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Motivation for Photovoltaic Application and Development

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Photovoltaics is the technological symbol for a future sustainable energy supply system in many countries. A considerable amount of money is invested in research, development and demonstration; several governments set up substantial market introduction programs and industry invests in larger production facilities. No other renewable energy technology receives such a strong appreciation by the public and to an increasing extent also by the politicians and the industrial and financial sectors. This is a remarkable situation since at the same time photovoltaic (PV) electricity is regarded as much too expensive compared to conventional grid electricity. The high and justified recognition of photovoltaics may be understood on the basis of a description of the main positive features of this kind of solar electricity conversion.

2.1 CHARACTERISTICS OF PHOTOVOLTAIC ENERGY CONVERSION

Photovoltaics aims at two areas of application. One is the power supply for off-grid professional devices and supply systems (e.g. telecommunication equipment, solar home systems) and the other is large-scale electricity generation as a substitute for and a complement to today's non-sustainable energy processes. With respect to the latter, the global potential of PV electricity is of key importance. Figure 2.1 shows the technical and the theoretical potential of several renewable energy sources. The theoretical potential does not take into account land use restrictions, conversion efficiencies, storage requirements and so on. The technical potential on the other hand must not be confused with short-term economic potentials, since price situations and capital requirements for activating these energy sources on a large scale are not considered.

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Resource	Current use	Technical potential	Theoretical potential
Hydropower	9	50	147
Biomass energy	50	>276	2900
Solar energy	0.1	>1575	3 900 000
Wind energy	0.12	640	6000

Units: exajoule per year

Figure 2.1 Current use and current potentials of selected renewable energy sources [1]. For comparison: global primary energy demand 402 exajoule/annum (1998). The electricity part of "current use" has been converted to primary energy utilising an efficiency factor of 0.385

Nevertheless, two important conclusions may be drawn from Figure 2.1: (1) even under strong area restrictions (e.g. utilisation of a small percentage of the land area) and guarded assumptions of overall technical efficiencies, solar energy conversion alone could in principle produce considerably more technical energy than is consumed today and (2) compared to other renewable sources, solar radiation is by far the largest. A sustainable global energy system that is strongly based on renewable sources will in the long run mainly be a solar energy system. With respect to the technology of solar electricity production, this means solar thermal power plants and photovoltaics. The application of thermal power plants is restricted to areas with high and direct insulation; flat-plate (standard) PV modules may be applied practically everywhere in the world since they convert diffuse and direct (beam) radiation with approximately the same efficiency.

Photovoltaic energy conversion meets the important requirements of a sustainable energy production in an obvious way. During operation there is no harmful emission or transformation of matter (generation of pollutants), nor any production of noise or other by-products. PV energy conversion is a technologically elegant one-step process avoiding conventional thermodynamic or mechanical intermediate steps. On the other hand, production of PV modules and system components will – as any industrial device production – include material transformation and the production of wastes. Thus, it is extremely important to realise PV conversion technologies that comply with the requirements of environmentally benign production schemes.

Though characterised by the high global potential given in Figure 2.1, the area-specific power density of solar radiation is relatively low, that is, approximately 100 W/m^2 on the average. This means that the global harvesting of solar resources necessarily requires a large-area production of energy converters. Appropriate recycling strategies will thus be essential for the energy-relevant application of photovoltaics. Already today standard silicon-wafer PV-technology meets in principle the requirements with respect to recycling and sustainable production.

Photovoltaic energy conversion is highly modular. Installations may vary between milliwatts for consumer products (watches) to megawatts in the case of grid-connected power plants. From a market point of view, this gives rise to a broad variety of PV applications. For the professional energy supply business, modularity is especially important with respect to the development of electricity supply systems in many rural and remote areas where grid extension is economically not feasible. Starting from low power installations, PV modules may be gradually added to suitable systems in order to cope with the growing energy demands. In this way electricity supplies can be realised avoiding too high initial investments. In the context of rural electrification and also for the professional energy supply of off-grid electronic devices, the low maintenance characteristic of photovoltaics is regarded as a considerable advantage. The absence of moving parts, the robustness against harsh environment and the lack of fuel supply requirements (exception: hybrid systems) make photovoltaics a well-suited energy supply technique for a vast area of stand-alone energy supplies.

Another positive characteristic of PV is that it may be seen as part of the rapidly growing semiconductor industry/market. This relation facilitates a strong technology transfer from a mature industry to the emerging PV industry. Parallel to this the affinity opens the prospect of new big industries creating considerable business and employment opportunities.

The strong market growth of photovoltaics over the last two decades (Figure 2.2) and the high recognition of this technology could not be understood if there had not been a continuous and strong reduction in PV system and module prices.

Figure 2.3 shows the price-experience curve (learning curve) until 2000. Each doubling of the module shipment resulted on the average in a market price reduction of 20%. It is generally accepted that it is possible to cut down the prices by another factor of two utilising mass production lines based on today's crystalline silicon-wafer technology. Considerable further cost reduction seems feasible since new and most probably least costly PV technologies are already in the state of pilot production (thin-film cells) or under investigation in laboratories: cells based on III/V materials and optical concentration, cells using dyes or organic compounds for energy conversion and so on. Thus, there is a good

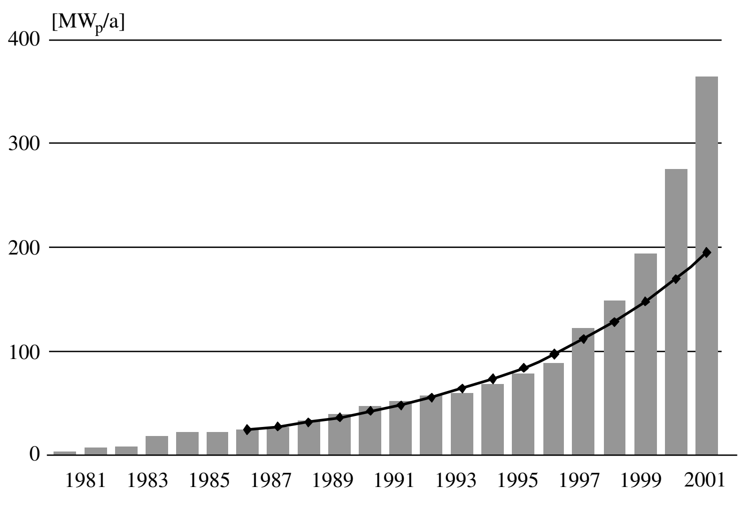

Figure 2.2 Evolution of the global photovoltaic market [2]. Until 1996 the growth rate was approximately 15%/annum. Today's growth rates are in the order of 30%/annum

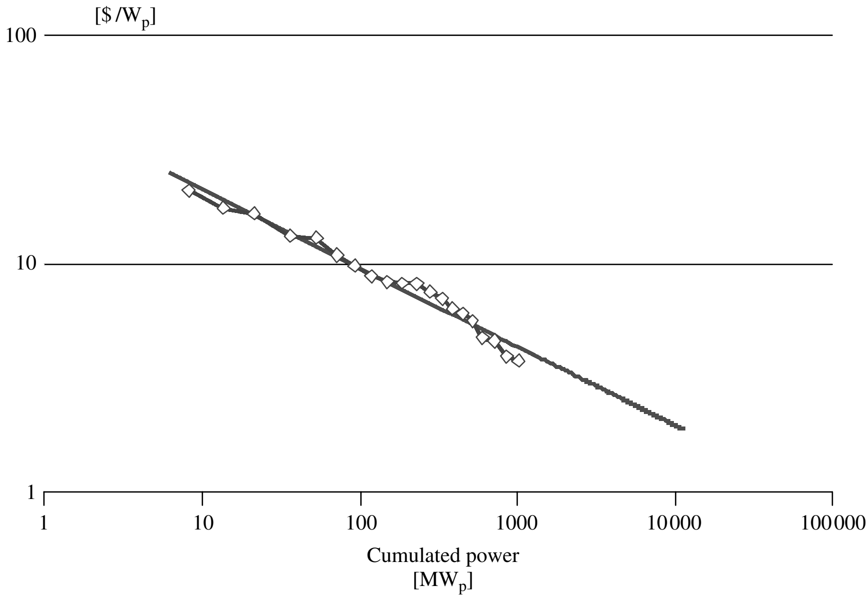

Figure 2.3 Price-experience curve of the photovoltaic market until 2000 [2]. Scale: double logarithmic. The slope of the curve is characterised by a factor $f = 0.8$. This means that a doubling of the photovoltaic shipment resulted in a price reduction down to 80%

chance of at least a break even between PV electricity and conventional electricity prices, given that the external (social) costs of non-sustainable electricity are properly taken into account.

2.2 A LONG-TERM SUBSTITUTE FOR TODAY'S CONVENTIONAL ELECTRICITY PRODUCTION – THE ECOLOGICAL DIMENSION OF PHOTOVOLTAICS

A sustainable development has to respect certain guard rails. With respect to the energy supply system, these are mainly determined by the global warming/CO_2 problem (Figure 2.4). A global warming of more than 2°C (with respect to the pre-industrialised period) and a warming rate of 0.2°C per decade seems to be the upper limits for a development that may be kept under control. These settings are in accordance with the results of recent studies of the International Panel on Climate Change [3].

Since preservation and expansion and especially the transformation of energy systems require important investments, a strategy of large stopping-distances seems reasonable. For example, the German Advisory Council on Global Change proposes a continuous CO_2 reduction rate of 1% per year over the next 150 years [3]. If one strives for a fair and rational distribution of the worldwide reduction obligations, the highly industrialised nations have to reduce their CO_2 emissions until 2050 by almost 80% relative to the 1990 level [3]. This reduction mainly affects the energy sector including fuels for transportation.

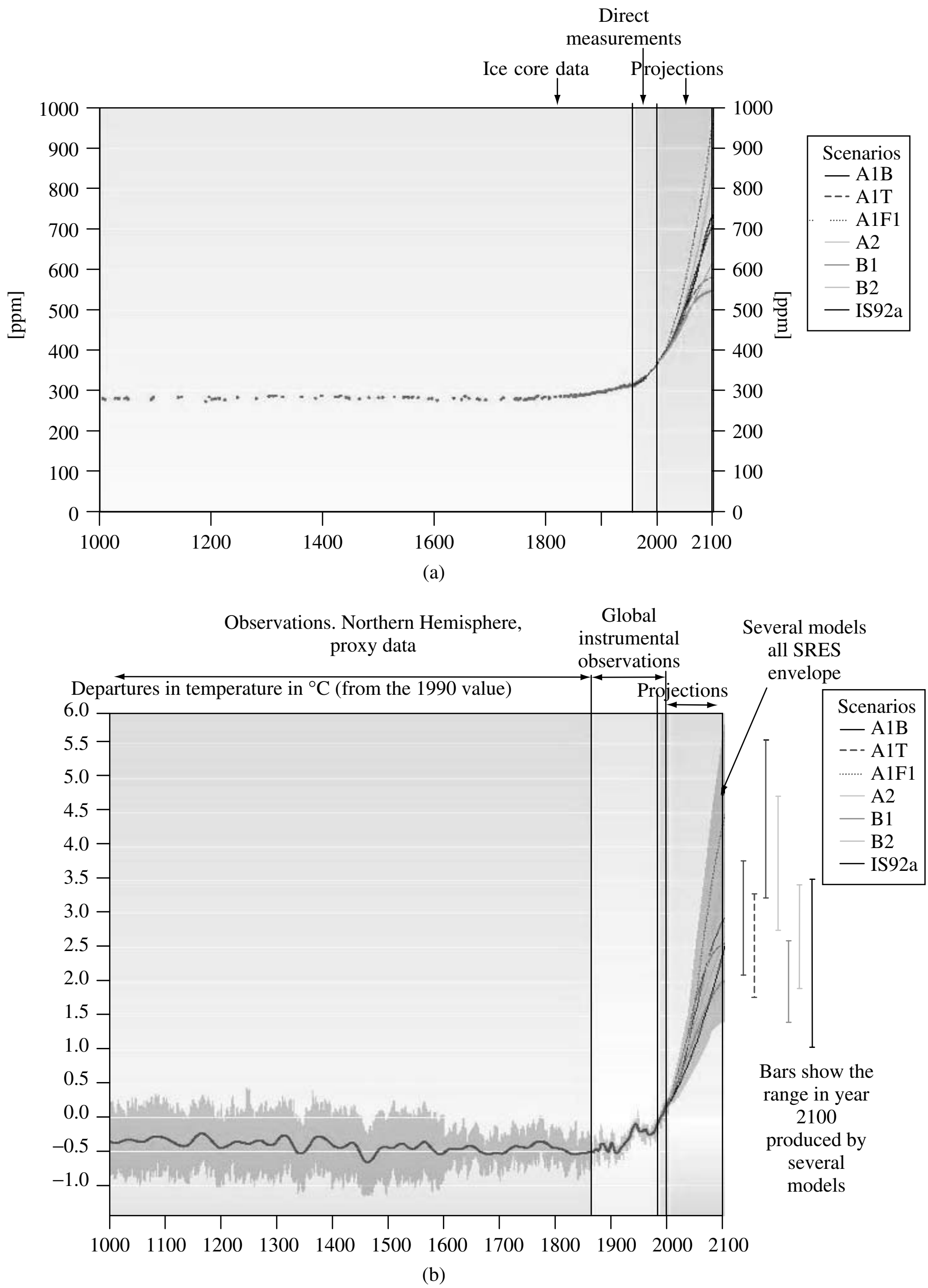

Figure 2.4 Past and future CO_2 atmospheric concentrations (a) and variations of the Earth's surface temperature (b). Time span: year 1000 to year 2100. The projections on the right sides are based on scenarios of the Intergovernmental Panel on Climate Change (IPCC) [4]. Reproduced by permission of Cambridge University Press

As far as can be seen today, such reduction goals may – in a socially acceptable way – only be realised if renewable energy technologies are applied worldwide on a really large scale. For electricity production, this means above all the use of photovoltaics and to a lesser (but important) extent wind energy, biomass conversion and solar thermal power plants. Thus, the principal ecological dimension of photovoltaics is extremely high. The question arises of course whether we can activate this potential in due time. With respect to this, at least two sub-problems have to be addressed: (1) how fast can the industry produce the required large-area PV energy conversion systems and (2) is it possible to establish a strong long-lasting market-driving mechanism that conforms with today's ideas of a competitive market.

During the last few years, annual market growth rates and thus the increase in industrial PV production have been in the order of 15 to 30% (Figure 2.2). The main drivers behind this impressive growth are several governments and consumers who see an urgent need for a transformation of today's energy systems towards sustainability [5–7]. Financial-support mechanisms have been developed that include clear components of competition inside well-defined areas of energy supply technologies. The financial support is justified by the high potential of PV electricity and its ecologically benign character. On the other hand, such schemes have to be limited in time, which is especially important if the promoted markets evolve exponentially. Thus, the question arises whether grid-coupled PV electricity will become cost-effective within reasonable time frames. Figure 2.5 shows a cost projection of base-load, peak-load and photovoltaic electricity.

The assessment is based on an extrapolation of the prize experience curve given in Figure 2.3, a PV-market growth rate of 20%/annum and an increase of conventional electricity costs by 2% per year. Under these assumptions, a break even between peak load and

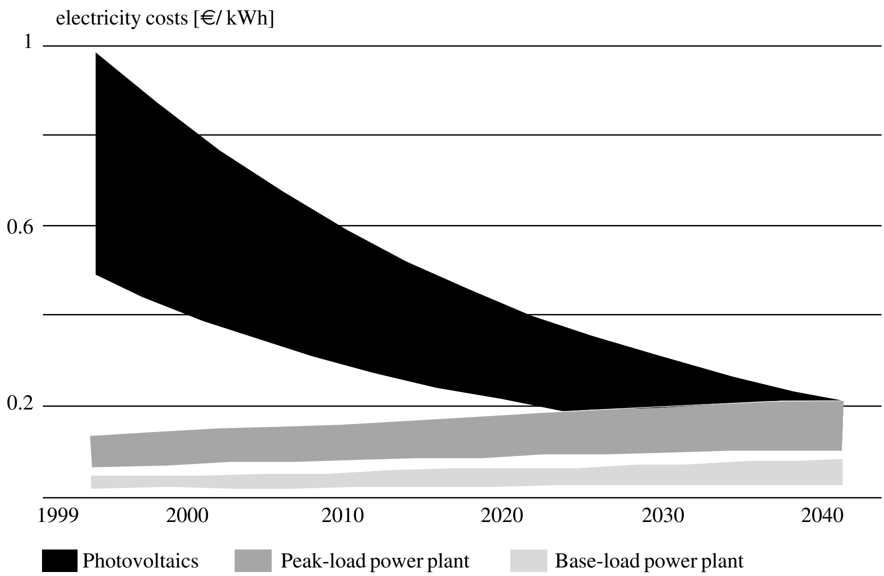

Figure 2.5 Cost projections for photovoltaic electricity. The upper boundary of photovoltaic costs reflects the meteorological situation of Germany, the lower boundary that of Southern Europe [8]

solar electricity is found around 2025; a break even with costs from conventional base-load power plants is not reached in the first half of this century.

The extrapolation of a prize experience curve over several decades bears, of course, a considerable risk. On the other hand, there are good technological arguments that the price-experience curve will continue to decrease in a similar way as in the past for a considerable time span; a strong reduction in the slope of the curve most probably will not be encountered before a further price reduction by a factor of 3 to 5 is reached. It is important (and essential) to mention that most probably this statement is also valid for the balance of system components such as power electronics and so on.

Many conclusions may be drawn from a graph such as that given in Figure 2.5 (based partly on an arbitrary set of parameters). If one aims, for example, at an efficient transformation of today's electricity supply system, one may propose an energy tax on environmentally and socially non-benign energy sources in order to establish competitive market situations at a significantly earlier time. This tax could be based on the internalisation of external costs of the different competing energy supply technologies. In order to allow for a smooth evolution towards sustainability, such a tax should be introduced gradually. If one assumes, for example, a continuous additional tax-induced cost increase of electricity from conventional peak- and base-load power plants of 2% per year, the break even in Figure 2.5 for peak load would occur around 2015 and that for base load around 2030. The public income from such an energy tax could be invested in research and development in the field of renewable energies and in energy efficiency measures. This would support, for example, the continuity of cost reduction of photovoltaics (Figure 2.3) as well as the reduction of the gross energy demand and thus of the energy-related financial burdens.

From an industrial point of view, a strong evolution of PV electricity generation could produce an interesting global market. A long-term price-experience factor $f = 0.82$ (see caption to Figure 2.3) and a market growth rate of 20% per year would generate, for example, the following global markets for PV-modules: 2010 2×10^9 €, 2020 9×10^9 € and 2030 30×10^9 € [8]. The additional market for system components and integration will probably be of the same order. The prospects of such substantial markets are the motivation of today's considerable industrial investments in PV production capacities.

It has been shown so far that if it is possible to maintain a price-experience evolution as shown in Figure 2.3 and if governments adopt a serious energy tax strategy, electricity from photovoltaics may become cost-effective between approximately 2015 (peak power) and 2030 (bulk power). Attractive high-technology markets could develop in the near future. One question still to be answered is 'when will photovoltaics contribute considerably to the global electricity generation?'

In a speculative way, this question may be addressed by stipulating conceivable long-term growth rates for PV electricity generation (Figure 2.6). Rates of 26%/annum results in a growth factor of 10 over one decade. Starting at present-days low level it will – even under these conditions – take at least three to four decades for photovoltaics to contribute in a substantial way to the global electricity demand (for rural electrification see Section 2.3). After this starting period, photovoltaics can become one main supplier of electric energy in the future energy mix. Growth rates of 15% per year on the other hand produce just a growth factor of four over one decade; under such conditions, photovoltaics

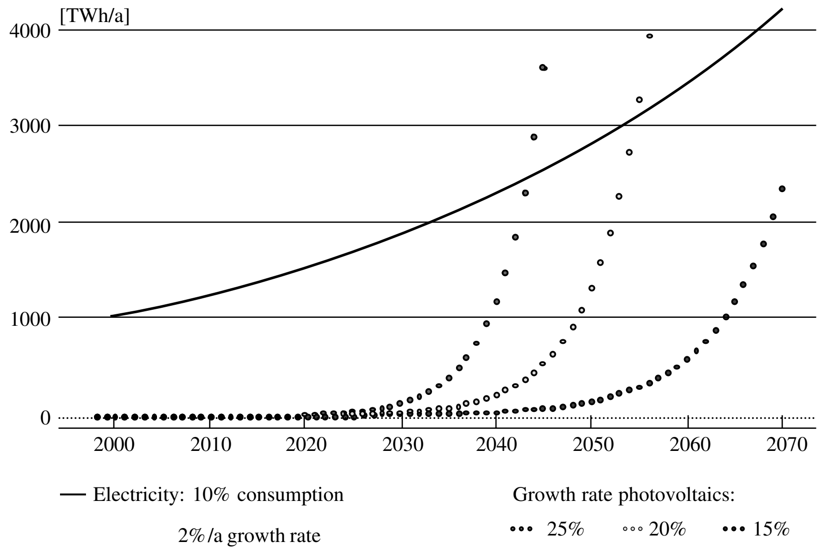

Figure 2.6 Scenarios of global photovoltaic electricity production under the assumption of constant growth rates of 25%/annum, 20%/annum and 15%/annum. The solid curve represents 10% of the global electricity demand assuming a constant growth rate of 2%/annum. A linear scale is used for the energy axis. Thus, although growing exponentially, the energy production by means of photovoltaics is not visible on the scale used until the year 2020

may become a major player only in the second half of our century. Since the man-made climatic problems call for a fast and forceful solution that is both environmentally benign and socially acceptable, high and continuously high growth rates for photovoltaics are extremely advisable.

The liberalisation of the energy market has led to new and innovative concepts, especially in the electricity sector. One of these is the distributed generation scheme – kilowatt to several megawatt installations instead of central units in the gigawatt range. Its main advantages are dispersed on-site heat and power cogeneration, electrical stabilisation of grids especially at the low voltage level, distributed reserves in the case of supply problems and partly favourable investment situations. PV electricity generation is well adapted to the distributed generation scheme (Figure 2.7). This is especially the case if peak-load conditions in the grids are considered that are strongly correlated with solar insolation: cooling and climatisation units. Also, the extreme modularity of photovoltaics turns out to be advantageous for distributed generation. Distributed peak power production will be most probably the first energy market application for optical concentrator PV power stations.

If performed on a continental or even intercontinental level, the highly dispersed application of photovoltaics will also lead to a strong levelling out of its stochastic local power generation characteristics. The remaining slowly varying time pattern of the lumped electricity production (diurnal, seasonal variations) can be compensated (of course, at extra costs) by the control of complementary electricity sources or in the long run by means of storage technologies.

Figure 2.7 Distributed power generation by means of photovoltaics. The roof-integrated photovoltaic system has a peak power of 5 kW

Another area that should be highlighted separately is façade- and roof-integrated grid-coupled photovoltaics. If done in an aesthetically promising way, PV claddings may substitute prestigious building elements. These applications may become the first mass market for homogeneous-looking thin-film PV modules. Even if the area-related investment costs of a PV building element is higher than the cost of conventional high-end elements, the electricity generated and the benefit of architectural double uses (Figure 2.8) may compensate for this difference within a reasonable time.

Figure 2.8 Photovoltaic integration into the glazing of a shed roof. In this case, photovoltaic cells serve also as optical shading elements for the space below, preventing overheating under summer conditions

2.2.1 In Summary

The technical potential of PV electricity is high enough to contribute considerably to the abatement of the man-made global CO_2 problem. With the help of medium-term financial supports and long-term energy taxes (motivated by external costs), the technical potential may be exploited economically. Under grid-coupled operation, photovoltaics will most probably become cost-effective for distributed peak power production and for applications in the building sector (as cladding element). Solar electricity generation has to grow by three orders of magnitude before it encounters a (extrapolated) 10% level of the global electricity demand. Assuming ambitious growth rates, this process of transformation will take three to four decades.

2.3 A TECHNOLOGICAL BASIS FOR OFF-GRID ELECTRICITY SUPPLY – THE DEVELOPMENT DIMENSION OF PHOTOVOLTAICS

Two billion people worldwide have no access to commercial electricity. When possible, they cover their needs for electricity-based services by means of primary batteries, rechargeable batteries (car batteries) or small fossil fuel–driven generator sets. In many (if not in most) cases these supply schemes are very costly, uncomfortable, unreliable and ecologically questionable. This results in the fact that for a large fraction of the global population, services such as electric light, radio, television, telecommunication, health services, clean water, cooling, electromechanical energy and so on are not at all available or are available only at a very low level. It must be stressed that these electricity-based benefits are amongst others crucial for education, business and small commercial activities (handicrafts, agriculture, food processing etc.). Thus the lack of a stable and affordable electricity supply hinders the development of many rural and remote areas. This is ethically not acceptable; it may lead to a destabilisation of regions and foster the growth of megacities, just to name three important reasons why this situation cannot be regarded as socially sustainable.

Beyond the low power level of primary batteries, there are mainly three worldwide applicable technology groups that are able to contribute in a professional way to the electricity supply of remote areas: grid extension, diesel generator sets and renewable energies. The most prominent amongst the renewables are small hydro, wind and photovoltaics. All technologies mentioned will eventually contribute to the electricity supply of rural and remote areas.

At first sight, grid extensions seem to be the most natural and technologically elegant way to overcome shortages in the electricity supply. It turns out, however, that the initial investments for such a strategy are prohibitively high if the consumers are scattered over large areas and if the average electricity demand, that is, the energy transported over the lines, is relatively small. Under these situations it is mostly impossible to recover the investments by selling electricity to the dispersed consumers or to raise it through subsidies from governmental organisations.

The alternatives to grid extension are renewables and diesel electric systems. In the following text, the benefits and characteristics of photovoltaics will be discussed.

Off-grid PV energy supply characteristics

- High reliability
- High lifetime
- Low maintenance
- No fuel required
- Favourable extensibility (modularity)
- Easy to transport (modularity)
- Suitable for harsh environmental conditions
- Suitable for mobile energy supply
- Environmentally benign (no waste, noise, fuel transports)

Figure 2.9 Characteristics of off-grid photovoltaic energy supply systems

Figure 2.9 summarises some of the salient features of photovoltaics for off-grid electricity supply. The main disadvantage of PV systems is the comparatively high initial investments. Diesel systems on the other hand produce relatively low initial investments but high running costs especially due to fuel requirements.

Off-grid electricity supply systems generally need energy storages. In the case of diesels these are the fuel tanks, and in PV systems electrochemical batteries are applied. Especially because of this fact, solar electric systems are not maintenance-free (though their behaviour with respect to maintenance and wear is generally significantly more favourable than it is for diesel systems). For reliable operation, the storage battery has to be exchanged at regular intervals. Figure 2.10 indicates clearly that at present it is not the PV module but the system electronics (including installation) and the storage devices that constitute the main lifetime cost factors. Thus research and development in the fields of system technology and solar batteries would be highly supportive for an accelerated introduction of PV off-grid systems worldwide.

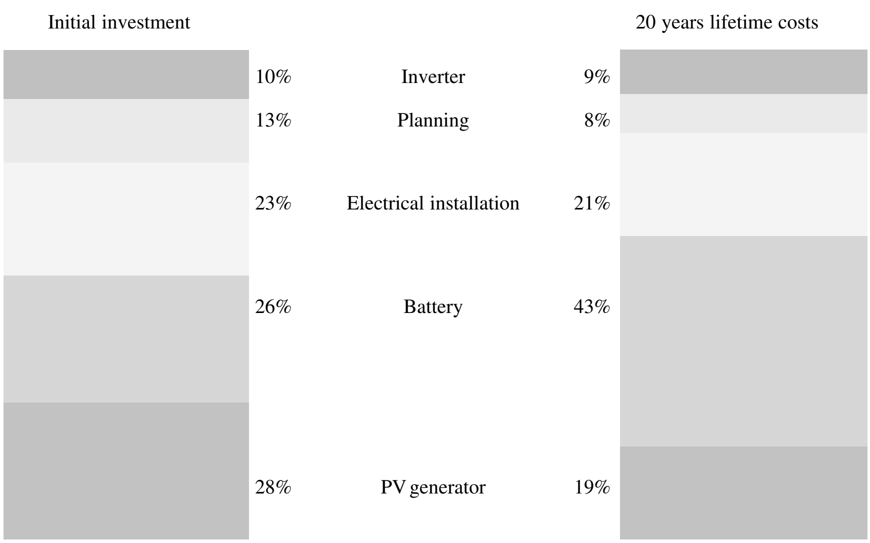

Figure 2.10 Initial versus lifetime costs of small professional autonomous photovoltaic systems – a typical example. System data: PV 1.3 kW_p, battery 35 kWh, battery lifetime 5.4 a, loss of load probability 0.1%, system site Mexico

At present, the main applications of photovoltaics in rural and remote areas are (1) photovoltaic (car-) battery-charging stations where the charged battery is transported to the electricity consumer, (2) photovoltaic solar home systems for the energy supply of electric lights, radios and simple television sets and (3) photovoltaic powered pumping stations for water supply for human requirements and agricultural irrigation.

In particular, the solar home systems have to be highlighted. As might have become clear from the above discussion, they present today in many cases the technical and economic optimal solution for a basic electrification in the areas under discussion. The market volume is in the order of 400 000 systems a year. System prices show increasingly favourable values (Figure 2.11).

The main barriers to a further accelerated introduction of these technologies into practice are non-technological in character. Appropriate financing schemes, social integration, training of engineers and trade and industry structures have to be developed and efficiently integrated into the societies. Photovoltaics may then become one of the main pillars of rural electrification. A market volume of 15 to 30 GW per year is expected in 10 to 20 years [8].

It has already been mentioned that modularity is one of the important characteristics of photovoltaics. In principle, solar home systems may be upgraded step by step. In suitable cases it will be possible to interconnect the individual systems to form PV village power supplies. Besides the social management of such structures, a prerequisite for their widespread applications is the development and industrial production of appropriate power electronics, load management devices and information schemes. For larger installations, hybrid systems (e.g. diesel/photovoltaic) may dominate the market in the near future. It is also conceivable that village power systems may be interconnected by transmission lines or even connected to the main (possibly weak) grids. All these measures increase the complexity and most probably also the cost of such systems. On the other hand, because of technical redundancies and load levelling effects, the performance of such advanced PV-based electricity supply systems could increase considerably.

	Price (US \$)	Price (%)	Lifetime (years)
PV-module (53 W) and support	200	47	>20
Battery (70 Ah)	40	9	4
Battery charge controller	35	8	10
Lamps, wiring, switches	35	8	5
Delivery, installation, retail margins	75	18	-
Duties and taxes	40	10	-
Total	425	100	

Figure 2.11 Cost break down of a typical solar home system

Off-grid PV electricity supply is by no means restricted to the rural areas of developing countries. Mountain lodges, remotely situated farms, holiday houses and so on represent a considerable market for PV energy supply also in industrialised countries. Such installations may be connected to the central grid as well. In these cases photovoltaics serves as a back-up electricity supply in case of line failure or unreliable electricity supply from the utility side.

2.3.1 In Summary

Photovoltaics is an excellently suitable solution for low power electricity supply in rural and remote areas in developing countries. Photovoltaics have a similar but smaller market in industrialised countries as well. In total, one-third of today's world population could benefit from off-grid PV installations. System electronics and storage batteries have to be further developed in order to address the market in an optimal way. Financial engineering, social integration of the new technology, training and the installation of an appropriate trade and industrial infrastructure are the most important prerequisites for a successful worldwide implementation of off-grid PV electricity supplies.

2.4 POWER SUPPLY FOR INDUSTRIAL SYSTEMS AND PRODUCTS – THE PROFESSIONAL LOW POWER DIMENSION

This segment of PV application comprises the electricity supply of consumer products, professional industrial systems and remote low power systems. In this area, photovoltaics substitutes or complements the traditional power supply via batteries or small fossil fuel motor generator sets. The average power demand, especially in the area of consumer products and professional systems, lies generally in the power range of several milliwatts to 100 W. On the other hand, a mass market of billions of units may be envisaged gaining market volumes in the 10-GW range in several decades [8]. The drivers of these markets are strong technological innovations in the field of telecommunication, dispersed electronic intelligence and remote sensors/actuators and so on (Figures 2.12. and 2.13).

Such equipments need small amounts of electric energy for operation and standby. Even if the electric grid is ready-to-hand, wireless and maintenance-free systems are generally preferred by the users. Maintenance-free here means that costly primary batteries with limited energy content can be avoided. In many cases photovoltaics may enter this field of energy supply (1) if the devices are at least temporarily under illumination and (2) if suitable storage devices are applicable. Thus the availability of small and efficient storages (rechargeable batteries, capacitors) is a prerequisite for a widespread application of PV cells in this area.

In this market segment there is a wide range of specific requirements for PV cells. Communication equipment like mobile phones being characterised by low surface area and relatively high energy demand call for high efficiency (e.g. 20%) solar cells; wrist watches on the other hand can be powered by PV cells having only some percentage of efficiency. PV car roofs need aesthetically optimised precision products, while powering a last mile repeater for telecommunication links may be done with small standard PV

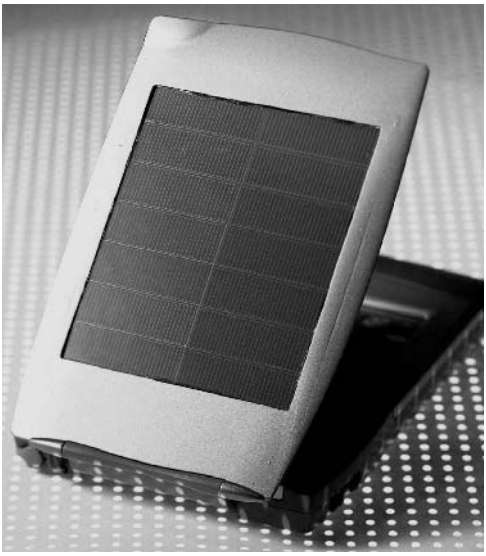

Figure 2.12 Personal digital assistant powered by high efficient silicon solar cells. Module efficiency at one sun >20%; efficiency at 1/100 sun, 17%

Figure 2.13 Autonomous emergency phone and information system using photovoltaic power supply

modules. The optimal integration of PV cells into the surface of electronic devices may ask for flexible, geometrically tailored or even coloured components.

Especially for indoor applications it is essential to have light-energy converters with high conversion efficiencies at low illumination levels.

These diverse and partly conflicting requirements will result in the development of different types of PV converters, well suited to the individual applications. Dye or organic solar cells may find their first application in such market segments.

2.5 POWER FOR SPACECRAFT AND SATELLITES – THE EXTRATERRESTRIAL DIMENSION OF PHOTOVOLTAICS

The power supply of satellites has been the first professional application of photovoltaics (Vanguard I, 1958). While at the beginning military activities have been in the foreground of space power supply, today commercial activities play an important role as well: powering satellites for telecommunication, remote sensing, navigation and so on.

In these obviously off-grid applications, PV power supplies are more or less without technological competitors. Thus, solar electric systems of this kind would have been

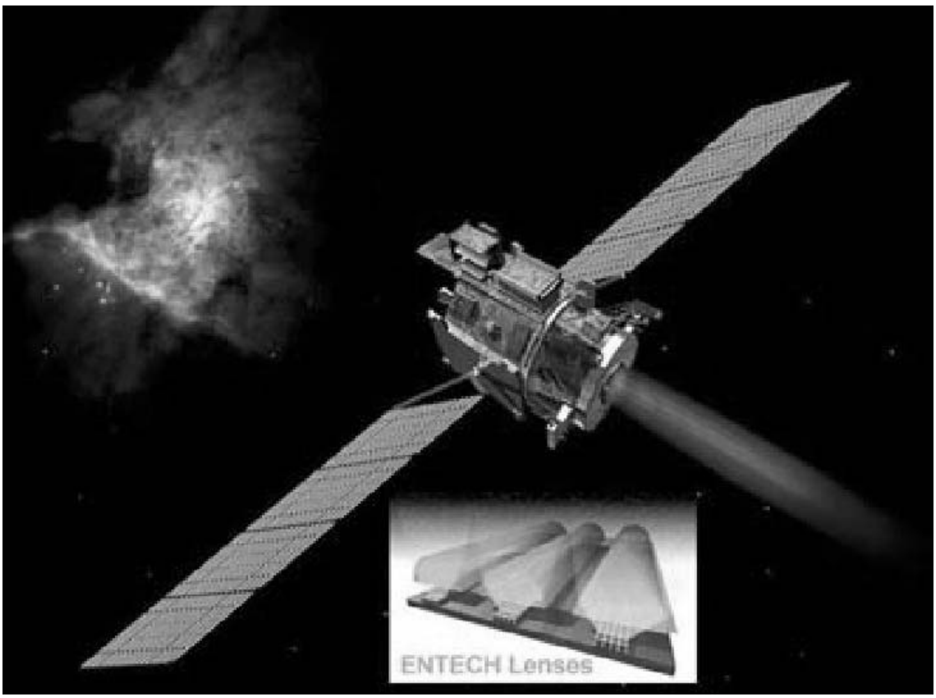

Figure 2.14 Artists view of the "Scarlet Deep Space One Satellite". The satellite is equipped with triple-junction GaInP/GaAs/Ge photovoltaic cells. For the first time, optical concentration was applied with III/V space cells. Courtesy of NASA/JPL/Caltech

successfully developed even without the terrestrial market addressed above. On the other hand, the parallel (but partly deferred) evolution of space and terrestrial photovoltaics has led to many fruitful and essential cross-stimulations.

Solar modules for space applications (Figure 2.14) have to meet other and mostly more stringent requirements than terrestrial devices such as lowest weight and highest efficiency, extremely high reliability, high resistivity against extraterrestrial particle radiation (high lifetime) and spectral sensitivity that is well matched to the extraterrestrial solar spectrum.

Photovoltaic modules meeting corresponding standards have been realised in a relatively short time span. This success was based on many ingenious inventions and on the fact that cost reduction has not been the most important issue in the first decade of satellite technology. Thus, space photovoltaics became, at least initially, the technological breeder for today's silicon-wafer-based terrestrial solar cell technology.

A similar technology fertilisation might occur again: About one-half of today's space solar cells are already made from GaAs and related compound semiconductors (Figure 2.14). Such solar cells exhibit considerable higher efficiencies and lifetimes than Silicon cells. There is a realistic chance that these space-proven technologies become the basis for a new class of solar cells having light conversion efficiencies in the range of 40 or even 50%. Besides advanced flat-plate solar modules such solar cells, in conjunction with optical concentrators, constitute a strong technological option for future terrestrial large-scale electricity generation.

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