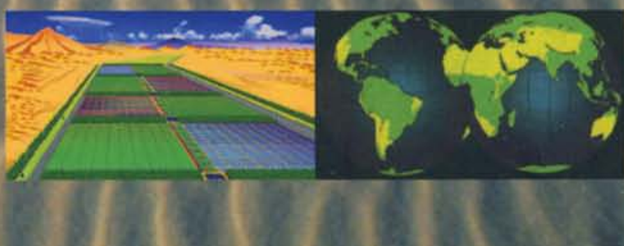
Energy from the Desert

Feasibility of Very Large Scale Photovoltaic Power Generation (VLS-PV) Systems



EDITOR Kosuke Kurokawa

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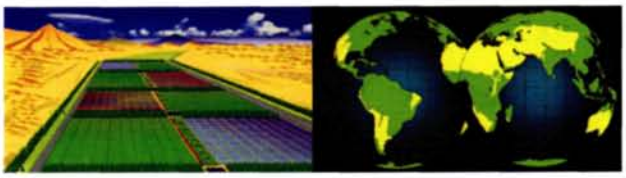

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Contents

Foreword

The International Energy Agency's Photovoltaic Power Systems Programme, IEA PVPS, is pleased to publish this study on very large-scale photovoltaic (VLS-PV) systems.

VLS-PV systems have been proposed on different occasions and they may also represent a controversial theme. The present market focus is indeed on small-scale, dispersed stand-alone photovoltaic power systems as well as small and medium-sized building-integrated grid-connected photovoltaic power systems. Both applications have proven large potentials, of which only a very small fraction has been realized until now. However, in the longer term, VLS-PV systems may represent a future option for photovoltaic applications and thereby contribute even more to the world energy supply.

For the first time, the present study provides a detailed analysis of all the major issues of such applications. Thanks to the initiative of Japan, Task VIII of the IEA PVPS Programme was designed to address these issues in a comprehensive manner, based on latest scientific and technological developments and through close international co-operation of experienced experts from different countries. The result is the first concrete set of answers to some of the main questions that have to be addressed in this context. Experience with today's technology is used, together with future projections, to make quantified estimations regarding the relevant technical, economic and environmental aspects. Besides the specific issues of VLS-PV, the subject of long-distance high-voltage transmission is also addressed.

This study includes a number of case studies in desert areas around the world. These case studies have been carried out in order to investigate the VLS-PV concept under specific conditions and to identify some of the local issues that can affect the concept.

I would like to thank the IEA PVPS Task VIII Expert Group, under the leadership of Prof. K. Kurokawa and Dr K. Kato, for an excellent contribution to the subject investigated. The study provides an objective discussion base for VLS-PV systems. This is very much in line with the mission of the IEA PVPS Programme, aimed at objective analysis and information in different technical and non-technical areas of photovoltaic power systems.

I hope that this study can stimulate the long-term discussion on the contribution of photovoltaics to the future energy supply by providing a thorough analysis of the subject investigated.

S. Nowak

Stefan Nowak
Chairman, IEA PVPS Programme

Preface

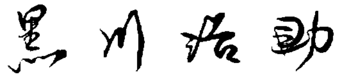
'It might be a dream, but ...' has been a motive for continuing our chosen study on *Very Large Scale Photovoltaic Power Generation – VLS-PV.* Now, we are confident that this is not a dream. A desert truly does produce energy. This report deals with one of the promising recommendations for solving world energy problems in the 21st century.

This activity first started in 1998 under the umbrella of IEA Task VI. The new task, Task VIII: 'Very Large Scale PV Power Generation Utilizing Desert Areas', was set up for feasibility studies in 1999.

To initiate our study, a lot of imagination was required. It was felt that dreams and imagination are really welcome, and that it is worth while to consider things for future generations, our children and grandchildren. People have to imagine their lives after 30 or 50 years, even 100 years, since it requires a longer lead-time to realize energy technology. In this sense, studies in terms of VLS-PV include plant design by extending present technologies as well as discussing basic requirements for PV energy in the future energy-supplying structure, the social impact on regions, and the local and global environmental impact.

It is known that very large deserts in the world have a large amount of energy-supplying potential. However, unfortunately, around those deserts, the population is generally quite limited. Then, too much power generation by PV systems becomes worthless. However, world energy needs will grow larger and larger towards the middle of the 21st century. In addition, when global environmental issues are considered, it is felt that future options are limited. These circumstances became the backbone and motive force for VLS-PV work.

Finally, all the Task VIII experts wish to thank the IEA PVPS Executive Committee and the participating countries of Task VIII for giving them valuable opportunities for studies.



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Our activity, Task VIII, started in 1999, continuing on from IEA PVPS Task VI/Subtask V, which had been executed in 1998, as advanced research for VLS-PV.

We would all like to thank Mr Kunisuke Konno, Mr Ken-ichiro Ogawa and Mr Ichiro Hashimoto (NEDO, Japan), who provided us with a great deal of support as the OA country's members of the IEA PVPS Executive Committee.

Mr Anzero Invernizzi, Mr John Peter Meisen, Mr John Benner, Mr Kong Li and Mr Anding Li gave us impressive and attractive presentations, in the preparatory workshop in 1997, which became the first step of international activity before the VLS-PV project started as an activity of PVPS.

Mr Winfried Rijssenbeek, Mr Jeroen van der Linden and Mr Pim Kieskamp, who were members of Task VI/ Subtask V, in which a preliminary study on VLS-PV systems was carried out prior to the initiation of Task VIII, and who participated in the early stage of this PVPS Task VIII, contributed a lot to the initiation of this task. Mr Rudolf Minder, who was a member of Task VI/Subtask V, also contributed to the initiation of this task. Mr Göran Andersson, who was also a member of Task VI/Subtask V, contributed to 'Trends in power transmission technology' in this report.

The case study on the Gobi Desert was developed thanks to the members of the Japanese domestic committee for VLS-PV: Mr Tetsuo Kichimi (Resources Total System), Mr Hiroyuki Sugihara (Kandenko), Mr Tetsu Nishioka (GETC), Mr Kazuyuki Tanaka (CRIEPI), Mr Makoto Tanaka (Sanyo), Mr Masahiro Waki (Sanyo) and Mr Masakazu Ito (TUAT). Also, we would like to thank Mr Ken-ichi Isomura (NEDO), Mr Yukihiko Kimura (NEDO) and Mr Tsunehisa Harada (PVTEC) for supporting and managing that committee.

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Finally, all the Task VIII members thank the IEA PVPS Executive Committee and the participating countries of Task VIII for giving them valuable opportunities for studies.

II

Comprehensive summary

OBJECTIVE

The scope of this study is to examine and evaluate the potential of very large-scale photovoltaic power generation (VLS-PV) systems (which have a capacity ranging from several megawatts to gigawatts), by identifying the key factors that enable VLS-PV system feasibility and clarifying the benefits of this system's application to neighbouring regions, as well as the potential contribution of system application to protection of the global environment. Renewable energy utilization in the long term also will be clarified. Mid- and long-term scenario options for making VLS-PV systems feasible in some given areas will be proposed.

In this report, the feasibility and potential for VLS-PV systems in desert areas are examined. The key factors for the feasibility of such systems are identified and the (macro-)economic benefits and the potential contribution to the global environment are clarified. First the background of the concept is presented. Then six desert areas are compared, and three of these are selected for a case study. Finally, three scenario studies are performed to ensure sustainability.

BACKGROUND AND CONCEPT OF VLS-PV

A very large-scale PV system is defined as a PV system ranging from 10 MW up to several gigawatts (0,1–20 km^2 total area) consisting of one plant or an aggregation of multiple units operating in harmony and distributed in the same district. These systems should be studied with an understanding of global energy scenarios, environmental issues, socio-economic impact, PV technology developments, desert irradiation and available areas:

- All global energy scenarios project PV to become a multi-gigawatt generation energy option in the first half of this century.
- Environmental issues which VLS-PV systems may help to alleviate are global warming, regional desertification and local land degradation.
- PV technology is maturing with increasing conversion efficiencies and decreasing prices per watt. Prices of 1,5 USD/W are projected for 2010, which would enable profitable investment and operation of a 100 MW plant.
- Solar irradiation databases now contain detailed information on irradiation in most of the world's deserts.
- The world's deserts are so large that covering 50 % of them with PV would generate 18 times the world primary energy supply of 1995.

VLS-PV CASE STUDIES

Electricity generation costs of between 0,09 and 0,11 USD/kWh are shown, depending mainly on annual irradiation level (module price 2 USD/W, interest rate 3 %, salvage value rate 10 %, depreciation period 30 years). These costs can come down by a factor of a half to a quarter by 2010. Plant layouts and introduction scenarios exist in preliminary versions. I/O analysis shows that 25 000–30 000 man-years of local jobs for PV module production are created per 1 km^2 of VLS-PV installed. Other findings of the three case studies (two flat-plate PV systems and one two-axis tracking concentrator PV) are as follows:

- The case study in the Gobi Desert describes a VLS-PV system built of strings of 21 modules combined into arrays of 250 kW consisting of 100 strings. Two of these arrays are connected to an inverter of 500 kW. Two hundred of these sets of two arrays are distributed over an area of approximately 2 km^2. Total requirements for construction of the plant based on local module assembly are 848 485 modules, 1 700 tons of concrete for foundations and 742 tonnes of steel for the array supports. The life-cycle CO_2 emission is around 13 g-C/kWh, due mainly to manufacturing of the modules and the array supports.
- In the Sahara case study, several distributed generation concepts were compared to minimize transmission costs. A potentially attractive option is 300 dispersed plants of 5 MW PV systems, the total capacity of which is 1,5 GW, located along the coast of Northern Africa, connected to the grid by a single 1–10 km medium-voltage line. A complete I/O analysis was also carried

out, resulting in 2 570 induced jobs by the operation of a 5 MW/year PV module production facility.
- In the Negev Desert in the Middle East, a 400-sun concentrator dish of 400 m^2 was evaluated. Simulations indicated that 16,5 % overall system efficiency is achievable, and an economically attractive operation with generation costs of less than 0,082 USD/kWh is possible.

SCENARIO STUDIES

Three sustainable scenario studies were developed showing that *sustainable local economic growth, sustainable technological–environmental development and non-technological demonstration* and *sustainable financial (stakeholder) support* are possible when a long-term perspective is developed and maintained:

- In the concept of sustainable local economic growth, the first local PV module production facility has an annual output of 5 MW. This local production supplies for the construction of the local VLS-PV system. In subsequent years, four more 5 MW module production facilities are brought into operation, so that annually 25 MW is supplied to the local VLS-PV system. After 10–15 years, a module production facility of 50 MW is put into operation. Every 10 years this facility is replaced by a more modernized one. Thus after approximately 40 years a 1,5 GW VLS-PV plant is in operation, and the local production facility supplies for replacement. In this way, local employment, and thus the economy, will grow sustainably.
- To reach the point of a 1 GW system, four intermediate stages are necessary: R&D stage, pilot stage, demonstration stage, and deployment (commercial) stage. From stage to stage, the system scale will rise from 2,5 MW to 1 GW, and module and system cost will go down by a factor of 4. Production will be shifted more and more to the local economy. Technological issues to be studied and solved include reliability, power control and standards. Non-technical items include training, environmental anti-desertification strategies, industrialization and investment attraction. These four stages have a total duration of 15 years.
- To realize the final commercial stage, a view to financing distribution is developed for all of the three previous stages, consisting of direct subsidies, soft loans, equity, duty reduction, green certificates and tax advantages. It is clear that direct subsidies will play an important role in the first three stages (R&D, pilot and demonstration). Ultimately, in the commercial stage, enough long-term operating experience and track record are available to attract both the soft loans and equity for such a billion-dollar investment.

UNDERSTANDINGS

From the perspective of the global energy situation, global warming and other environmental issues, as well as from the case studies and scenarios, it is apparent that VLS-PV systems can:

- contribute substantially to global energy needs
- become economically and technologically feasible
- contribute considerably to the environment
- contribute considerably to socio-economic development.

RECOMMENDATIONS

To secure that contribution, a long-term scenario (10–15 years) perspective and consistent policy are necessary on technological, organizational and financial issues. Action is required now to unveil the giant potential of VLS-PV systems in deserts. In such action, the involvement of many actors is needed. In particular, it is recommended that, on a policy level:

- national governments and multinational institutions adopt VLS-PV systems in desert areas as a viable energy generation option in global, regional and local energy scenarios;
- the IEA-PVPS community continues Task VIII to expand the study, refine the R&D and pilot phases, involve participation by desert experts and financial experts, and collect further feedback information from existing PV plants;
- multilateral and national governments of industrialized countries provide financing to generate feasibility studies in many desert areas around the world and to implement the pilot and demonstration phases;
- desert-bound countries (re-)evaluate their deserts not as potential problem areas but as vast and profitable (future) resources for sustainable energy production, recognizing the positive influence on local economic growth, regional anti-desertification and global warming.

Background and concept of VLS-PV

We are in a new age beyond the 20th century, which was the age of high-consumption society maintained by a mass supply of fossil fuels and advances in science and technology. But our activities in such a society will have a serious impact on us, such as in energy security, global environmental issues, population problems, etc. Therefore, it is necessary to reconstruct a new society with new values and new lifestyles in order to sustain our world from now on. Finding solutions for energy and environmental issues is essential for realizing a sustainable world, since it will take a long time to develop energy technologies and to recover from the destruction of the global environment.

Renewable energy such as solar, hydropower, geothermal and biomass is expected to be the main energy resource in future. Photovoltaic (PV) technology is one of the most attractive options of these renewables, and many in the world have been trying to develop PV technologies for the long term.

In Part I, the informative introductory part of the whole report, both global energy and environmental issues, including the potential of renewable energy sources and the market trends in PV technology, are reviewed as a background for this report. General information on PV technology, such as trends in solar cells and systems, operation and maintenance experiences, and a case study on added values of a PV system for utilities, are summarized. World irradiation data are also important to start a discussion about the potential of VLS-PV systems. In the last chapter of Part I, the concept ofVLS-PV systems, which is the theme of this report, is introduced.

A.1 WORLD ENERGY ISSUES

The two oil crises in the 1970s made us aware that fossil fuels are exhaustible and triggered development of alternative energy resources such as renewable energy. Nevertheless, most of the primary energy still depends on fossil fuels, and current utilization of renewables is negligibly small, except for hydropower. According to the IEA report, generally the total amount of fossil-fuel resources in the world will not exhaust the energy supply until 2030, although there are possibilities of a rapid increase in energy demand, a geographical imbalance between supply and demand, and temporal and local supply problems. There is a forecast that the world primary energy supply in 2030 will increase to over 1,5 times as much as that in 2000, as shown in Figure A.1.

In addition, energy demand in Asian countries will increase much more than in OECD countries. Even beyond 2030, rapid growth in developing countries may continue further, reflecting the economic gap between the developing and the industrialized countries. In addition to

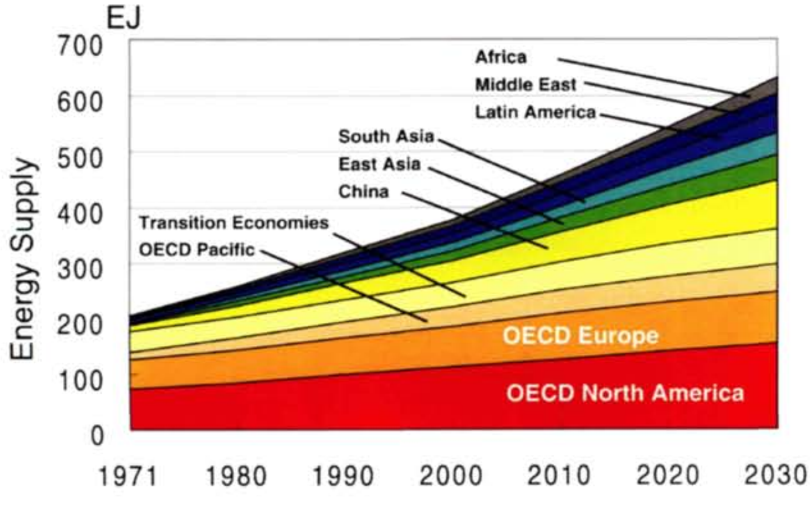

Figure A.1 World primary energy supply by region, 1971–2030. Source: IEA

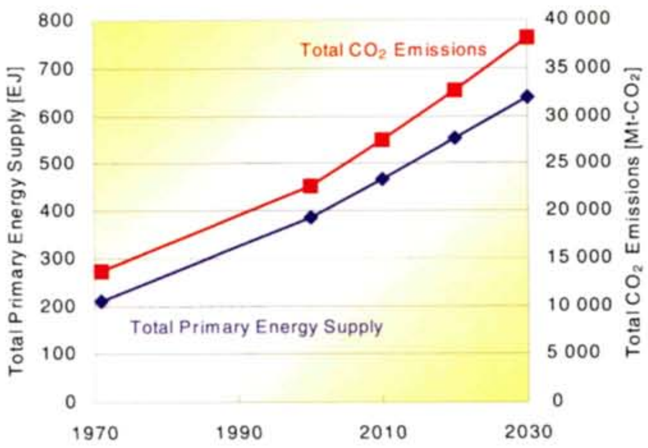

Figure A.2 World primary energy supply and CO_2 emissions, 1971–2030. Source: IEA

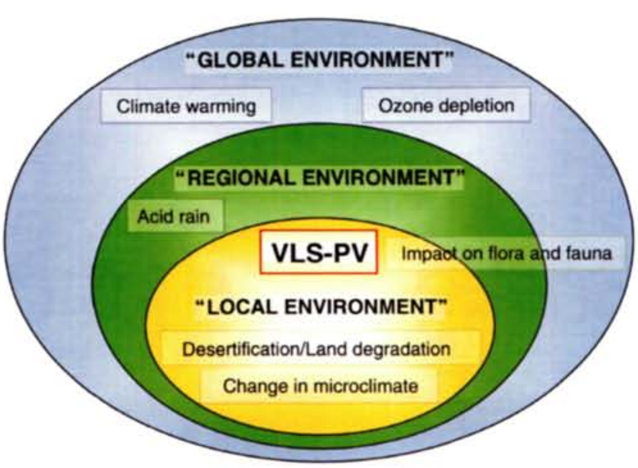

Figure A.3 Possible environmental issues impacted by VLS-PV systems

the long-term world energy problem, global warming is another urgent issue because CO_2 emissions are caused by the combustion of fossil fuels (see Figure A.2). As pointed out at Kyoto COP-3, simple economic optimization processes for world energy supply can no longer be accepted to overcome global warming.

In any consideration of future energy problems, basic conditions and tendencies may be summarized as follows:

- World energy demands will rapidly expand towards the middle of this century due to world economic growth and population increase.
- The sustainable prosperity of human beings can no longer be expected if global environmental issues are ignored.
- The share of electrical energy is rising more and more as a secondary energy form.
- Although the need for nuclear power will increase as a major option, difficulties in building new plants are getting more and more notable at the same time.
- Thinking about the long lead-time for the development of energy technology, it is urgently necessary to seek new energy ideas applicable for the next generation.

In order to solve global energy and environmental issues, renewable energy resources are considered to have a large potential as well as to provide energy conservation, carbon-lean fuels and CO_2 disposal/recovery. Among the variety of renewable energy technologies, photovoltaic (PV) technology is expected to play a key role in the middle of this century, as reported by Shell International Petroleum Co. and the G8 Renewable Energy Task Force (see Table A.1).

The world PV market as well as the world PV system installation has been growing rapidly for the past several years. Besides, PV industries in the USA, Europe and Japan recently established their long-term vision of the PV market. According to their vision, potential cumulative PV installation will be in the hundreds of gigawatts in 2030.

A.2 ENVIRONMENTAL ISSUES

Recently, great concern about environmental issues, most of which have been caused by human activities, has spread throughout the entire world. The environmental impact of VLS-PV systems may be divided into three categories from a geographical viewpoint, i.e. global, regional and local environmental issues, as shown in Figure A.3. The global environmental issues are matters related to global changes. Regional issues are trans-boundary environmental issues, including atmospheric and water pollution. Local environmental issues are changes restricted to the local environment that surrounds the VLS-PV installation site. The most important phenomenon in this issue may be desertification and land degradation. Change in microclimate is another local environmental issue.

Among environmental issues, global warming is one of the most important issues because it has a large variety of impact in various respects. According to the IPCC (Intergovernmental Panel on Climate Change) Third Assessment Report, the global average surface temperature has increased by (0,6 ± 0,2) °C since the late 19th century. It is very likely that the period from 1990 to 2000 was the warmest decade. Also, the global average surface temperature has been projected to increase by 1,4–5,8 °C between 1990 and 2100. The projected rate of warming is much

Table A.1 Installed global capacity estimated by G8 renewable energy task force (GW)

	Coal IGCC	Gas FC	Bio conv.	Bio IGCC	Bio FC	Small hydro	Wind	Solar PV	Solar thermal	Geothermal
2000	0,3	0,3	24,3	0,3	0,1	0,3	12,5	1,0	1,4	6,9
2012	14,3	14,3	34,6	15,7	15,8	18,9	90,5	31,8	9,7	17,4
2020	39,7	35,7	36,7	28,9	28,9	38,8	196,3	118,8	32,6	27,6
2030	142,5	114,0	40,5	68,0	67,5	95,8	554,6	655,8	156,4	49,5

greater than the observed changes during the 20th century, and is very likely to be without precedent at least during the last 10 000 years.

To mitigate the projected future climate change and influences, the UN Framework Convention on Climate Change (UNFCCC) has activated a negotiating process. In COP-3 held in Kyoto in 1997, the Kyoto Protocol was adopted and six greenhouse gases (GHGs) have been designated for reduction by the first commitment period. In November 2001, COP-7 was held in Marrakesh, Morocco. At this conference, the Marrakesh Accords were adopted, and many have expressed a wish for the Kyoto Protocol to enter into force in 2002. The finalized Kyoto rulebook specifies how to measure emissions and reductions, the degree to which carbon dioxide absorbed by carbon sinks can be counted towards the Kyoto targets, how the joint implementation and emissions trading systems will work, and the rules for ensuring compliance with commitments. The meeting also adopted the Marrakesh Ministerial Declaration as input for the 10th anniversary of the Convention's adoption and the 'Rio+10' World Summit for Sustainable Development (Johannesburg, September 2002). The Declaration emphasizes the contribution that action on climate change can make to sustainable development and calls for capacity building, technology innovation and co-operation with the biodiversity and desertification conventions.

Desertification is the degradation of land in arid, semi-arid and dry subhumid areas. It occurs because dryland ecosystems, which cover over one-third of the world's land area, are extremely vulnerable to overexploitation and inappropriate land use. Desertification reduces the land's resilience to natural climate variability. Soil, vegetation, freshwater supplies and other dryland resources tend to be resilient. They can eventually recover from climatic disturbances, such as drought, and even from human-induced impacts, such as overgrazing. When land is degraded, however, this resilience is greatly weakened. This has both physical and socio-economic consequences.

Combating desertification is essential to ensuring the long-term productivity of inhabited drylands. Unfortunately, past efforts at combating desertification have too often failed, and around the world the problem of land degradation continues to worsen. Recognizing the need for a fresh approach, 179 governments have joined the UNCCD as of March 2002. The UNCCD promotes international co-operation in scientific research and observation, and stresses the need to co-ordinate such efforts with other related Conventions, in particular those dealing with climate change and biological diversity. New technologies and know-how should be developed, transferred to affected countries, and adapted to local circumstances. For example, photovoltaic and wind energy may reduce the consumption of scarce fuelwood and deforestation. These technologies, however, should also be environmentally sound, economically viable and socially acceptable.

VLS-PV systems will be one of the promising technologies for solving environmental problems. However, if some projects involving environmentally safe and sound technology are proposed, we should pay attention not only to the operation but also to the entire life-cycle, including production and transportation of components and incidental facilities, construction and decommissioning. For this purpose, *life-cycle assessment* (LCA) is a useful approach and is becoming a general method of evaluating various technologies. Besides the contribution to reducing gas emissions such as CO_2, projects for developing and introducing new technologies, such as the Clean Development Mechanism (CDM), must accompany the sustainable social and economic development of the region.

A.3 AN OVERVIEW OF PHOTOVOLTAIC TECHNOLOGY

A.3.1 Technology trends

PV technology has several specific features such as solar energy utilization technology, solid-state and static devices, and decentralized energy systems. The long history of R&D on solar cells has resulted in a variety of solar cells. Crystalline (single-crystalline, polycrystalline) silicon is the most popular material for making solar cells. In 2001, crystalline Si PV modules had approximately 80 % of the market share.

Mainly because of the lack of sufficient supply of suitable silicon material and because of the limited possibilities for further improvements in manufacturing costs for wafer-based silicon solar cells, much of the worldwide R&D effort is spent on the development of thin-film solar cells. Since extensive expertise has been gained with silicon as a semiconductor material, the first candidates for replacing wafer-based solar cells use silicon as an active layer. The most popular thin-film technology today uses amorphous silicon as the absorber layer; low-cost manufacturing techniques have been designed and amorphous silicon solar panels are the most cost-effective in the market today. Multiple cell concepts, using a combination of amorphous silicon and microcrystalline silicon cells (micromorph concept), show interesting potentials for increasing solar-cell efficiencies at relatively low cost. Another group of thin-film silicon solar cells make use of high-temperature deposition techniques and grow the silicon thin films on high-temperature resistant (mostly ceramic) substrates. Making use of lift-off and transfer techniques, silicon layers that have been grown on silicon substrates at high temperatures can be transferred to low-cost substrates and the original substrate can be re-used. A different approach using silicon thin films for enhancing the efficiency of a silicon solar cell is the combination of crystalline silicon wafers with amorphous silicon cells (hetero-junction cells). Compound thin-film solar cells using material other than silicon (CIGS, CdTe) have demonstrated their high efficiency capability and offer a promising future for this type of thin-film solar cells. Dye-sensitized and organic solar cells have potential of low cost; today, their efficiencies are still and probably will remain low, and the lifetime of the cells is a major concern. Long-term reliability of thin-

Table A.2 Actual operation and maintenance costs

Project name	Total project cost (USD)	Actual (USD)	Actual (USD/kW)	Actual (USD) / Total project cost
Solarex Residential (329 kW)	2 050 723	6 502	19,76	0,32 %
Sacramento Metropolitan Airport Solarport (128 kW)	1 324 122	7 500	58,59	0,68 %
Rancho Seco PV-3 Ground-Mounted Substation System (214 kW)	2 580 008	4 167	19,47	0,25 %

film solar panels is, as with other types of semiconductors, very much dependent on the encapsulation.

The general trend for all future design activities will be to improve the conversion efficiency of the cell, the simplicity, the throughput and the yield of the production process, and the long-term reliability of the module. Looking at the present status of R&D, manufacturing and market penetration of the various technologies, it can be expected that amorphous silicon will remain the dominant thin-film technology in coming years. In particular, the combination with microcrystalline silicon offers higher and more stable efficiency, which is needed in many applications. The next dominant thin-film technologies may be polycrystalline compound solar cells, like CIS and CdTe. Next to that, thin-film silicon cells, either on ceramic materials or via transfer techniques, may offer the best price/performance ratio for most applications. For the longer term, organic cell concepts may also enter the market. In principle, all the cell concepts mentioned above have the potential to reach and even pass the 1 USD/W level. It can be expected that research activities on all concepts will be continued and that all concepts, at some time in the future, will be commercially available. These are all major drivers towards lower cost per unit of electricity.

A.3.2 Experiences in operation and maintenance of large-scale PV systems

According to the facts of three projects of SMUD, operation and maintenance cost of large-scale PV system seems to be low, less than 1 % of gross total project cost, as shown in Table A.2.

The long-term reliability of solar cell and modules was discussed by reviewing long-term data on field exposure in four regions: Pacific Rim, USA, Europe and Negev Desert. In general, the performance degradation of a crystalline Si solar-cell module ranges between 0,4 and 2,0 %/year. In this report, performance degradation was classified into three levels: *typical* (0,5 %/year), *severe* (1,0 %/year), and *worst* (1,5 %/year).

A.3.3 Cost trends

Although PV is currently at a disadvantage because of its high cost, we believe PV has the best long-term potential because it has the most desirable set of attributes and the greatest potential for radical reductions in cost. Costs for the entire system vary widely and depend on a variety of factors, including system size, location, customer type, grid connection and technical specifications. For example, for building-integrated systems (BIPV), the cost of the system will vary significantly depending on whether the system is part of a retrofit or is integrated into a new building structure. 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 for equipment in the target sector. The installation of PV systems for grid-connected applications is increasing year by year, while the grid-connected market must still depend upon government incentive programmes at present. The installed cost of grid-connected systems also varies widely in price. Figure A.4 shows the trends of PV system and module prices in some countries. Although, in more recent years, this shows a slight increase in some markets due to high demand, there appears to be a continued downward trend.

We need to accelerate that trend. One way to do that is to step up the scale of the typical PV plant. The largest plant has a capacity approaching 100 MW/year. It would take such a plant, running flat out, 100 years to produce enough equipment to match the power-generating capacity of one medium-sized combined-cycle gas turbine power plant. We believe there may be significant economies of scale to be reaped as we move up to 50–100 MW plants. Another path towards radically lower costs is technology step change. The technology in use today is based on crystalline silicon. This is an inherently material-intensive technology. It requires batch production methods, and is now relatively mature. The great hope for the future lies with thin-film technologies, which are much less material-intensive and suitable for continuous production

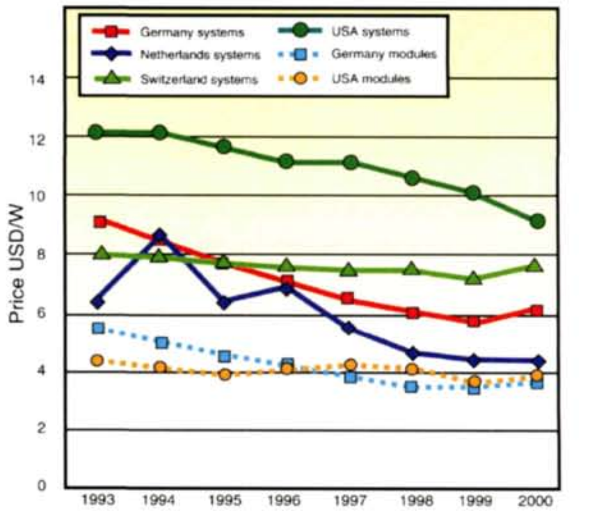

Figure A.4 PV module and system price trends in some countries processes. They offer the potential to shift on to a lower and steeper learning curve. However, we need to be a little cautious about predicting when thin film will start to realize its commercial potential. Both of these routes – stepping up the scale, and backing the new technology – carry large risks, both technical and commercial. Taking bold steps will require a great deal of confidence in the rapid emergence of a mass market.

Today's cost of single-crystal and polycrystalline silicon modules (although proprietary) is such that the present factory price of 4 USD/W includes all costs, as well as marketing and management overheads, for that product line. Note that module prices for single-crystal and polycrystalline silicon have been essentially stable, between 3,75 and 4,15 USD/W, for nearly 10 years, while manufacturing costs have been reduced by over 50 %. Based on the studies cited and on further analysis, it seems likely that fully loaded manufacturing costs for a 100 MW single-crystal silicon module will be 1,40 USD/W. This would permit a profitable price of 2,33 USD/W. Prices at this level are likely to be required in order to open up the massive grid-connected and building-integrated markets. The cast-ingot polycrystalline option continues to have module costs slightly lower than those of the single-crystal, allowing this option to offer profitable prices at the 2 USD/W level. Thin films and concentrators could have manufacturing costs that will allow profitable prices of 1,25 USD/W. In this forecast, the PV market continues to grow at 15–25 %. However, in order for this forecast to become a reality, several major events need to occur. First, the existing subsidized grid-connected programmes in countries such as Japan, Germany, the Netherlands and the USA need to stimulate the installation of quality, reliable systems in sufficient quantities to stimulate investment in large-volume module manufacturing plants. Secondly, continuing decrease in the price of modules must be realized. There must be profitable modules below 2 USD/W by the year 2005 and even lower prices, approaching 1,5 USD/W, must occur by 2010. Thirdly, in the transitional phase towards competitive prices, marketing and financing schemes have to be introduced more widely which will allow the customers to opt for this solution in spite of costs.

A.3.4 Added values of PV systems

PV technology has unique characteristics different from those of conventional energy technologies, and additional values are hidden in PV systems besides their main function, which is, of course, power generation. Table A.3 shows a summary of non-energy benefits that can add value to PV systems. Nowadays, many people are becoming aware of the additional benefits offered by PV systems. Unfortunately, this awareness does not contribute to the effective promotion of PV systems since current added values are not quantitative but qualitative. Thus research activities on quantitative analysis of this issue should be continued.

There is a case study on the added values of a PV system for SMUD. The utility benefits evaluated are as follows.

- Energy: avoided marginal cost of system-wide energy production.
- Capacity: avoided marginal cost of system-wide generation capacity.
- Distribution: distribution capacity investment deferral.
- Sub-transmission: sub-transmission capacity investment deferral.
- Bulk transmission: transmission capacity investment deferral.
- Losses: reduction in electricity losses.
- REPI: renewable energy production incentive.
- Externalities: value of reduced fossil emissions.
- Green pricing: voluntary monthly contributions from PV pioneers.
- Fuel price risk mitigation: value of reducing risk from uncertain gas price projections.

Table A.3 Summary of non-energy benefits that can add value to PV systems

Category	Potential values
Electrical	kWh generated; kW capacity value; peak generation and load matching value; reduction in demand for utility electricity; power in times of emergency; grid support for rural lines; reduced transmission anddistribution losses; improved grid reliability and resilience; voltage control; smoothing load fluctuations; filtering harmonics and reactive power compensation.
Environmental	Significant net energy generator over its lifetime; reduced air emissions of particulates, heavy metals, CO_2, NO_x, SO_x, resulting in lower greenhouse gases; reduced acid rain and lower smog levels; reduced power station land and water use; reduced impact of urban development; reduced tree clearing for fuel; reduced nuclear safety risks.
Architectural	Substitute building component; multi-function potential for insulation, water proofing, fire protection, wind protection, acoustic control, daylighting, shading, thermal collection and dissipation; aesthetic appeal through colour, transparency, non-reflective surfaces; reduced embodied energy of the building;reflection of electromagnetic waves; reduced building maintenance and roof replacements.
Socio-economic	New industries, products and markets; local employment for installation and servicing; local choice, resource use and control; potential for solar breeders; short construction lead-times; modularity improves demand matching; resource diversification; reduced fuel imports; reduced price volatility; deferment of large capital outlays for central generating plant or transmission and distribution line upgrades; urban renewal; rural development; lower externalities (environmental impact, social dislocation, infrastructure requirements) than fossil fuels and nuclear; reduced fuel transport costs and pollution from fossil-fuel use in rural areas; reduced risks of nuclear accidents; symbol for sustainable development and associated education; potential for international co-operation, collaboration and long-term aid to developing countries.

Table A.4 Estimation result of utility benefits of fixed PV systems (USD/kW, 1996)

Benefits	Bulk transmission	Sub-transmission	Primary voltage	Secondary voltage
Service revenues	708	708	708	708
REPI	221	221	221	221
Externalities	324	327	338	340
Fuel price risk	192	194	200	201
Green pricing	0	0	44	44
Distribution	0	0	0	117
Sub-transmission	0	0	39	39
Bulk transmission	0	15	16	16
Generation capacity	296	300	314	315
Energy	768	775	800	805
Total	2 509	2 540	2 680	2 806

Table A.5 Examples of world irradiation database

Name	Website address
Ground observation	
1. Negev Radiation Survey	http://www.bgu.ac.il/solar
2. WRDC solar radiation and radiation balance data	http://wrdc-mgo.nrel.gov/
3. BSRN: Baseline Surface Radiation Network	http://bsrn.ethz.ch/
4. NOAA NCDC GLOBALSOD	http://www.ncdc.noaa.gov/
5. METEONORM 2000 (commercial product)	http://www.meteotest.ch/
Satellite-derived data	
6. SeaWiFS surface solar irradiance	http://www.giss.nasa.gov/data/seawifs/
7. LaRC Surface Solar Energy dataset (SSE)	http://eosweb.larc.nasa.gov/sse/
8. ISCCP datasets	http://isccp.giss.nasa.gov/isccp.html

- Service revenues (economic development): net service revenues from local PV manufacturing plant (result of economic development efforts).

Table A.4 is an estimation result of utility benefits of fixed PV systems.

A.4 WORLD IRRADIATION DATABASE

Irradiation data are important to start a discussion about the potential ofVLS-PV systems. The Japan Weather Association (JWA) collected irradiation and air temperature data during 1989 and 1991 from every meteorological organization in the world. Data items are monthly means of global irradiation, monthly means of ambient air temperature, and monthly means of snow depth. The data were collected from 150 countries, and data from 1 601 sites throughout the world are available. Monthly global irradiation was estimated from monthly sunshine duration where there were no irradiation data.

The Negev Radiation Survey, which was established in the 1980s by the Israel Ministry of National Infrastructures, monitors the following meteorological parameters at nine stations in the Negev Desert: normal direct beam irradiance, global horizontal irradiance, ambient temperature, humidity ratio, wind speed, and wind direction. The data are available from the Ben-Gurion National Solar Energy Centre, in the form of a CD-ROM, which contains a set of *Typical Meteorological Year* (TMY) files (updated every three years) together with all previous years of actual data for each site.

Besides these, there are a variety of worldwide databases of solar energy resources. Table A.5 shows the name and website address for some of these.

Figure A.5 World deserts (unit: 10^4 km^2)

A.5 CONCEPT OF VLS-PV SYSTEM

A.5.1 Availability of desert area for PV technology

Solar energy is low-density energy by nature. To utilize it on a large scale, a massive land area is necessary. However, one-third of the land surface of the Earth is covered by very dry deserts, as shown in Figure A.5. High-level insolation and large spaces exist. It is estimated that if a very small part of these areas, say 4 %, were used for the installation of PV systems, the annual energy production would equal world energy consumption.

A rough estimation was made to examine the potential of desert under the assumption of a 50 % space factor for installing PV modules on the desert surface as the first evaluation. The total electricity production becomes

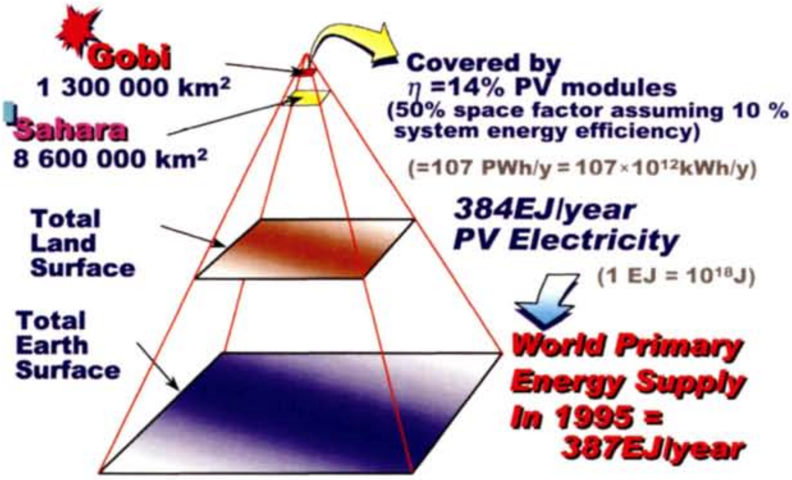

Figure A.6 Solar pyramid

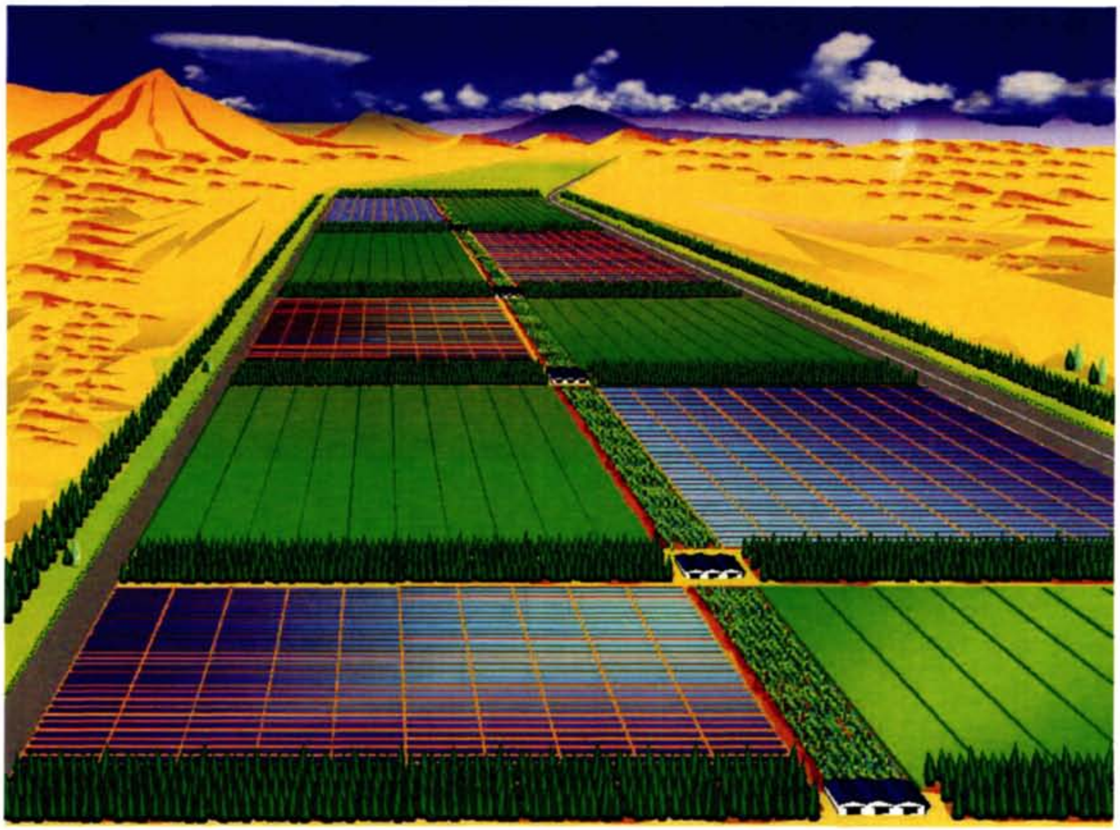

Figure A.7 Image of a VLS-PV system in a desert area

1 942,3 × 10³ TWh(= 6,992 × 10²¹ J = 1,67 × 10⁵ Mtoe), which means a level almost 18 times as much as the world primary energy supply, 9 245 Mtoe (107,5 × 10³ TWh = 3,871 × 10²⁰ J) in 1995. These are quite hypothetical values, ignoring the presence of loads near these deserts. However, at least these indicate high potential as primary resources for developing districts located in such solar-energy-rich regions.

Figure A.6 also shows that the Gobi Desert area between the western part of China and Mongolia can generate as much electricity as the present world primary energy supply. In Figure A.7, an image of a VLS-PV system in a desert area is shown.

A.5.2 VLS-PV concept and definition

Presently, three approaches are under consideration to encourage the spread and use of PV systems.

(a) Establish small-scale PV systems that are independent of each other. There are two scales for such systems: installing stand-alone, several hundred-watt PV systems for private dwellings; and installing 2–10 kW systems on the roofs of dwellings as well as 10–100 kW systems on office buildings and schools. Both methods are already being used. The former is used to furnish electrical power in developing countries, the so-called SHS (solar home system), and the latter is used in Western countries and in Japan. This seems to be used extensively in areas of short- and medium-term importance.

(b) Establish 100–1 000 kW mid-scale PV systems on unused land on the outskirts of urban areas. The PVPS/ Task VI studied PV plants for this scale of power generation. Systems of this scale are in practical use in about a dozen sites in the world at the moment, but are expected to increase rapidly in the early 21st century. This category can be extended up to multi-megawatt size.

(c) Establish PV systems larger than 10 MW on vast, barren, unused lands that enjoy extensive exposure to sunlight. In such areas, a total of even more than 1 GW of PV system aggregation can be easily realized. This approach makes it possible to install quickly a large number of PV systems. When the cost of generated electrical power is lowered to a certain level in the future, many more PV systems will be installed. This may lead to a drastically lower cost of electricity, creating a positive cycle between cost and consumption. In addition, this may become one of the solutions to future energy and environmental problems across the globe, and ample discussion of this possibility is believed to be worthwhile.

The third category corresponds to *very large-scale PV* (VLS-PV) *systems*. The definition of VLS-PV may be summarized as follows:

- The size of a VLS-PV system may range from 10 MW to one or a few gigawatts, consisting of one plant, or an aggregation of many units that are distributed in the same district and operate in harmony with each other.
- The amount of electricity generated by VLS-PV systems can be considered significant for people in the district, in the nation or in the region.
- VLS-PV systems can be classified according to the following concepts, based on their locations:
  - land based (arid to semi-arid, deserts)
  - other concept (water-based, lakes, coastal, international waters)
  - locality options (D.C.: lower, middle, higher income; large or small countries; OECD countries).

Although VLS-PV systems include water-based options, in principle, many different types of discussions are required on this matter. It is not neglected but it is treated as a future possibility outside the major efforts of this study.

A.5.3 Potential of VLS-PV: advantages

The advantages of VLS-PV systems are summarized as follows:

- It is very easy to find land around deserts appropriate for large energy production by PV systems.
- Deserts and semi-arid lands are, normally, high-insolation areas.
- The estimated potentials of such areas can easily supply world energy needs in the middle of the 21st century.
- When large-capacity PV installations are constructed, step-by-step development is possible through utilizing the modularity of PV systems. According to regional energy needs, plant capacity can be increased gradually. This is an easier approach for developing areas.
- Even very large installations are quickly attainable to meet existing energy needs.
- Remarkable contributions to the global environment can be expected.
- When a VLS-PV system is introduced to a certain region, other types of positive socio-economic impact may be induced, such as technology transfer to regional PV industries, new employment and economic growth.
- The VLS-PV approach is expected to have a major, drastic influence on the 'chicken-and-egg' cycle in the future PV market. If this does not happen, the distance to VLS-PV systems may become a little far.

These advantages make it a very attractive option, and worthy of discussion regarding global energy in the 21st century. The image of this concept is illustrated by Figure A.8.

A.5.4 Synthesis in a scenario for the viability of VLS-PV development

Basic case studies were reported concerning regional energy supply by VLS-PV systems in desert areas, where solar energy is abundant. According to this report, the following scenario is suggested to reach a state of large-scale PV introduction. First, the bulk systems that have been installed individually in some locations would be interconnected with each other by a power network. Then they would be incorporated with regional electricity demand growth. Finally, such a district would become a large power source. This scenario is summarized in the following stages according to Figure A.9:

1 A stand-alone, bulk system is introduced to supply electricity for surrounding villages or anti-desertification facilities in the vicinity of deserts.
2 Remote, isolated networks germinate. Plural systems are connected by a regional grid. This contributes to load levelling and the improvement of power fluctuation.

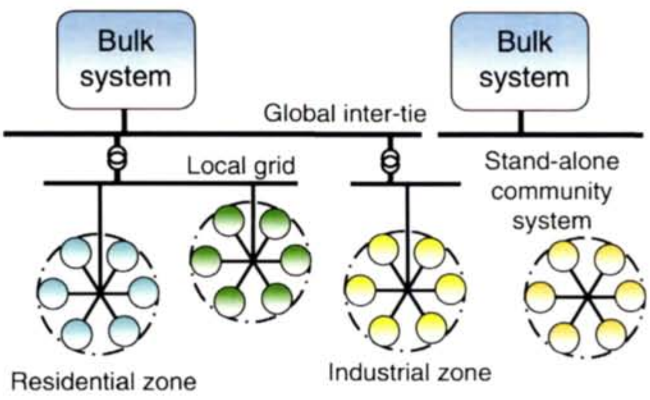

Figure A.8 Global network image

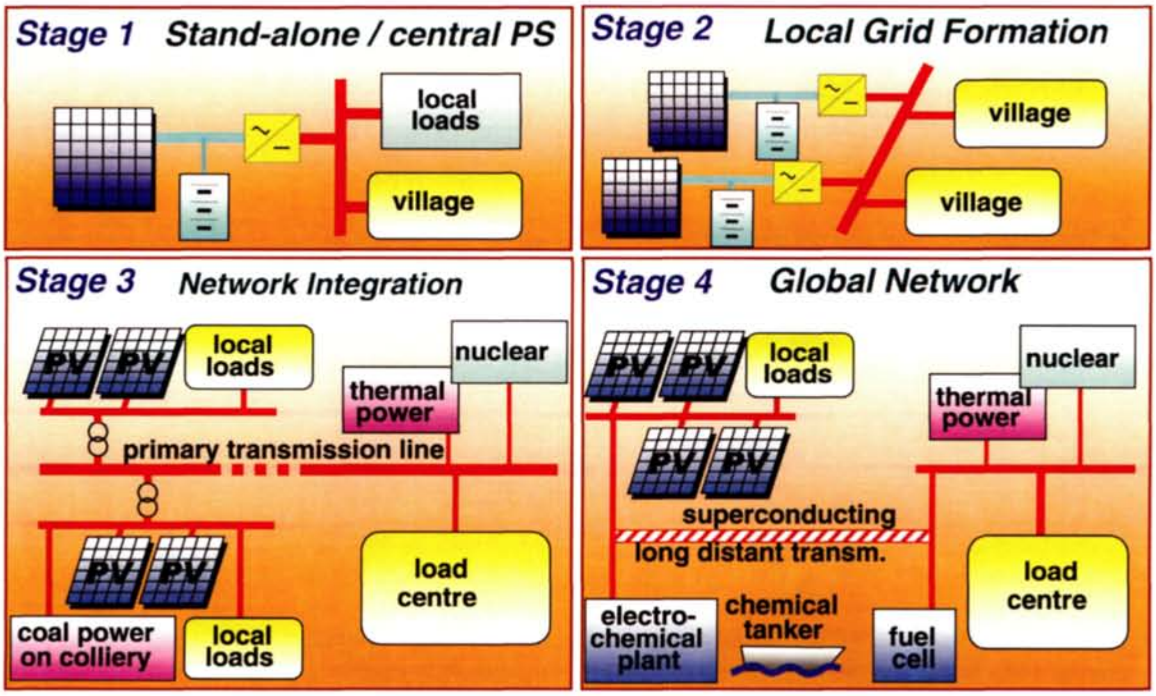

Figure A.9 Very large-scale PV system deployment scenario

3 The regional network is connected to a primary transmission line. Generated energy can be supplied to a load centre and industrial zone. Total use combined with other power sources and storage becomes important for matching to the demand pattern and the improvement of the capacity factor of the transmission line. Furthermore, around the time stage 3 is reached, in the case of a south-to-north inter-tie, seasonal differences between demand and supply can be adjusted. An east-to-west tie can shift peak hours.

4 Finally, a global network is developed. Most of the energy consumed by human beings can be supplied through solar energy. For this last stage, a breakthrough in advanced energy transportation will be expected on a long-term basis, such as superconducting cables, FACTS (flexible A.C. transmission system), or chemical media.