Rabl, 2003)

At the moment, however, thin-film technology has substantially lower cell efficiency figures than silicon-wafer cells and lacks experience in the lifetime performance of the modules. Commercially available modules have their efficiencies around 10% (EPIA and Greenpeace, 2004;Jager-Waldau and Ossenbrink, 2004), although in laboratory conditions cell efficiencies verging on 20% have been obtained.

Different thin-film technologies have been developed using various semiconductor materials. These include silicon in an amorphous form and polycrystalline metal-semiconductor compounds such as copper indium diselenide and cadmium telluride. All of these thin-film technologies have been commercialized. Thin-film polycrystalline silicon is also a promising alternative which may be entering the market soon.

Amorphous silicon was the first thin-film material to enter commercial use, and in 2003 had a share of 4.5% of the total market (EPIA and Greenpeace, 2004). The amorphous silicon technology relies on a simple and standardized manufacturing process, where integrated modules are made on hard and flexible substrates. Amorphous silicon differs from crystalline silicon by not having a crystal structure. This disorder results in the gradual degradation of the cell by exposure to light. Stabilized efficiencies remain low, at 6-8% (Surek, 2005). Amorphous silicon cells are improved by stacking multiple cells into a tandem or triple structure together with silicon germanium alloys. (Alsema, 1996;Andersson and Jacobsson, 2000;Chopra *et al*, 2004;U.S. Department of Energy: Energy efficiency and renewable energy, 2005)

Copper indium diselenide (CIS) has been recently introduced to the market. Prototype cells achieve efficiencies of more than 13% and the highest recorded efficiency in the laboratory is 18.4% (Green *et al*, 2005). Nonetheless, in the long term the scarce supply of indium may make it difficult to implement CIS technology on a large scale: it has been estimated that if all known resources of the world's supply of indium were converted into solar cells overnight, they could generate only 1% of the present world's electricity requirements over their operating life. (Green, 2000;Green, 2000)

Cadmium telluride (CdTe) works particularly well in solar cells because of its optoelectronic and chemical properties. The CdTe device structure characteristics provide the potential for high-efficiency modules with low-cost manufacturing processes. The highest cell efficiency achieved is 16.5% (Green *et al*, 2005). However, CdTe research and sales have been hampered by the lack of public acceptance of a PV product based on toxic material on what is fundamentally a 'green' market. (Chopra *et al*, 2004;Green, 2000;Green, 2003;U.S. Department of Energy: Energy efficiency and renewable energy, 2005)

Recent development in thin-film technology has introduced the concept of thin-film polycrystalline silicon deposited directly onto glass substrates. Thin-film silicon is considered a very promising approach as it combines the low cost of thin films with the high efficiency and established durability of crystalline silicon. The thin-film silicon layer can be made 100-200 times thinner than traditional crystalline silicon and still achieve cell efficiencies of some 10%. (Basore, 2003;Green, 2003;U.S. Department of Energy: Energy efficiency and renewable energy, 2005)

1.2.3 Multijunction cells and new concepts

Much research is also being conducted on third generation high-efficiency solar cells. High efficiency in this context refers to energy conversion values that double or triple the currently targeted range of 15-20%. Single-junction solar cells have an upper efficiency limit of 33%, but the thermodynamic limit of sunlight conversion is 87% (Jager-Waldau and Ossenbrink, 2004;Kurokawa, 2003). In pursuing high efficiencies, the fundamental concepts in the design of third-generation photovoltaics are changed: attention is drawn to heat losses and the structural properties of semiconductors. (Green, 2001)

Multijunction cells have already proven that cell efficiencies can be enhanced beyond single junction limits. The efficiency in multijunction cells is increased by stacking several solar cells on top of one another, and can reach values above 35%. However, using multiple cells together makes the system more complex and significantly increases costs. To save solar cell material, the multijunction cells are generally used with concentrated sunlight focused on a small area. (Green, 2001;Jager-Waldau and Ossenbrink, 2004) Multijunction modules are common in space applications but are at present too expensive for terrestrial use.

Other solar cells concepts capable of very high efficiencies have also been suggested, namely quantum dots, hot carrier cells, up/down converters, and thermophotovoltaic conversion. Quantum dots can generate electricity from a wide spectrum which is not limited to visible light. Hot carrier cells seek to avoid the loss from thermalisation of carriers in order to enhance the voltages generated. With up/down converters, the incident spectrum is modified to make better use of the coming irradiation. Thermophotovoltaic conversion uses an intermediate emitter brought close to the solar cell to gain greater energy transfer at relatively low operating temperatures. These approaches may profit from future improvements in the material engineering area (Green, 2001;Jager-Waldau and Ossenbrink, 2004;UNSW,). However, they are currently studied at the cell-level and have a long way to go until they can be utilized in large-area PV modules.

Organic cells are a novel PV technology based on materials such as dyes and polymers instead of the inorganic semiconductor materials used in most solar cells. Organic materials are appealing because their chemical properties can be adapted to needs and they show potential for being manufactured inexpensively. Their main constraints are their low efficiency (less than 3%) and stability issues (Chopra *et al*, 2004;Kurokawa, 2003).

Dye-sensitized solar cells are organic solar cells whose operating principles bear similarities to photosynthesis. They use a dye-impregnated layer of nanocrystalline metal oxides such as titanium dioxide to generate a voltage. Because titanium dioxide is relatively inexpensive, it offers the potential to significantly cut the cost of solar cells. Cell efficiencies generally remain low, but a promising record value of 8.2% has been obtained in laboratory conditions (Green *et al*, 2005). Furthermore, dye-sensitized cells make possible to produce transparent modules based on infrared absorbing dyes. (Gordon, 2001;U.S. Department of Energy: Energy efficiency and renewable energy, 2005;WADE, 2003) While some prototype large-area organic modules have been demonstrated, a number of unresolved issues still remain in scaling up these PV technologies from cells to modules.

1.2.4 PV systems

A PV system consists of solar cell modules and balance-of-system (BOS) equipment, such as cabling and interconnection components, an inverter, a support structure and protective devices, depending on the use. The modules act as the electrical conversion device and the BOS components take care of the other essential functions involved in the electricity production and use. The PV module itself can function properly for decades whereas the BOS components require maintenance as some of them have to be replaced every 5 to 10 years. (IEA, 2003;Ross and Royer, 1999)

Most PV systems are flat-plate with fixed orientation: they collect solar energy directly on the module and remain static. However, the intensity of solar radiation changes during the day as the Earth rotates around the sun. To consider this, a structure called tracker can be used to direct the module towards the sun by automatically adjusting the tilt and / or orientation of the module with one or two axes. The sun tracking can increase the yield by more than 25% with two axes, although the equipment and maintenance costs will be elevated as well. (PV-TRAC, 2005;Ross and Royer, 1999)

Another kind of PV system is the concentrator system which differs from flat-plates in that it uses lenses or reflectors as well as sun tracking to focus sunlight onto a small-area multijunction solar cell. The required amount of PV material is thus reduced, whereas the cell efficiencies can reach 30% (Surek, 2005). However, the concentrator lens and its assembly as well as the multijunction solar cell have proven to be more expensive than the saved area of PV material. (PV-TRAC, 2005)

A PV system can either be grid-connected or stand-alone. When applied for distributed generation, the grid-connected PV systems complement well the grid as they can feed any excess power during the daylight hours into the local electricity network, and at other times electricity can be imported from the grid. In contrast, stand-alone PV systems are completely independent of the grid and can provide electricity for rural and remote areas. The segmentation of PV applications into grid-connected and off-grid is presented in Figure 3: it can be clearly seen that grid-connected photovoltaics has steadily grown to dominate the market.

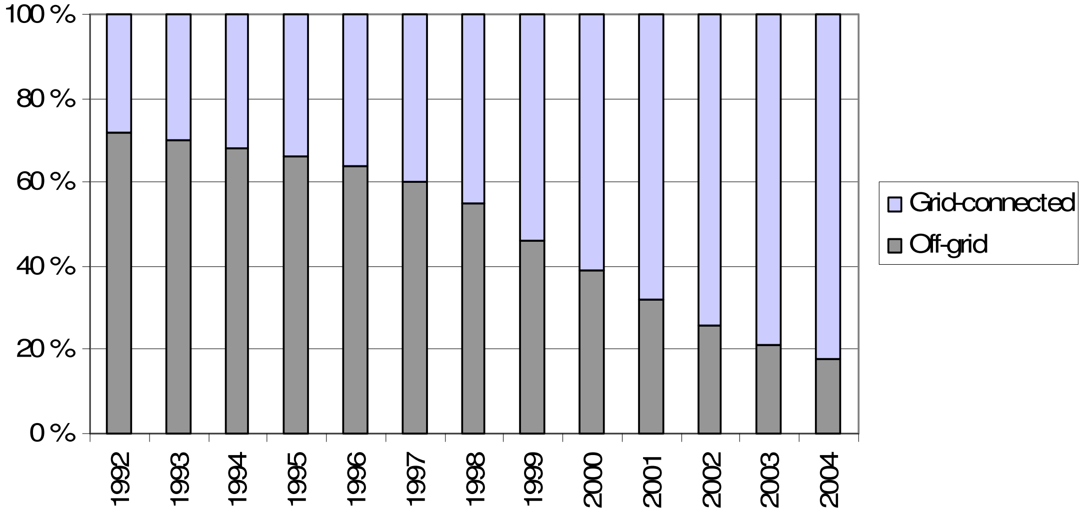

Figure 3. Percentages of grid-connected and off-grid PV power in IEA countries (IEA, 2005)

Grid-connected and stand-alone PV systems differ also in their size. Grid-connected PV systems range typically from medium to large scale in electricity production; the largest grid-connected PV systems reach the size of several megawatts. In contrast, stand-alone systems are much smaller, generating from a few milliwatts up to several kilowatts of power (PV-TRAC, 2005). In addition to this, stand-alone PV systems are not suitable for large-scale electricity production because of storage problems and the inflexibility of the system.

A possibility for PV system siting is to integrate the panels into buildings: on roofs, facades, or shadowing elements. Building-integrated photovoltaics (BIPV) offer three main benefits. Firstly, it eliminates the need for land acquisition and mounting constructions. Secondly, it ensures that the electricity generator is very close to the end-user, potentially reducing transmission and distribution losses. Thirdly, they can replace conventional cladding materials and protect the building from the weather. This improves their cost-efficiency remarkably, as the cost of the cladding function can be deducted as an avoided cost. The panels are designed to fit in our living environment in a way that minimizes their visual impact. (EPIA, 2004;Kaan and Reijenga, 2004;Oliver and Jackson, 2000)

According to PV-TRAC, grid-connected PV systems “have the biggest potential to make a substantial contribution, in quantitative terms, to the sustainable energy supply in Europe.” (PV-TRAC, 2005) The report envisions central PV power plants spread out on dedicated areas and solar panels installed on buildings in urban, densely populated areas. Another option for using grid-connected PV systems is investigated by the IEA: large-scale systems in desert areas. (Kurokawa, 2003)

1.2.5 Future Photovoltaic Trends

The PV industry has for a long time been expected to make a transition from crystalline silicon towards thin-film technologies. However, crystalline silicon wafer-based technology has got a strong hold of the PV market, as can be seen from Figure 4. It can therefore be expected that silicon wafers will continue to dominate for at least the next 10 years. (Arya, 2004;Green, 2001) The cost benefits of thin-film technology are expected to manifest themselves when thin-film PV production capacity passes some critical threshold in factory size. Presently thin-film PV production is below this limit, but the expanding PV market may eventually shift the competitive benefit toward thin-films.

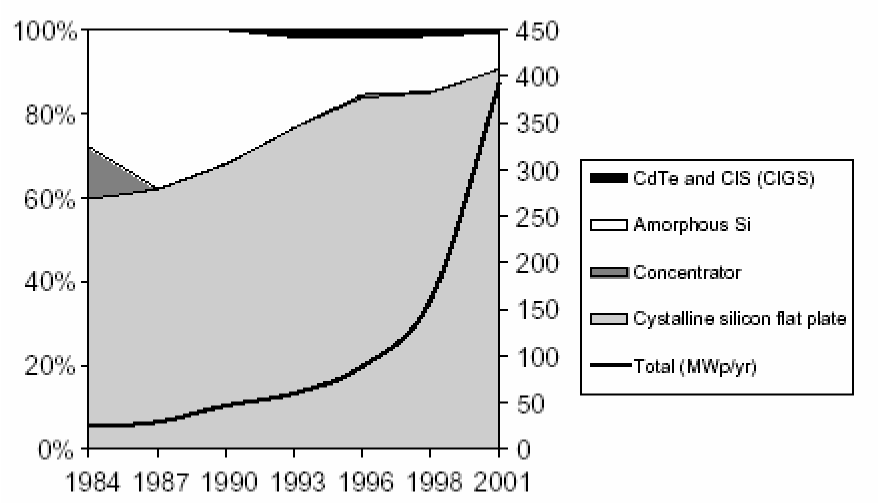

Figure 4. PV market growth—crystalline silicon dominates the market. Left scale and areas: The market shares of competing PV technologies. Right scale and line: total annual PV production (MWp/yr). (Sanden, 2005)

The predicted development trends of different PV technologies are presented in Figure 5. Besides cell efficiencies, other factors have been considered as well, such as the maturity of the technology in terms of its degree of industrialization (Hoffmann, 2001). The currently studied organic dye cells are far from commercial use but may bring cost reductions in the long term if they can be successfully translated to large-area modules. As for the silicon technologies, thin-film silicon is a particular favorite among experts, combining the assets of both crystalline silicon and thin-film technologies. (Green, 2000)

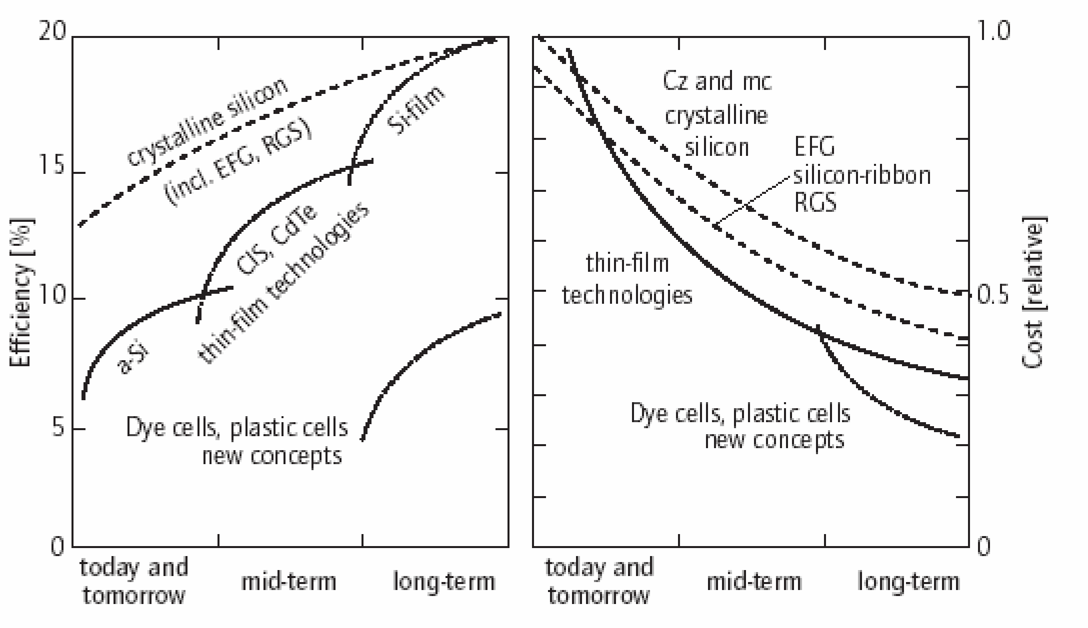

Figure 5. A conceptual road map for photovoltaic cell technology (Hoffmann, 2001)

1.3 Present Photovoltaic Market

In recent years, the PV industry has developed from small scale manufacturing to a mass-producing industry. The major obstacle still facing the PV industry is the price of photovoltaics, which does not encourage their uptake for common applications. In order to fight for its market share the PV industry has to focus on improving its competitiveness and developing more efficient manufacturing processes and conversion devices. Governments can also encourage the uptake of photovoltaics. (Jäger-Waldau, 2003;PV-TRAC, 2005)

After a slow start, the world PV market has been growing at an average annual rate of more than 30% for the past few years (EUREC, 2005;EurObserv'ER, 2005;Jäger-Waldau, 2003). The upswing in the market has been driven by market stimulation as well as extensive research over the last decade. Japan in particular has taken a leap in module shipments and technological development efforts, followed by the United States and Europe. Government-subsidized, grid-connected, residential rooftop programs worldwide have also contributed to PV’s recent success. (Green, 2003;Kurokawa, 2003;PV-TRAC, 2005)

By the end of 2003, the total installed capacity of PV systems exceeded 2,400 MWp (EPIA and Greenpeace, 2004), with 700 MWp of module power sold worldwide during 2003 (EPIA, 2004). The solar electricity industry was worth more than an annual 3 billion € in 2004 (EPIA and Greenpeace, 2004). The worldwide PV cell and module production is presented in Figure 6.

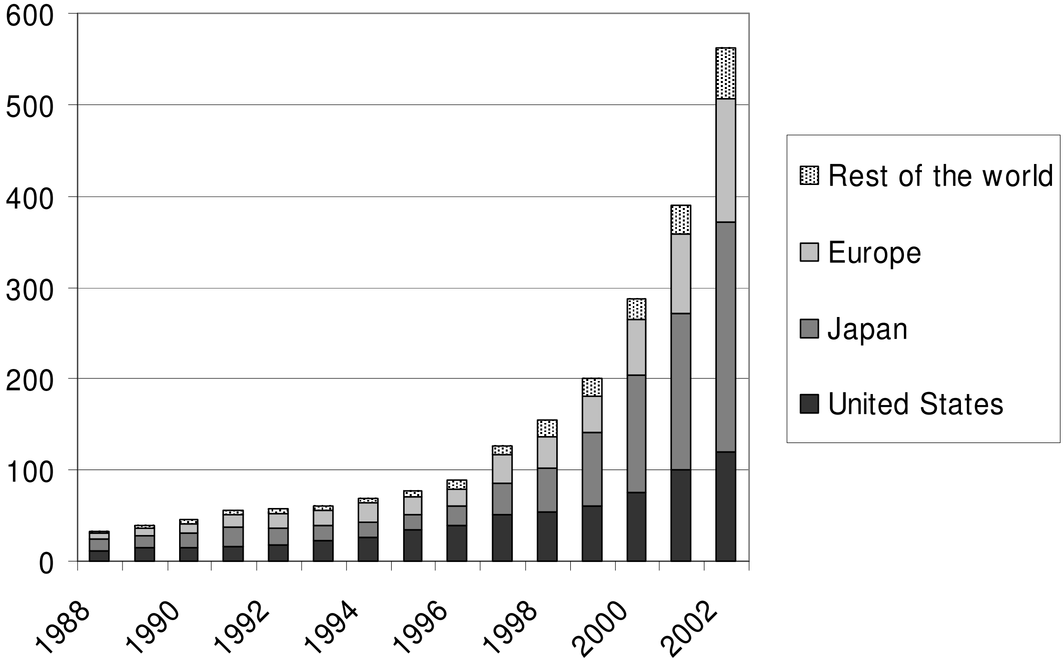

Figure 6. Worldwide PV cell/module production (MW) (Jäger-Waldau, 2003)

At the same time as the PV market has been growing substantially, the cost of PV electricity has decreased. The current total system cost for crystalline silicon lies in the range of 3-8 €/Wp and for thin-film between 2 and 7 €/Wp, depending on the supplier, country, type and size of the system. Based on the learning curve analysis, the cost of PV is expected to decrease some 20% every time the total installed capacity is doubled. This would lead to electricity price dropping by half by 2015 and falling to less than 1 €/Wp in the long term. (EPIA and Greenpeace, 2004;PV-TRAC, 2005;van der Zwaan and Rabl, 2004;WADE, 2003)

The high cost of electricity generation results mainly from the PV system itself, since there are few additional costs. Roughly 60% of installation costs are represented by the module, 15% by the inverter and 25% by the BOS components and the assembly of the unit. As for the additional costs, the operation and maintenance costs have the potential to be minimal as very little upkeep is required. However, at present, maintenance costs can reach 1% of capital investment per year (WADE, 2003).

Research and development efforts are trying to bring down the price of the PV system by using less material and energy. The building integrated PV system cost development curve is presented in Figure 7 and it shows a clear trend of cost reduction, although not as steep as the increase in module production of Figure 6. As the manufacturing costs fall at a rate of about 5% annually over the last two decades, the PV costs become more and more dominated by those of the constituent materials. (EPIA and Greenpeace, 2004;Green, 2001)

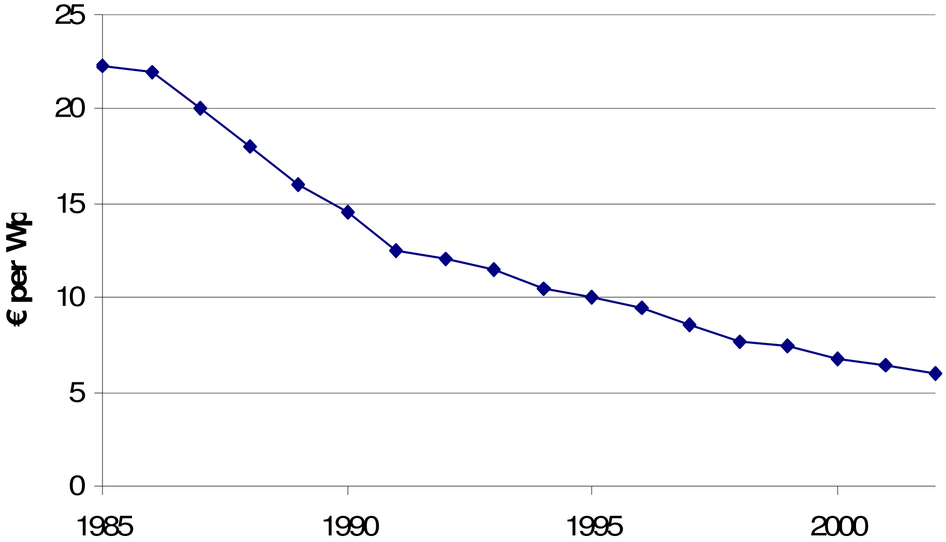

Figure 7. Building integrated PV system cost development (€/Wp) (IEA, 2003)

PV technology still faces economic and institutional barriers. Apart from high capital costs, PV suffers to some extent from immature products and service delivery chains. In relation to potential consumers there remains a lack of information, expertise and standards. The general attitude towards PV electricity is characterized by a reluctance to pay extra for solar electricity since the added value is not appreciated enough when environmental externalities are not included. (IEA, 2005;Watt, 2001)

On the institutional level, PV-related policies are often inconsistent. The governments could, however, promote the uptake of PV electricity by lowering the barriers hindering their development. Already several Western countries recognize the importance of PV technology and express this by frequently providing financial support for PV systems. As the systems are not yet cost-competitive, financial incentives must be implemented in order to start a process of self-sustained growth. More specifically, policy measures could encourage the construction of grid-connected PV systems and sustain variety in solar cells to hold back the short-sighted turns in the market. (Andersson and Jacobsson, 2000;Kaan and Reijenga, 2004;United States Photovoltaics Industry, 2003;van der Zwaan and Rabl, 2004)

In terms of employment, the PV industry creates a number of job opportunities as workforce is needed in manufacturing and installation. Currently, the worldwide solar electricity industry provides jobs for 35,000 people. The opening of new PV facilities can result in about 20 jobs per MWp of capacity. In addition, tasks in wholesale, retail, installation and maintenance services provide another 30 jobs per MW of installed capacity. (EPIA, 2004;Pearce, 2002)

1.4 Future Development

Photovoltaics is a small energy source today, but it has potential to grow significantly larger by the year 2030. Future growth will depend on energy policy decisions and technological development. Changes in the PV industry could be large and predictions of future development therefore contain a considerable amount of uncertainty. At the present time crystalline silicon technologies dominate the photovoltaic market. The other commercialized technology is thin-film photovoltaics which includes diverse module types, each with its own benefits and drawbacks. In general, the best thin-film photovoltaic technologies can be expected to pass crystalline silicon in market share at some point before 2030. This development will be mainly due to upscaling of production capacity, since large-scale manufacturing captures the benefits of thin-film technology. Many experimental photovoltaic concepts with potential for very high efficiencies or very cheap production costs are also being developed in laboratory-scale processes today. It is not possible to estimate the potential of these technologies for large-scale electricity production yet, because no large-area modules have been demonstrated and several open questions remain.

The price of photovoltaic electricity in sunny locations such as Spain has been projected to drop from about 0.3 € / kWh today to 0.1 € / kWh in 2020 and < 1 € / kWh by 2030. In less sunny locations such as Germany, the price would be approximately double. (EPIA, 2004). Improved efficiency will be an important component of reduced price. It can be expected that module efficiencies will improve from 10–15% today to 15–25% by 2030. Larger manufacturing volumes will also contribute to reducing unit price. Numerical values for energy, ecology and economy are presented in Appendix B. The CO_2 emissions of photovoltaic electricity depend only on the energy expended in the manufacturing process. In Appendix B, it has assumed that the energy mix remains constant. In this case, CO_2 emissions per kWh depend on the efficiencies and market shares of the different PV technologies. Assumptions regarding market share development are stated in the Appendix.

References

Alsema,E.A. 1996. Environmental aspects of solar cell modules. 96074. Department of Science, Technology and Society, Utrecht University, Utrecht, the Netherlands

Alsema,E.A., Baumann,A.E. and Hill,R., et al. 1997. Health, safety and environmental issues in thin-film manufacturing. 97052. 14th European PV Solar Energy Conference, Barcelona, Spain

Alsema,E. and Nieuwlaar,E. 1997. Environmental aspects of PV power systems. 97072. IEA PVPS Task 1 Workshop, Utrecht, the Netherlands

Andersson,B.A. and Jacobsson,S. 2000. Monitoring and assessing technology choice: the case of solar cells. Energy Policy Vol 28:14, 1037-1049

Arya,R.R. 2004. Technology and market challenges to mainstream thin-film photovoltaic modules and applications. Arya International, Inc., Williamsburg, VA, USA

Basore,P.A. 2003. Large-area deposition for crystalline silicon on glass modules. Pacific Solar Pty Limited, Sydney, Australia

Battisti,R. and Corrado,A. 2005. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. Energy Vol 30:7, 952-967

Burnham,L., Johansson,T.B. and Kelly,H., et al. 1993. Renewable energy - sources for fuel and electricity. Island Press, Washington, D.C., United States

Chopra,K.L., Paulson,P.D. and Dutta,V. 2004. Thin-film solar cells: an overview. Progress in Photovoltaics: Research and Applications Vol 12:2-3, 69-92

EPIA. 2004. EPIA Roadmap. European Photovoltaic Industry Association, Brussels, Belgium

EPIA and Greenpeace. 2004. Solar generation - Solar electricity for over 1 billion people and 2 million jobs by 2020. European Photovoltaic Industry Association & Greenpeace International

EUREC. 2005. FP7 Research priorities for the renewable energy sector. European Renewable Energy Centres Agency, Brussels, Belgium

EurObserv'ER. 2005. Photovoltaic energy barometer. European Commission

Frankl,P., Corrado,A. and Lombardelli,S. 2004. Photovoltaic (PV) systems, final report ECLIPSE. European Commission

Fthenakis,V.M. 2004. Overview of potential PV hazards. Brookhaven National Laboratory; Energy Research Centre of the Netherlands; Utrecht University

Gordon,J. 2001. Solar energy - the state of the art. James & James Ltd, UK

Green,M.A. 2001. Third generation photovoltaics: ultra-high conversion efficiency at low cost. Progress in Photovoltaics: Research and Applications Vol 9, 123-135

2000. The future of crystalline silicon solar cells. Progress in Photovoltaics: Research and Applications Vol 8:1, 127-139

Green,M.A., Emery,K. and King,D.L*.,* *et al*. 2005. Solar cell efficiency tables (version 26). Progress in Photovoltaics: Research and Applications :13, 387-392

Green,M.A. 2003. Crystalline and thin-film silicon solar cells: state of the art and future potential. Solar Energy Vol 74:3, 181-192

2000. Silicon solar cells: at the crossroads. Progress in Photovoltaics: Research and Applications Vol 8, 443-450

Hoffmann,W. 2001. PV solar electricity: one among the new millennium industries. RWE Schott, 17th European Photovoltaic Solar Energy Conference, Munich, Germany

IEA. 2005. Trends in photovoltaic applications - Survey report of selected IEA countries between 1992 and 2004. T1-14:2005. International Energy Agency, Switzerland

2003. Renewables for power generation - Status and prospects. International Energy Agency

Jäger-Waldau,A. 2003. Research, solar cell production and market implementation in Japan, USA and the European Union. European Commission, Institution for Environment and Sustainability, Ispra, Italia

Jager-Waldau,A. and Ossenbrink,H. 2004. Progress of electricity from biomass, wind and photovoltaics in the European Union. Renewable and Sustainable Energy Reviews Vol 8:2, 157-182

Kaan,H. and Reijenga,T. 2004. Photovoltaics in an architectural context. Progress in Photovoltaics: Research and Applications Vol 12, 395-408

Kurokawa,K. 2003. Energy from the desert: Feasibility of very large scale photovoltaic power generation (VLS-PV) systems. James & James Ltd, Hong Kong

Oliver,M. and Jackson,T. 2000. The evolution of economic and environmental cost for crystalline silicon photovoltaics. Energy Policy Vol 28:14, 1011-1021

Pearce,J.M. 2002. Photovoltaics -- a path to sustainable futures. Futures Vol 34:7, 663-674

Phylipsen,G.J.M. and Alsema,E.A. 1995. Environmental life-cycle assessment of multicrystalline silicon solar cell modules. 95057. Department of Science, Technology and Society, Utrecht University

PV-TRAC. 2005. A vision for photovoltaic technology. European Commission, Brussels

Realini,A. 2003. Photovoltaics lasts: you can depend on it! Scuola Universitaria Professionale della Svizzera Italiana, Canobbio

Ross,M. and Royer,J. 1999. Photovoltaics in cold climates. James & James Ltd, Malta

Sanden,B.A. 2005. The economic and institutional rationale of PV subsidies. Solar Energy Vol 78:2, 137-146

Sørensen,B. 2000. Renewable energy: Its physics, engineering, use, environmental impacts, economy and planning aspects. Academic Press, Great Britain

Surek,T. 2005. Crystal growth and materials research in photovoltaics: progress and challenges. Journal of Crystal Growth Vol 275:1-2, 292-304

U.S. Department of Energy: Energy efficiency and renewable energy. 2005. Photovoltaics.

United States Photovoltaics Industry. 2003. Solar electric power - the U.S. photovoltaic industry roadmap. National Renewable Energy Laboratory

UNSW. 2005. Third generation photovoltaics. http://www.pv.unsw.edu.au/Research/3gp.asp

van der Zwaan,B. and Rabl,A. 2004. The learning potential of photovoltaics: implications for energy policy. Energy Policy Vol 32:13, 1545-1554

2003. Prospects for PV: a learning curve analysis. Solar Energy Vol 74:1, 19-31

WADE. 2003. Guide to decentralized energy technologies. World Alliance for Decentralized Energy, Edinburgh, Great Britain

Watt,M. 2001. Added values of photovoltaic power systems. IEA-PVPS, Australia

Appendix A

Tables

Energy:

1) Range of unit size and project size [MW]	Module size: 50-500 Wp Project size: 0.0005-10 MWp
2) Nominal efficiency [%]	
i) For electricity generation only	Crystalline silicon modules: 11-14 Amorphous silicon modules: 5-7 CIS thin-film modules: 7-9
ii) For combined heat and power	-
3) Efficiency at partial load	N.A.
4) Flexibility towards fuel, fuel resource availability, plant siting and infrastructures	Access to solar resource
5) Flexibility towards exploitation:	
i) Cold start [minutes from 0% to 90% of nominal power]	PV output varies directly with the level of solar irradiation
ii) Warm/lukewarm start [minutes from 0% to 90% of nominal power]	-
iii) Uncontrollable variation in load [% from nominal power]	-

Ecology and resource use:

	Crystalline silicon system[1]	Thin-film amorphous silicon system[2]	Thin-film CIGS system[3]
1) Exhaust [tons/$MWh_{electricity}$]			
i) CO_2	0.0483	0.0419	0.0425
ii) SO_2	0.0000100	0.00000883	0.00000587
iii) NO_x	0.0000954	0.0000907	0.00000477
iv) PM_{10}	0.00000565	0.00000223	0.00000415
v) NMVOC	0.0000158	0.0000106	0.0000107
vi) Methane	0.000114	0.0000769	0.0000828
vii) N_2O	0.000000420	0.000000426	0.000000163
viii) C_{14} *[kBq/kWh]*	0.000416	0.000197	0.000300
ix) Heavy metals [most important ones, $g/MWh_{electricity}$*]*	0.0169	0.0092	0.0125
2) Thermal exhaust [TJ/$GWh_{electricity}$]			
i) Into air	-	-	-
ii) Into water source	-	-	-
3) Liquid waste [tons/$MWh_{electricity}$]			
i) Total liquid waste	0.00130	0.00224	0.0028
ii) Total nitrogen into water source	0.0000000913	0.0000000353	0.000000124
iii) Total phosphor into water source	0.00000000103	0.00000000195	0.00000000127
iv) Total chlorides into water source	0.00000729	0.00000344	0
v) Total sulfates into water source	0.000178	0.000133	0.00015
vi) Others ($KMnO_4$*, iron, organic materials, solid*	Iron 0.0000163	Iron 0.00000581	iron 0.0000108

---

[1] The crystalline silicon system referred to in the ecology and resource use figures is a retrofit roof system in Central Italy, with peak power of 1 kWp, module efficiency of 10.7%, and lifespan of 25 years. The module is made of glass-tedlar with an aluminium frame. Regarding the electricity needed for the production of the PV systems and related emissions, an average of the production mix in certain European countries has been used. {{76}}

[2] The figures for the thin-film amorphous silicon system are from a retrofit tilted roof system with aluminium frame in Central Italy, with peak power of 1kWp, module efficiency of 6%, and lifespan of 20 years.

[3] The figures for the thin-film CIGS system are from a retrofit tilted roof system with aluminium frame in Central Italy, with peak power of 1 kWp, module efficiency of 9%, and lifespan of 20 years.

materials)	Solid waste 0.000051	Solid waste 0.000149	solid waste 0.00019
4) Solid waste [tons/MWh$_{electricity}$]			
i) Flue dust	0.00000371	0.000000261	0.0000000119
ii) Slurry	N.A.	N.A.	N.A.
iii) Hazardous waste	0.000000304	0.000000580	0.000000367
iv) Radioactive waste	0.0000000000939	0.00000000000294	0.00000000000335
v) Other solid waste	Total: 0.00634	Total: 0.00700	Total: 0.00442
5) Safety and health impacts			
i) Population affected by worst perceived accident during operation [nr of persons]	N.A.		
ii) Number of deaths over the fuel cycle [persons/MWh$_{electricity}$]	-		
iii) Other effects			
6) Visual impact and noise	No noise		
7) Footprint and use of resources			
i) Primary material moved for construction [tons/MW$_p$ of nominal power]	36,900	15,600	24,200
ii) Secondary material moved for construction [tons/MW$_p$ of nominal power]	0.000000134	0.0000000545	0.572
iii) Main materials uses for construction (five) [tons/MW$_p$ of nominal power]	1. coal 406 2. lignite 286 3. bauxite 139 4. iron 99 5. sand 66	1. bauxite 228 2. coal 220 3. iron 165 4. lignite 140 5. sand 122	1. coal 267 2. lignite 184 3. sand 161 4. bauxite 145 5. iron 113
iv) Primarily material moved for usage e.g. fuel [tons/ MWh$_{electricity}$]	-	-	-
v) Secondary material moved for usage e.g. fuel [tons/ MWh$_{electricity}$]	-	-	-
vi) Critical materials in construction and usage (materials that may become a limiting factor for the technology) [tons/MW$_p$ of nominal power]	1. silver 0.0762		1. selenium 0.254 2. indium 0.0828 3. cadmium 0.0013

Economy (without subsidies, price level for 2003):

1) Investment cost [euro/MW]	Crystalline silicon systems: 4-10 €/Wp Amorphous silicon and CIS systems: 3-6 €/Wp
2) Availability [hours per year]	Circa 50%
3) Operational time [hours of nominal power/year]	Depends on the site, about 800 to 2000 in the EU
4) Reliability [%]	95-100% {{13}}
5) Technical life span [years]	Crystalline silicon systems: 40-50 Amorphous silicon and CIS systems: 30
6) Construction time [years]	< 1
7) Fuel cost [euro/MJ]	-
8) Operation and Maintenance (O&M) cost [euro/MWh$_{electricity}$]	1% of capital investment per year or less {{15}}
9) Waste handling and dismantling [euro/ MWh$_{electricity}$]	N.A.

Appendix B

Calculated with assumptions:

1. The market share of thin-film PV technologies grows linearly from 5% today to 90% by 2030
2. Average crystalline silicon module efficiencies improve linearly from 14% today to 24% by 2030
3. Average thin-film module efficiencies improve linearly from 7–9% today to 15% by 2030
4. Resource use for producing one module remains constant

Table B1.

§ Energy:

	2010	2020	2030
1) Range of unit size and project size [MW]	Unit: 0.00005 – 0.0005 Project: 0.0005 – 15	Unit: 0.0001 – 0.001 Project: 0.001 – 25	Unit:0.0001–0.002 Project: 0.002 – 40
2) Nominal efficiency			
i) For electricity generation only [%]	10–15	15–25	15–25
ii) For combined heat and power [%]	n.a.	n.a.	n.a.

§ Ecology and resource use:

1) Exhaust:			
i) CO_2 [kg/kWh$_{electricity}$]	0.041212	0.031878	0.025754
ii) SO_2 [kg/kWh$_{electricity}$]	8.27E-06	5.9E-06	4.14E-06
iii) NO_x [kg/kWh$_{electricity}$]	7.45E-05	4.42E-05	1.9E-05
iv) PM_{10} [kg/kWh$_{electricity}$]	4.65E-06	3.37E-06	2.43E-06
v) NMVOC [kg/kWh$_{electricity}$]	1.31E-05	9.46E-06	6.82E-06

vi) Methane [kg/kWh$_{electricity}$*]*	9.49E-05	6.96E-05	5.16E-05
vii) N_2O [kg/kWh$_{electricity}$*]*	3.42E-07	2.31E-07	1.45E-07
viii) C_{14} [kg/kWh$_{electricity}$*]*	0.000343	0.000249	0.00018
ix) Heavy metals [most important ones, g/kWh$_{electricity}$*]*	0.014018	0.010245	0.007535
2) Thermal exhaust [TJ/GWh$_{electricity}$]			
i) Into air	–	–	–
ii) Into water source	–	–	–
3) Liquid waste			
i) Total liquid waste [kg/kWh$_{electricity}$*]*	0.001298	0.001329	0.001477
ii) Total nitrogen into water source [kg/kWh$_{electricity}$*]*	8.04E-08	6.82E-08	6.26E-08
iii) Total phosphor into water source [kg/kWh$_{electricity}$*]*	9.48E-10	8.33E-10	7.96E-10
iv) Total chlorides into water source [kg/kWh$_{electricity}$*]*	5.54E-06	3.07E-06	9.82E-07
v) Total sulfates into water source [kg/kWh$_{electricity}$*]*	0.000151	0.000115	9.02E-05
vi) Others ($KMnO_4$, iron, organic materials, solid materials)	7.36E-05	8.47E-05	0.000103
4) Solid waste [tons/MWh$_{electricity}$]			
i) Flue dust	2.77E-06	1.48E-06	3.68E-07
ii) Slurry	N.A.	N.A.	N.A.
iii) Hazardous waste	2.79E-07	2.44E-07	2.32E-07
iv) Radioactive waste	7.02E-11	3.79E-11	1.02E-11
v) Other solid waste	Total: 0.005356	Total: 0.003993	Total: 0.003041
5) Safety and health impacts			
i) Population affected by worst perceived accident during operation [nr of persons]	N.A.		
ii) Number of deaths over the fuel cycle [persons/MWh$_{electricity}$*]*	N.A.		
iii) Other effects	N.A.		
6) Visual impact and noise	No noise		
7) Footprint and use of resources			
i) Primary material moved for construction [kg/kW$_p$ *of nominal power*	30171.94	21343.95	14768.63

ii) Secondary material moved for construction [kg/kW$_p$ of nominal power	0.051887	0.139277	0.235529
iii) Main materials uses for construction (five) [kg/kW$_p$ of nominal power]	1.coal 334 2. lignite 234 3. bauxite 124 4. iron 90 5. sand 68	1. coal 238 2. lignite 166 3. bauxite 104 4. iron 76 5. sand 73	1. coal 167 2. lignite 115 3. bauxite 93 4. sand 83 5. iron 71
iv) Primarily material moved for usage e.g. fuel [tons/ MWh$_{electricity}$]	–	–	–
v) Secondary material moved for usage e.g. fuel [tons/ MWh$_{electricity}$]	–	–	–
vi) Critical materials in construction and usage (materials that may become a limiting factor for the technology) [kg/kW$_p$ of nominal power]	Crystalline silicon: Silver 0.067 Thin films: Selenium 0.222 Indium 0.072 Cadmium 0.001	Crystalline silicon: Silver 0.053 Thin films: Selenium 0.178 Indium 0.058 Cadmium 0.001	Crystalline silicon: Silver 0.044 Thin films: Selenium 0.148 Indium 0.048

- Economy (without subsidies, price level for 2003):

1) Investment cost [euro/MW]	2.5 – 7 x 10^6	1.5 – 4 x 10^6	1 – 2 x 10^6
2) Availability [hours per year]	4380	4380	4380
3) Operational time [hours of nominal power/year]	800–2000	800–2000	800–2000
4) Reliability [%]	95–100%	95–100%	95–100%
5) Technical life span [years]	40	50	60
6) Construction time [years]	< 1	< 1	< 1
7) Fuel cost [euro/MJ]	–	–	–
8) Operation and Maintenance (O&M) cost	1% or less of capital	1% or less of capital	1% or less of

[euro/MWh$_{\text{electricity}}$]	investment	investment	capital investment
9) Waste handling and dismantling [euro/ MWh$_{\text{electricity}}$]	–	–	–