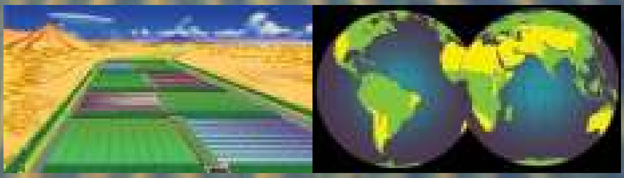
SUMMARY

Energy from the Desert

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



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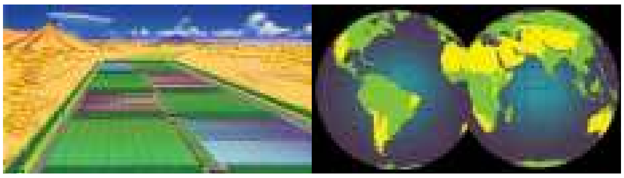

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Foreword

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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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 of VLS-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

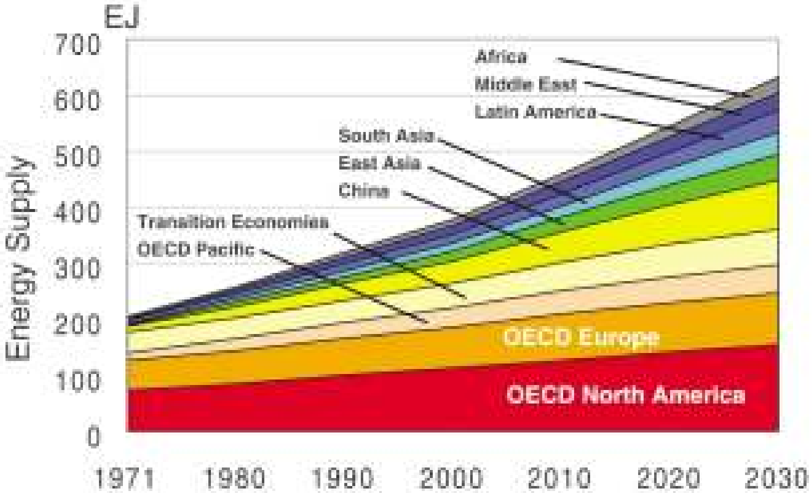


Figure A.1 World primary energy supply by region, 1971-2030. Source: IEA

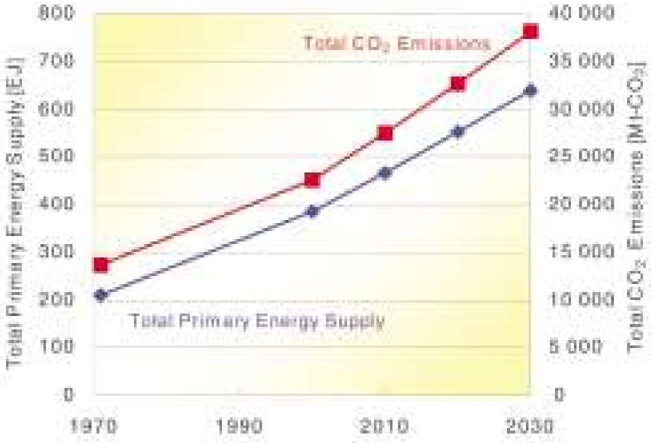


Figure A.2 World primary energy supply and CO_2 emissions, 1971–2030. Source: IEA

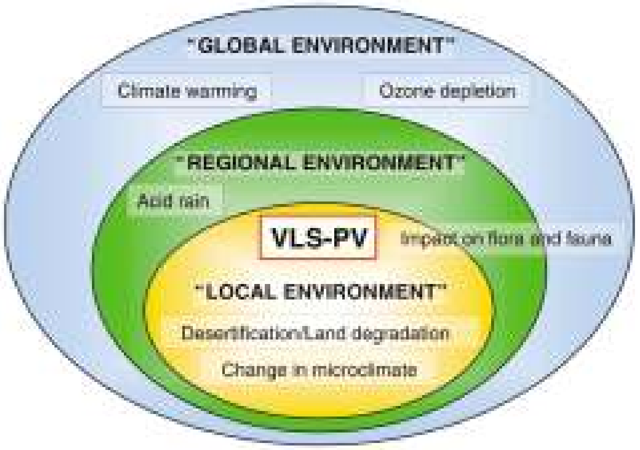


Figure A.3 Possible environmental issues impacted by VLS-PV systems

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 micro-climate 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 of VLS-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

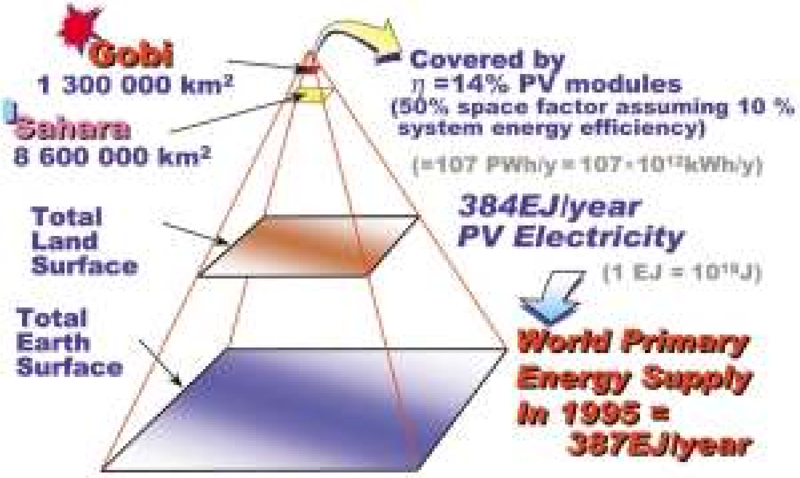


Figure A.6 Solar pyramid

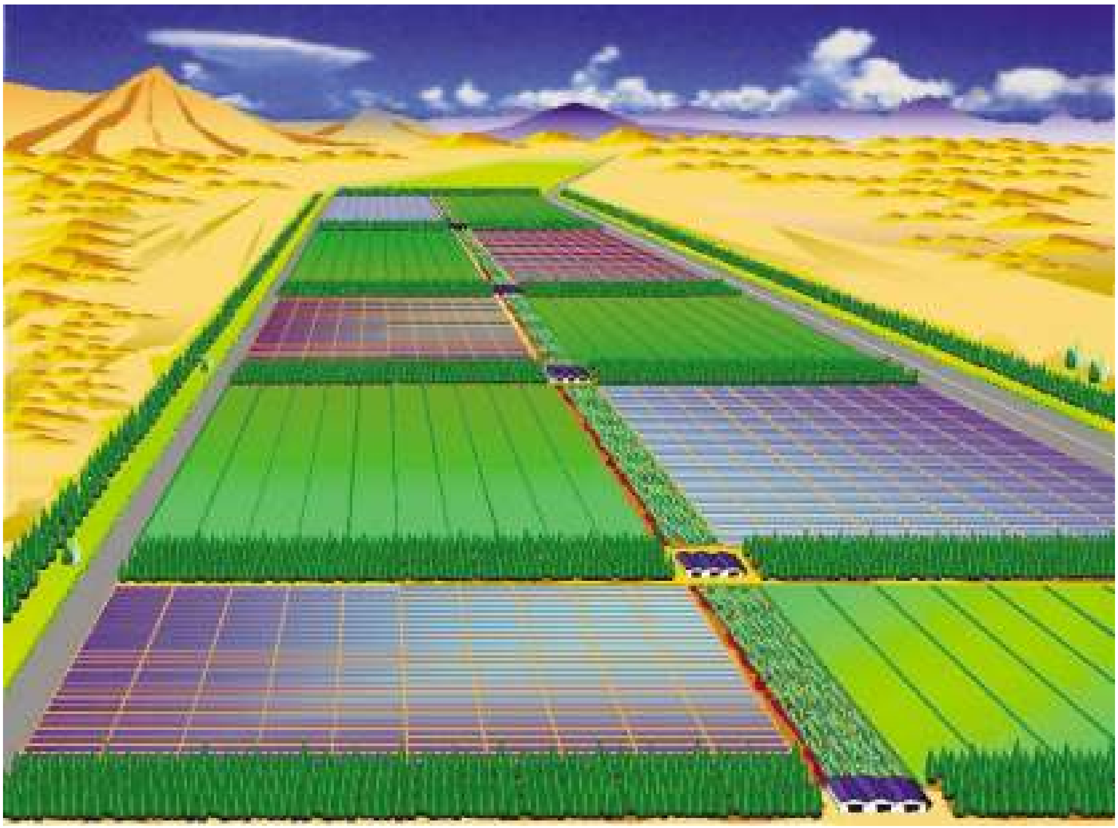


Figure A.7 Image of a VLS-PV system in a desert area

1 942,3 × 10^3 TWh(= 6,992 × 10^{21} J = 1,67 × 10^5 Mtoe), which means a level almost 18 times as much as the world primary energy supply, 9 245 Mtoe (107,5 × 10^3 TWh = 3,871 × 10^{20} 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.

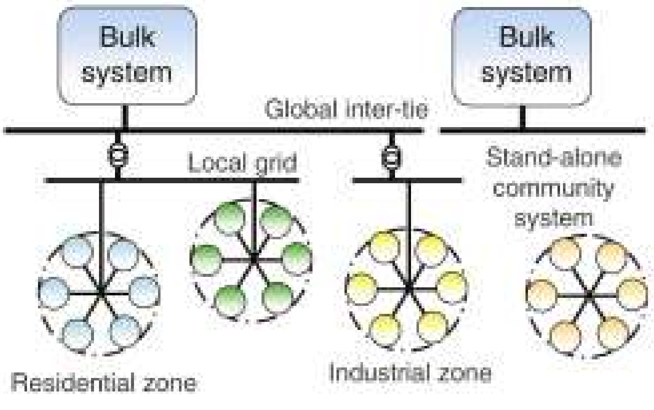


Figure A.8 Global network image

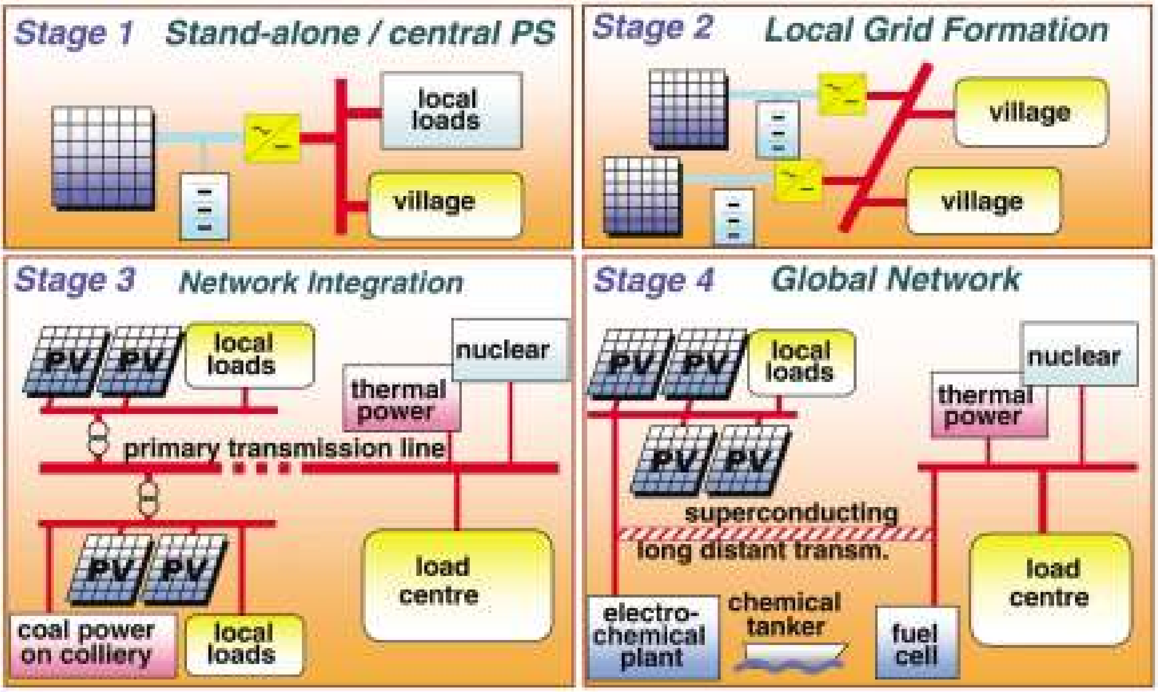


Figure A.9 Very large-scale PV system deployment scenario

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.

II EXECUTIVE SUMMARY B

VLS-PV case studies

VLS-PV systems are expected to generate a variety of advantages and will be one of the most attractive technologies for our future, particularly from the viewpoints of energy and the environment. However, realizing VLS-PV systems may constitute a long-term project, the nature of which we have not yet experienced. Therefore, the capability of VLS-PV systems and the configuration of each component must be assessed while taking into account site conditions, regional electricity demand, system performance, transmission technology or other alternative options, and concurrent use with other energy resources.

In Part II, some case studies on VLS-PV systems for selected regions were undertaken to employ the concepts of VLS-PV systems, after surveying general information concerning candidate sites. As case studies, first, introductory analyses on the generation costs of VLS-PV systems in world deserts were carried out. Secondly, energy payback time, CO_2 emissions and generation costs for VLS-PV systems in the Gobi Desert in China were evaluated in detail from a life-cycle point of view. Next, by assuming the Sahara Desert as the site, a network concept for a VLS-PV system was discussed and an estimation of the socio-economic impacts of technology transfer were analysed. Finally, using a simulation model for the Negev Desert located in the Middle East, fixed modules, one-axis tracking modules, two-axis tracking modules and a concentration system were summarized as expected technologies for VLS-PV systems.

B.1 GENERAL INFORMATION

The deserts that are the most promising sites for VLS-PV systems cover one-third of the land surface. The distribution is shown in Figure B.1. Because the degree of the impact of VLS-PV systems would depend upon the various conditions of particular regions, major indicators concerning major regions/countries with deserts were investigated. The selected regions/countries were China, India, the Middle East, North Africa, Mexico and Australia.

Although the economic state of these countries (except for Australia) is lower than the world average, it has been growing every year. Particularly, the growth in China and India is remarkable. With economic growth, energy consumption is increasing, most of which has depended upon fossil fuels for the commercial and industrial sectors. The trends for electricity were almost the same. In China, India and Australia, more than 75 % of the total electricity is generated by coal, while in the Middle East, North Africa and Mexico, oil and gas are the main resources for generating electricity. However, the candidate site is not limited to only one desert. That is to say, it may be concluded that all those deserts have the possibility to be candidate sites for VLS-PV systems.

As the methodologies for case studies, we focused on *life-cycle assessment* and *I/O analysis*. The former is a method for making environmental decisions, and is becoming increasingly popular in environmental policies. The latter is a method for estimating economic effects using an inter-industry table. These are effective methods to evaluate the impacts of VLS-PV systems. The former is applied in a case study on the Gobi Desert, and the latter is applied in a case study on the Sahara Desert focusing on socio-economic impact of VLS-PV systems.

B.2 PRELIMINARY CASE STUDY OF VLS-PV SYSTEMS IN WORLD DESERTS

To make a rough sketch of VLS-PV systems in desert areas and to investigate their economic feasibility, a preliminary case study was carried out. It was assumed that VLS-PV systems each with a 1 GW capacity would be installed in the six major deserts of the world, as shown in Figure B.2.

It was supposed that a 1 GW VLS-PV system, which is an aggregation of ten 100 MW PV systems with flat-plate fixed array structures, would be installed in each desert. Figure B.3 shows conceptual images of a 1 GW VLS-PV system. Assuming that the power output from a VLS-PV system would be transmitted to a given load centre, construction of 110 kV transmission lines would be taken into account. Though the transmission lines depend upon distance from the load centre to the VLS-PV system, a distance of 100 km was employed for all deserts to avoid complicated evaluation in this study.

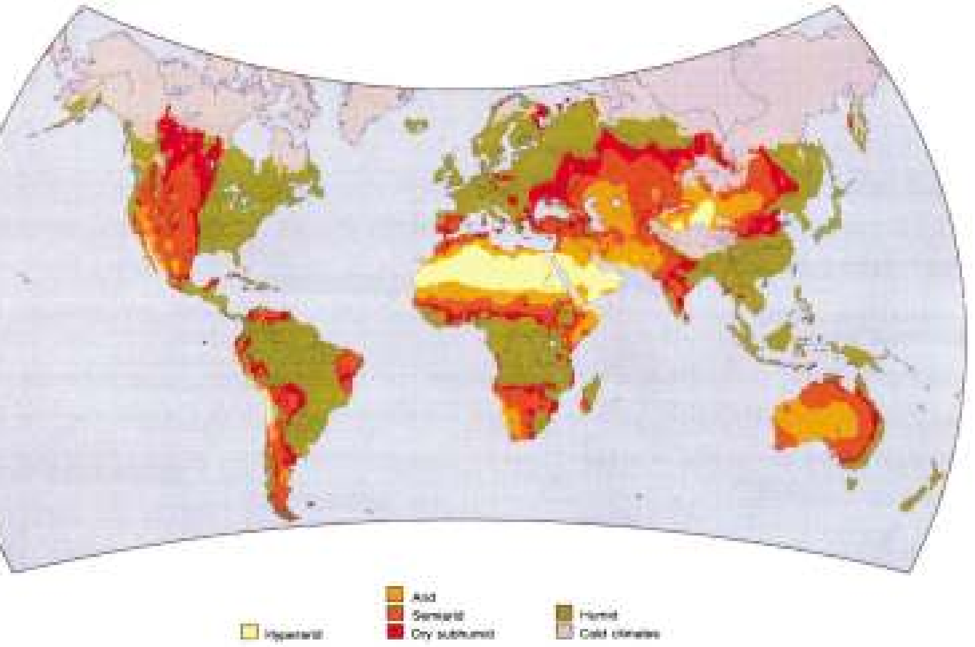


Figure B.1 Aridity zones of the world.
Source: World Atlas of Desertification (UNEP, 1992)

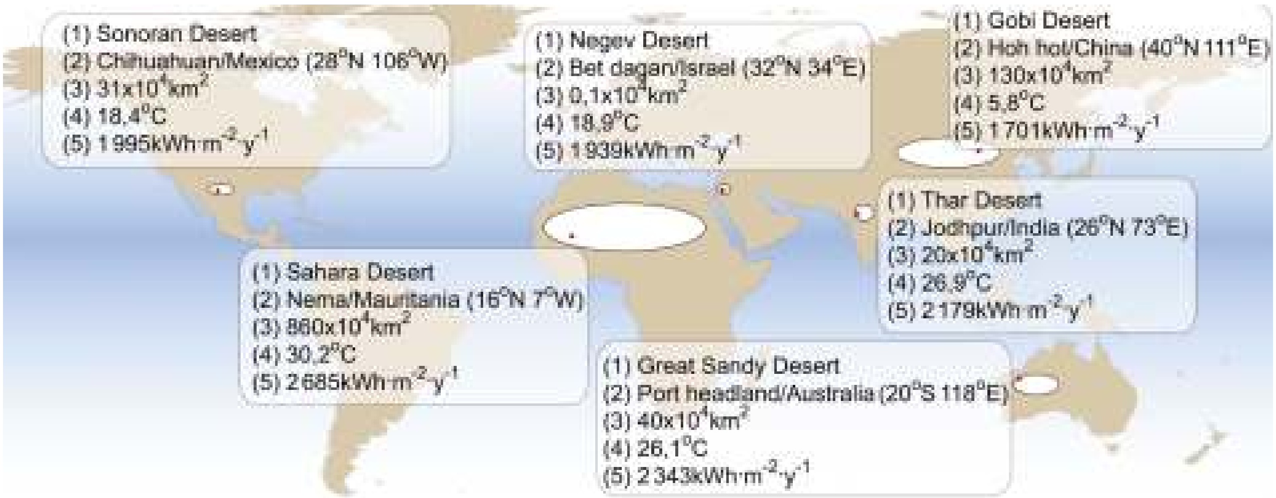


Figure B.2 The six deserts used in this case study: (1) desert name, (2) reference point, (3) area, (4) annual average ambient temperature, (5) annual horizontal global irradiation

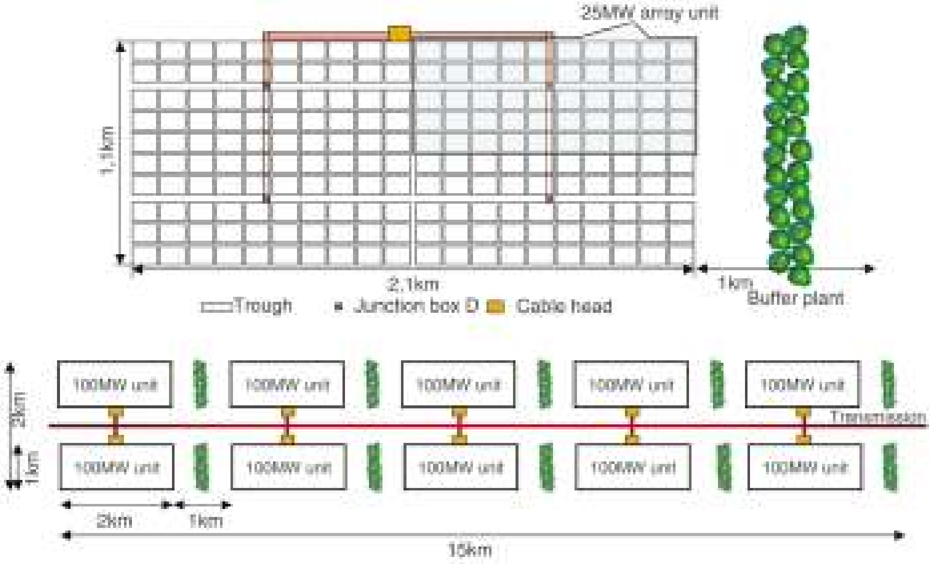


Figure B.3 Conceptual image of a 1 GW VLS-PV system

To calculate the annual power generation of the VLS-PV systems, cell temperature factors, load matching factors, efficiency deviation factors and inverter mismatch factors were taken into account in calculating the performance ratio (PR) for each installation site. The annual average in-plane irradiation was estimated from the annual global horizontal irradiation using a method for separating into direct and scattered radiation known as the *Liu-Jordan model*.

Initial costs, consisting of system component costs, transportation costs of the system components, system construction costs, and annual operation and maintenance (O&M) costs, were calculated in order to estimate the generation costs of VLS-PV systems installed in the six world deserts. No land cost was taken into account in this study, and cost data in Japanese yen were converted to US dollars at the (recent) exchange rate of 120 JPY/USD.

Based on estimates of the initial cost and the annual O&M cost, the total annual costs of 100 MW PV systems installed in the six deserts were calculated assuming an annual interest rate of 3 %, a salvage value rate of 10 %, a depreciation period of 30 years, and an annual property tax rate of 1,4 %. An annual overhead expense of 5 % of annual O&M costs was also taken into account. The generation costs are shown in Table B.1. The lowest generation costs were estimated when the array tilt angle was 20° independent of PV module price, except for the case of the Gobi Desert, where a tilt angle of 30° had the cheapest generation cost. The generation costs at a PV module price of 1 USD/W, which range from 5,2 to 8,4 US cents/kWh, are roughly one-third as great as those at a PV module price of 4 USD/W.

Figure B.4 represents the best estimates of generation costs for each desert as a function of annual global hori-

Table B.1 Generation cost of 100 MW PV system (US cents/kWh)

	Sahara		Negev	Thar	Sonoran	Great Sandy	Gobi
	Nema	Ouarzazate					
Module price = 4 USD/W							
Tilt angle = 10º	14,8	18,5	20,6	17,8	18,4	19,1	19,1
Tilt angle = 20º	**14,7**	**17,9**	**20,0**	**17,2**	**17,9**	**18,8**	18,1
Tilt angle = 30º	15,1	17,9	20,4	17,3	18,0	19,4	**17,6**
Tilt angle = 40º	16,1	18,3	21,3	17,9	18,7	20,5	17,6
Module price = 3 USD/W							
Tilt angle = 10º	11,6	14,5	16,6	14,0	14,5	15,5	15,0
Tilt angle = 20º	**11,5**	**14,0**	**16,1**	**13,6**	**14,1**	**15,4**	14,2
Tilt angle = 30º	11,8	14,0	16,5	13,7	14,2	15,9	**13,8**
Tilt angle = 40º	12,7	14,4	17,3	14,3	14,8	16,8	13,8
Module price = 2 USD/W							
Tilt angle = 10º	8,4	10,5	12,6	10,4	10,6	12,0	10,8
Tilt angle = 20º	**8,4**	**10,2**	**12,3**	**10,0**	**10,3**	**11,9**	10,3
Tilt angle = 30º	8,6	10,2	12,7	10,2	10,5	12,4	**10,0**
Tilt angle = 40º	9,3	10,6	13,4	10,7	11,0	13,2	10,0
Module price = 1 USD/W							
Tilt angle = 10º	5,2	6,5	8,6	6,6	6,7	8,5	6,7
Tilt angle = 20º	**5,2**	**6,3**	**8,4**	**6,4**	**6,5**	**8,4**	6,3
Tilt angle = 30º	5,4	6,4	8,8	6,6	6,7	8,8	**6,2**
Tilt angle = 40º	5,8	6,7	9,5	7,1	7,2	9,5	6,2

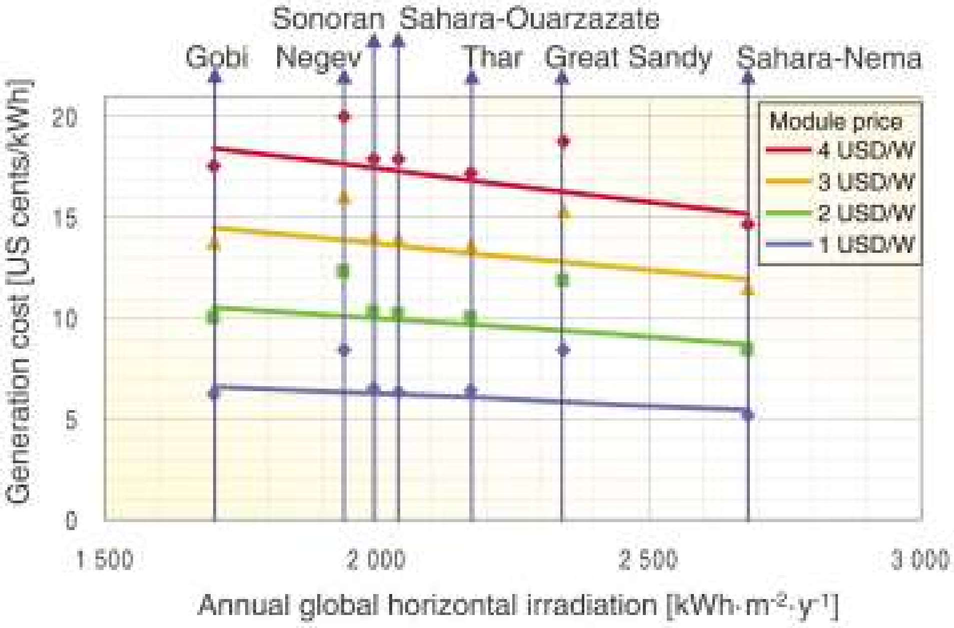


Figure B.4 Best estimates of generation cost for each desert as a function of annual global horizontal irradiation zontal irradiation. With the exception of the Negev Desert and the Great Sandy Desert, in which the generation costs are relatively higher because of high wages, the level of generation costs of a 100 MW PV system are roughly the same. Though the generation costs decrease gently according to the increase in annual irradiation, even the generation cost for the Gobi Desert, which has much less annual irradiation than the Sahara Desert, is on a level with that of the Sahara. Electricity from VLS-PV systems in these deserts would not be so cheap when the PV module price is expensive (such as at 4 USD/W), but the cost of the electricity will become economic even with the proven system technologies employed in this study when the PV module price is reduced to a level of 1 USD/W. The current market price of PV modules is not low enough for the realization of VLS-PV systems, but it is expected that PV module prices will decrease rapidly with the growth of the PV market. Therefore, VLS-PV systems in desert areas will be economically feasible in the near future.

B.3 CASE STUDIES ON THE GOBI DESERT FROM A LIFE-CYCLE VIEWPOINT

As shown previously, the introduction of VLS-PV systems in desert areas seems to be attractive from an economic point of view when PV modules are produced at a low price level, even though existing PV system technology is adopted. But we must pay attention not only to the economic aspect but also to the energy and environmental aspects, since PV systems consume a lot of energy at their production stage and therefore emit carbon dioxide (CO_2) indirectly, as a result. Therefore, the feasibility of VLS-PV systems was evaluated in depth from a life-cycle viewpoint by means of life-cycle analysis (LCA).

The Gobi Desert was chosen as the installation site of VLS-PV systems for LCA in this study. This desert, which lies in both China and Mongolia, is around $1{,}3 \times 10^6$ km^2 in size and is located between 40°N and 45°N. Installation of the VLS-PV systems in the Gobi Desert has some advantages: it is a stone desert rather than sand, and a utility grid exists relatively close to the desert. In this study, it was assumed that the 100 MW VLS-PV system would be installed in the Gobi Desert on the Chinese side.

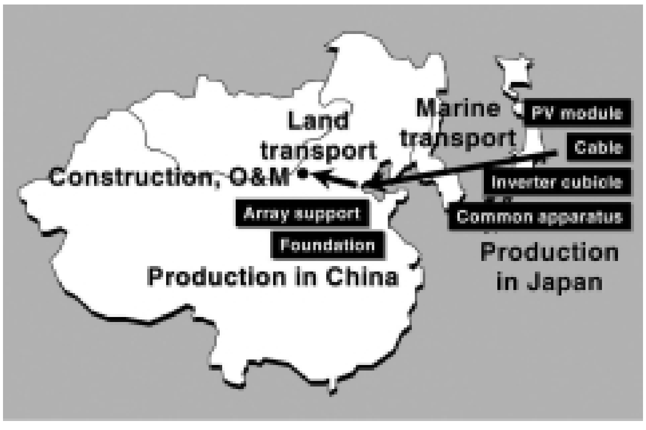


Figure B.5 Life-cycle framework of the case study

To execute LCA, a life-cycle framework of the VLS-PV system has to be prepared. Figure B.5 gives an image of the life-cycle framework of the VLS-PV system in this study. It was supposed that array support structures, transmission towers and foundations for the array support structures and the transmission towers would be produced in China and that other system components would be manufactured in Japan. All the components are transported to some installation site near Hoh-hot in the Gobi Desert by marine and/or land transport. Land transport is also taken into consideration. Land cost is not considered, but land preparation was considered here.

In this study, a south-facing fixed flat array structure was employed and the array tilt angle was given as a variable parameter (10°, 20°, 30°, 40°). Both PV module price and inverter price were also dealt with as variable parameters. System performance ratio (PR) was assumed to be 0,78 by consideration of operation temperature, cell temperature factor, load matching factor, efficiency deviation factor and inverter mismatch factor (= 0,90). It should be noted that the efficiency deviation factor involves long-term performance degradation (0,5 %/year) as well as short-term surface degradation by soil (= 0,95).

The number of PV modules in a string was taken to be 21 by consideration of the V_{oc} of the PV module and the D.C. voltage of the inverter. Then the rated output from one string is 2,52 kW. Accordingly a 250 kW PV array requires 100 strings. Two of these 250 kW PV arrays located north and south in parallel form the 500 kW system with a 500 kW inverter and a 6,6 kV/500 V transformer.

Figure B.6 illustrates an example of the field layout for such a 100 MW VLS-PV system with a 30° tilt angle. It was assumed that array supports were made of zinc-plated stainless steel (SS400), and the thickness of several types of steel material were chosen according to stress analysis assuming that the wind velocity is 42 m/s, based upon the design standard of structural steel by the Japanese Society of Architecture. A cubic foundation made of concrete was used. Its dimension was decided in accordance with the design standard of support structures for power transmission

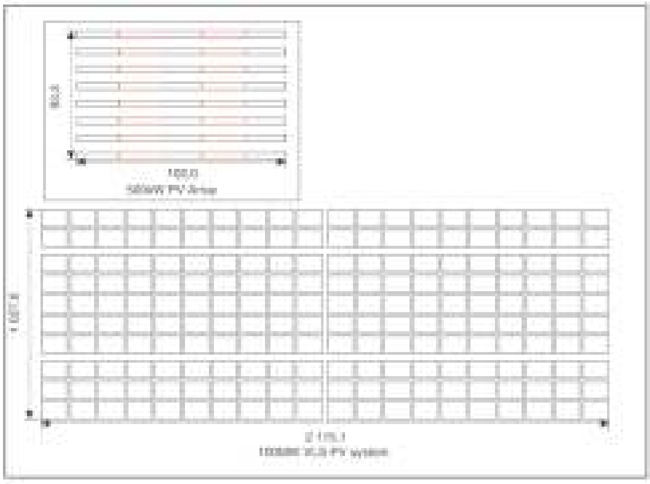


Figure B.6 Example of field layout for 100 MW VLS-PV system (30° tilt angle) (unit: m) by the Institute of Electrical Engineering in Japan. Taking into account Japanese experience in civil engineering and the local labour situation in China, local labour requirement was also estimated for system construction such as PV module installation, array support installation, production and installation of foundations, cable installation, and installation of common apparatus. Table B.2 shows a summary of requirements to construct a 100 MW VLS-PV system in the Gobi Desert in China.

Labour cost for the operation was estimated based on the assumption of a 100 MW VLS-PV system that was in service 24 hours a day by nine persons working in shifts. The annual labour cost for electrical engineering was assumed for these operators. Maintenance cost was also calculated based on actual results of a PVUSA project; that is, the cost of repair parts was 0,084 %/year of the total construction cost and labour for maintenance was one person per year.

Figure B.7 shows the results of the generation cost of the 100 MW PV system. Differences in the annual cost due to PV module price resulted in differences in these generation costs. Though the least annual cost was obtained at the least array tilt angle for any tilt angle, the minimum generation cost appeared at around 30° due to the increase in annual power generation as the array tilt angle increased. The generation cost stays at a high level, around 18 US cents/kWh (just less than the current consumer price for residential sectors in Japan), when the PV module price is 4 USD/W. But it decreases remarkably to less than 7,0 US cents/kWh (close to the current electricity tariff in China) if the PV module price goes down to 1 USD/W.

Figure B.8 represents the results of total primary energy requirement and energy payback time (EPT). EPT was estimated assuming that electricity from the PV system would replace utility power in China where recent conversion efficiency is around 33 %. As shown in these figures, the best EPT was obtained at 20° array tilt angle, and BOS components made of steel and concrete (such as array supports, transmission lines, foundations and troughs) contributed much to both energy requirements because these materials consume a great deal of energy to produce in China. Transportation also uses a certain amount of energy. Nevertheless, EPT resulted in a very low level. This suggests that the total energy requirement throughout the life-cycle of the PV system (considering production and transportation of system components, system construction, operation and maintenance) can be recovered in a short period much less than its lifetime. Therefore VLS-PV is useful for energy resource savings.

Figure B.9 shows the results of life-cycle CO_2 emissions and life-cycle CO_2 emission rate of the 100 MW PV system, assuming 30-year operation periods. Discussion of these results is the same as for the total primary energy requirement and the EPT. Considering the CO_2 emission rate of existing coal-fired power plants, about 300g-C/kWh, the life-cycle CO_2 emission rate of a 100 MW PV system is much lower. So the VLS-PV system in desert

Table B.2 Summary of total requirements for a 100 MW VLS-PV system in the Gobi Desert

Item		Unit	10º	20º	30º	40º
Material requirement						
PV module[a]		piece	848 485	848 485	848 485	848 485
Array support structure[a]		ton	8 291	8 606	9 658	10 763
Foundation[a]		m^3	46 487	46 487	69 391	98 801
Cable[a]	600 V CV 2 mm^2 (single core)	km	1 178	1 364	1 434	1 499
	600 V CV 8 mm^2 (double core)	km	173	173	173	173
	600 V CV 60 mm^2 (single core)	km	67	–	–	–
	600 V CV 100 mm^2 (single core)	km	–	88	106	122
	6,6 kV CV-T 22 mm^2	km	21	27	33	37
	6,6 kV CV 200 mm^2 (single core)	km	38	38	38	38
	110 kV CV 150 mm^2 (single core)	km	11	13	14	15
Trough[a]		m^3	35 235	37 450	39 406	41 037
Common apparatus						
Inverter (with transformer)[a]		set	202	202	202	202
6,6 kV capacitor[b]		set	202	202	202	202
6,6 kV GIS		set	4	4	4	4
110 kV/6.6kV transformer[b]		set	5	5	5	5
110 kV GIS		set	4	4	4	4
2,4 MVA capacitor		set	1	1	1	1
Common power board		set	1	1	1	1
Transportation						
Heavy oil consumption		ton	145	145	147	148
Diesel oil consumption		kl	6 101	6 261	7 941	10 031
Transmission						
Cable	110 kV TACSR410 mm^2	km	134	134	134	134
	A.C. 70 mm^2	km	16,7	16,7	16,7	16,7
Pylon (steel)		ton	742	742	742	742
Foundation		ton	1 715	1 715	1 715	1 715
Construction						
Diesel oil consumption		kl	128	170	207	238
Labour requirement		man-year	2 711	2 752	2 831	2 911

[a] *99 % of construction yield is considered.*

[b] *Spare sets are included.*

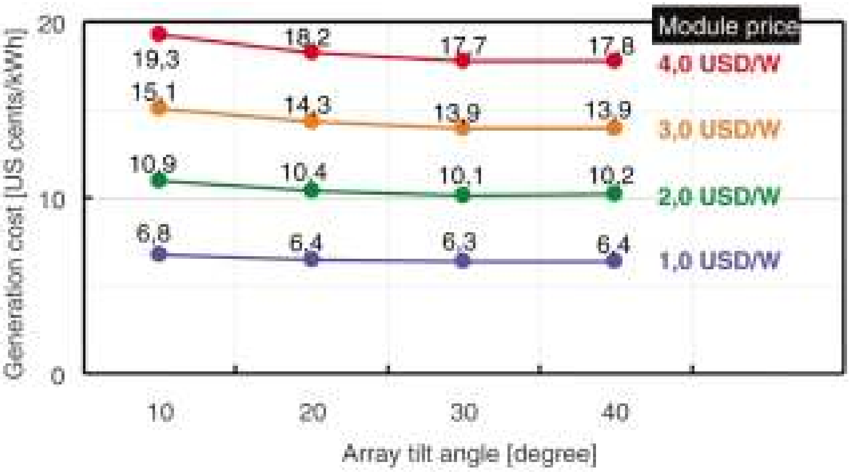


Figure B.7 Generation cost of a 100 MW PV system

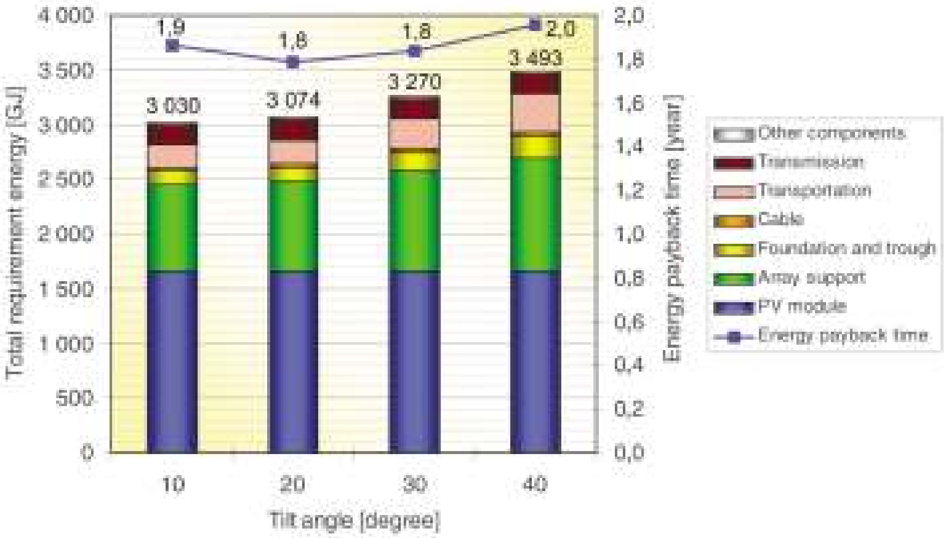


Figure B.8 Total primary energy (TPE) requirement and EPT of a 100 MW PV system

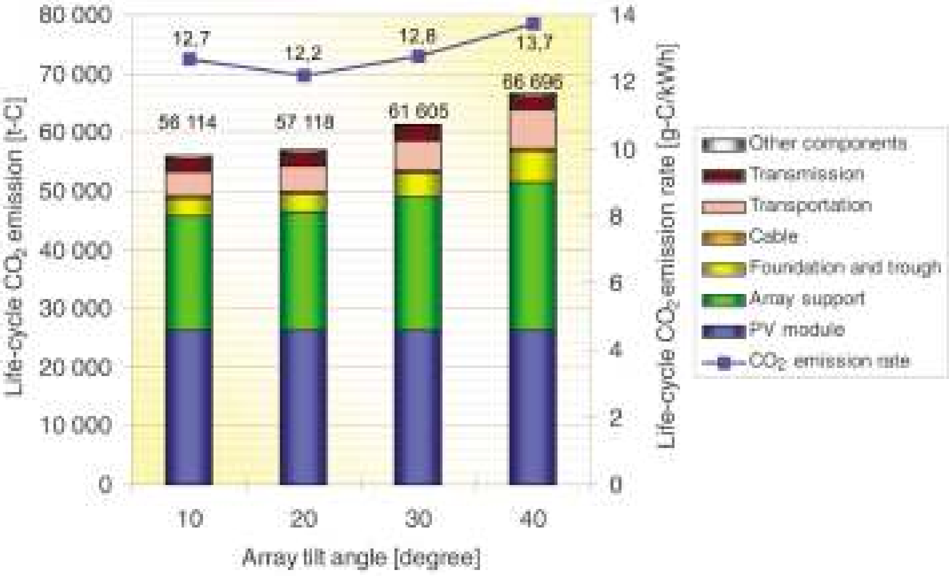


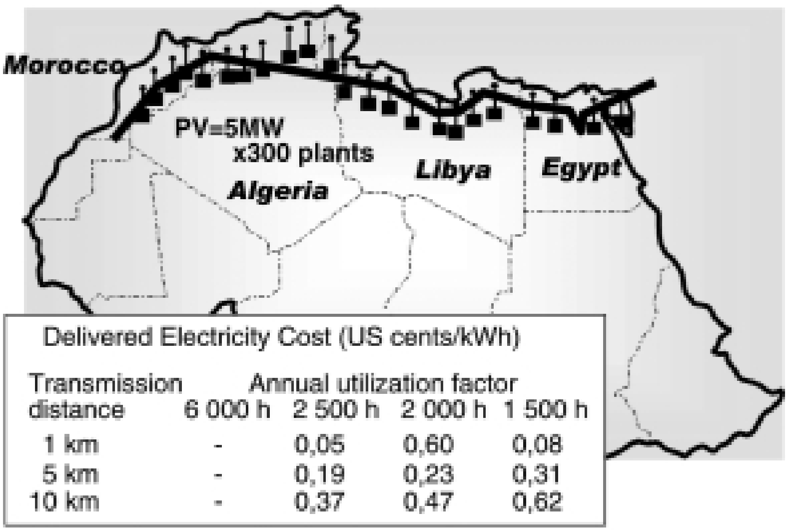
Figure B.9 Life-cycle CO_2 emissions and life-cycle CO_2 emission rate of a 100 MW PV system areas is a very effective energy technology for preventing global warming.

B.4 CASE STUDIES ON THE SAHARA DESERT

It is necessary to build a concept for supplying the electricity that VLS-PV generates, and the supply of such electricity may contribute to regional development. Additionally, VLS-PV may induce some economic impacts, such as an employment effect. A network concept for introducing VLS-PV in the Sahara Desert and the expected socio-economic impact of the technology transfer of PV module fabrication were discussed.

A transmission system devoted to the exploitation of remote energy resources has to be designed to minimize transmission costs, while respecting reliability and environmental requirements. Transmission costs depend on the transmission distances and the hours of yearly utilization. From these viewpoints, the transmission costs were analysed for three cases: (1) a 1,5 GW centralized PV power plant plus 300–900 km of transmission line; (2) 1,5 GW produced by 30 PV plants of 50 MW; and (3) 1,5 GW produced by 300 PV plants of 5 MW. The third case produced the most attractive results. Each of these plants should cover an area of approximately 10 ha (0,1 km^2), and the power would be typically delivered through single A.C. MV lines (for example, 20 kV). In this case, the PV plants would be distributed within the coastal strip of North African countries, placed less than 10 km from the HV/MV substations and the distribution networks that feed the loads. When assuming 5 km as a transmission distance, the transmission cost would range from 3,7 to 6,2 USD/MWh, depending upon yearly utilization of VLS-PV, as shown in Figure B.10.

Additionally, having a variety of technology transfers is very important for the sustainable expansion of VLS-PV, and the transfer of PV manufacturing facilities may bring about the stimulation of various economic activities as well as the establishment of a local PV industry. To grasp such impacts quantitatively, a technical analysis of an industrial initiative in the photovoltaic sector and evaluation of the socio-economic impacts of the PV demand in terms of gross domestic production and job creation were carried out by the I/O analysis method. When assuming the transfer of a facility with the capacity of 5 MW/year, it has been made clear that the local availability of cells (Case L) brings very different returns on investment in the local economy, and the induced production increases from 1,4 times to 3,5 times the expenditure, as shown in Figure B.11 and Table B.3. The induced job creation involved



Delivered Electricity Cost (US cents/kWh)

Transmission distance	Annual utilization factor 6 000 h	2 500 h	2 000 h	1 500 h
1 km	-	0,05	0,60	0,08
5 km	-	0,19	0,23	0,31
10 km	-	0,37	0,47	0,62

Figure B.10 Case of small PV systems along with network

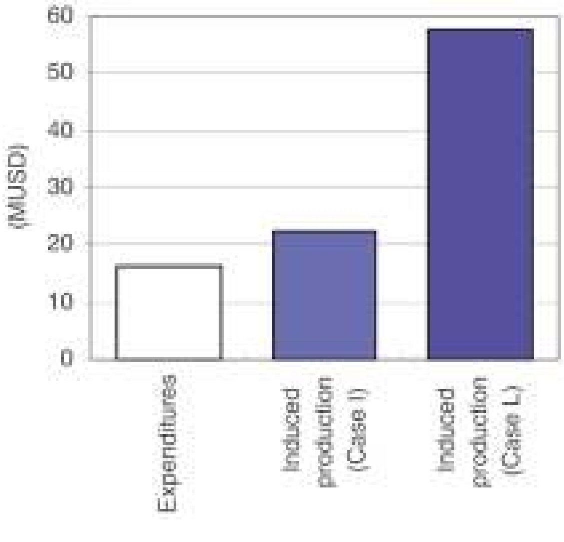


Figure B.11 Necessary expenditure and induced production (MUSD)

Table B.3 Induced impacts of transferring a PV module manufacturing facility

		Total induced (1 000 USD)		Value added (1 000 USD)		Job creation (man-years)	
		I	L	I	L	I	L
1	Photovoltaic	16 294	16 294	1 485	1 485	87	87
6	Misc. petroleum and coal products	205	1 248	160	975	23	138
7	Petroleum refineries	271	1 612	53	315	8	45
8	Electricity and water	335	1 492	85	377	12	53
18	Metals smelting and pressing	323	4 477	113	1 573	16	223
19	Fabricated metal products	301	1 082	113	406	16	58
20	Non-electrical machinery	44	599	18	248	3	35
22	Electrical and electronic equipment	501	16 350	170	5 567	24	791
24	Chemicals	1 039	3 718	318	1 138	45	162
25	Rubber and plastics	656	1 210	217	400	31	57
28	Commerce and transport	195	1 244	111	709	21	132
31	Insurance	500	539	157	169	28	30
32	Other services	648	2 326	415	1 492	73	262
	Others	947	5 389	446	2 317	103	497
	Total	**22 259**	**57 581**	**3 862**	**17 099**	**489**	**2 570**
	Induced production coefficient	*1,36*	*3,53*				

2 570 employees (Case L), while on the other hand, in the case of not assuming the availability of local cell production (Case I), the induced job creation involved 489 employees.

Besides the economic effects of manufacturing, the availability of PV systems contributes to support social and economic development of the region that is more environmentally sound. To perform technology transfer effectively, clear knowledge of the needs of, as well as the potential benefits to, the local population is required.

However, it is expected in the future that VLS-PV will be reinforced year by year with operating PV module facilities in the region, and that the electricity generated by VLS-PV will be able to supply global areas through the Mediterranean Network. As a result, an *electricity-for-technology* exchange scheme may be initially set up.

B.5 CASE STUDIES ON THE MIDDLE EAST DESERT

There are certain types of PV systems considered for constructing VLS-PV systems. In addition to the fixed-module VLS-PV, the use of sun-tracking non-concentrator and concentrator PV systems is expected. The relative performances – which involved static PV modules (oriented facing south, with tilt angle equalling geographic latitude), one-axis tracking modules (having a horizontal axis in the N–S direction), two-axis tracking modules, and a 400× point-focus concentrator PV system – are addressed and the potential economic benefits of employing highly concentrated solar radiation as an energy source for PV cells were considered. As a practical site, the Negev Desert was chosen, because the Negev is located at a truly representative 'point' among the principal deserts of the Middle East and has produced a wealth of documented detailed meteorological data.

Computer simulations were carried out, using a typical meteorological year (TMY) dataset for a specific Negev site, *Sede Boqer*. At Sede Boqer, a 25 m diameter multipurpose solar concentrator operating at a solar concentration of 400×, as shown in Figure B.12, already exists.

Simulations have indicated that, in a typical Middle Eastern desert, 8,5 % total system efficiency from a conventional static PV system, 10,7 % effective system efficiency for a one-axis sun-tracking system, and 11,8 % effective system efficiency for a two-axis tracking system are to be expected, where all three system types employ identical, polycrystalline Si PV modules. However, using a dense array of Si concentrator PV cells in a 400-sun point-focus system, the simulations have indicated that 16,5 % total system efficiency (17,2 % effective system efficiency) may be attainable if the cells are actively cooled so as to remain at a fixed temperature of 60 °C. Here, *effective system efficiency* was defined as the total annual A.C. energy output divided by the annual global irradiance that would be received by a static system of similar aperture area, irrespective of the type of PV system that was being discussed (i.e. one-axis, two-axis, or concentrator).

Regarding the prospects for a concentrated VLS-PV plant, it was concluded that a single 1 m^2 concentrator PV module exposed to a light flux of 400 suns (where 1 sun is

Figure B.12 The PETAL (Photon Energy Transformation and Astrophysics Laboratory) 400 m^2 aperture parabolic dish reflector at Sede Boqer (the square screen at its focal point is 1 m x 1 m in size)

Table B.4 Comparison of predicted area-related performance parameters for various VLS-PV systems at Sede Boqer

	Static 30° tilt	One-axis tracking	Two-axis tracking	Concentrator (CPV)
System yield (kWh · kW^{-1} · y^{-1})	1 644[a]	2 071[a]	2 279[a]	1 754[b]
Yield per PV module area (kWh · m^{-2} · y^{-1})	189	238	262	154 000
Yield per 400 m^2 light capture area (kWh·y^{-1})	75 600	95 200	104 800	154 000
Land area/light capture area	2,89	3,42[c]	7,90[d]	7,90[d]
Yield per land area (kWh · m^{-2} · y^{-1})	65,4	69,6	33,2	48,7

[a] *Solarex MSX64 modules.*
[b] *Modified SunPower Heda 303 cells.*
[c] *Rancho Seco plant.*
[d] *Hesperia Lugo plant.*

here defined as 1 000 W/m^2) would produce nearly 100 kW of electric power. Table B.4 compares a number of area-related output parameters of interest for all four types of systems.

The estimation of the cost of a 30 MW turnkey project was approximately 136 500 USD per concentrator (CPV) unit, where in a typical meteorological year each unit would generate 154 000 kWh of A.C. electricity at Sede Boqer. When assuming 30-year financing, the electricity would work out to 0,045 USD/kWh in the case of 3 % interest and to 0,064 USD/kWh in the case of 6 % interest. By considering annual O&M costs to be 2 % of the capital cost, 0,018 USD/kWh would be added to the electricity costs given above.

There is a wealth of hardware and performance data available for non-concentrator PV systems for validation, while the experimental situation is sparse for concentrated PV systems. However, it might be concluded that the economics of a concentrator VLS-PV plant could turn out to be attractive.

Scenario studies and recommendations

Through Parts I and II, it was suggested that the VLS-PV system would be an attractive energy source in the 21st century. However, the long-term sustainable operation of VLS-PV systems must be discussed considering local benefits to be brought about by introduction and expansion of the VLS-PV system. Then the step-by-step enlargement of the PV system might be an effective way to prevent financial, technological and environmental risks caused by its rapid development. In addition, it is expected that this activity will be continued with properly allotted efforts for further quantitative discussion and necessary evaluation of VLS-PV to improve our knowledge, to overcome its defects and to establish an international network with other interested people. In Part III, based on the generalized understandings from Parts I and II, scenario studies were carried out and 'recommendations' to stakeholders as conclusions were described.

In the scenario studies, a concept for the sustainable growth of VLS-PV was discussed, which included both the long-term economic aspects and the life-cycle point of view, and a development scenario assuming actual stages was proposed. Further, the financial and organizational sustainability on proposed stage was discussed.

Finally, in order to propose mid- and long-term scenario options that would enable the feasibility of VLS-PV, recommendations for considerable stakeholders were given to realize such long-term targets gradually.

C.1 SUSTAINABLE GROWTH OF THE VLS-PV SYSTEM CONCEPT

VLS-PV has a huge generating power capacity and it will be more feasible to enhance the capacity gradually. Therefore, for the introduction of VLS-PV, a development scheme for sustainable growth is needed. Considering the economic aspects of VLS-PV is also important for a sustainable initiative.

The domestic production of PV modules is one of the most important issues for the successful introduction of VLS-PV. As an example, a conceptual scheme of PV module manufacture through technology transfer to the region, as shown in Figure C.1, was considered. PV modules produced at the facilities will be installed in desert areas as part of a centralized system.

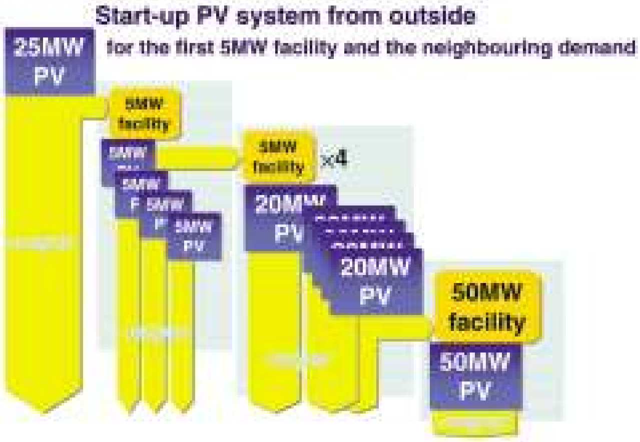


Figure C.1 Conceptual view of a sustainable, technology transfer scheme

The power-generating capacity of the system will be reinforced yearly with operating PV module facilities and a VLS-PV system will be developed. Figure C.2 shows the sustainable scheme for VLS-PV development, which supposes that the capacity of VLS-PV will be over 1 GW in 28 years, and will reach 1,5 GW in 43 years. With the replacement of PV modules and facilities, and with operating facilities, the VLS-PV will be a sustainable power plant. Further, when a variety of VLS-PV components are produced near the VLS-PV and waste management, like recycling, is introduced, 'scrap and build' for VLS-PV will be realized, as shown in Figure C.3.

In the economic analysis, the generation cost for VLS-PV was estimated to be around 3–5 US cents/kWh for 1,5 GW. However, to obtain long-term economic benefits, providing advantageous incentives will be needed in the first stage. Further, for deploying domestic/regional manufacturing of VLS-PV system components, it is necessary to build a financial mechanism for investing in facility operation, not only investment for constructing the facility. Some organizational/institutional support will be indispensable and this will contribute not only to profitability in the long term but also to successful technology transfer.

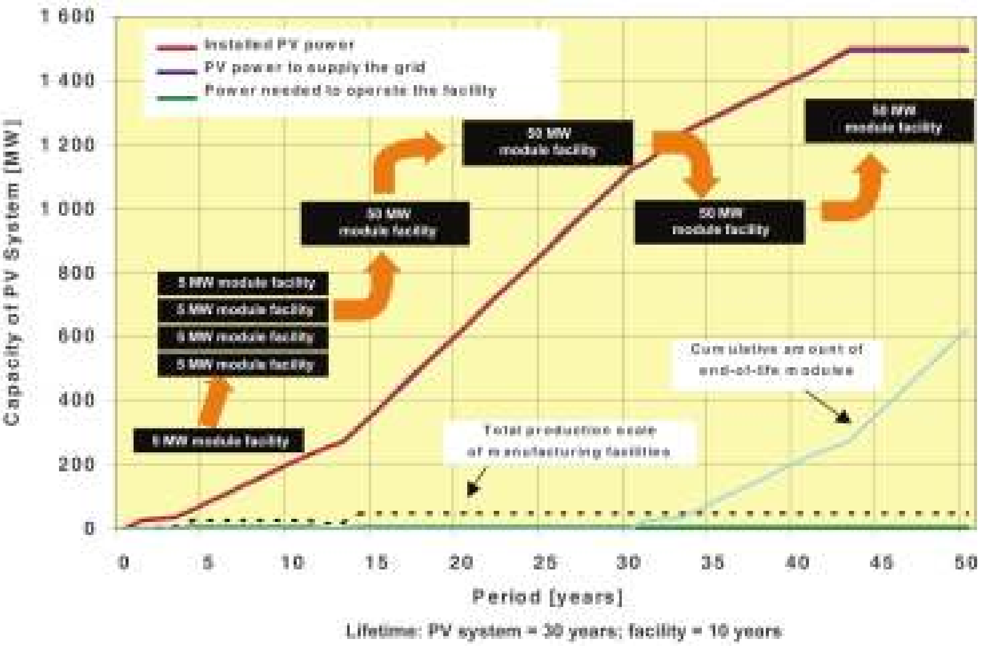


Figure C.2 Sustainable scheme for VLS-PV development

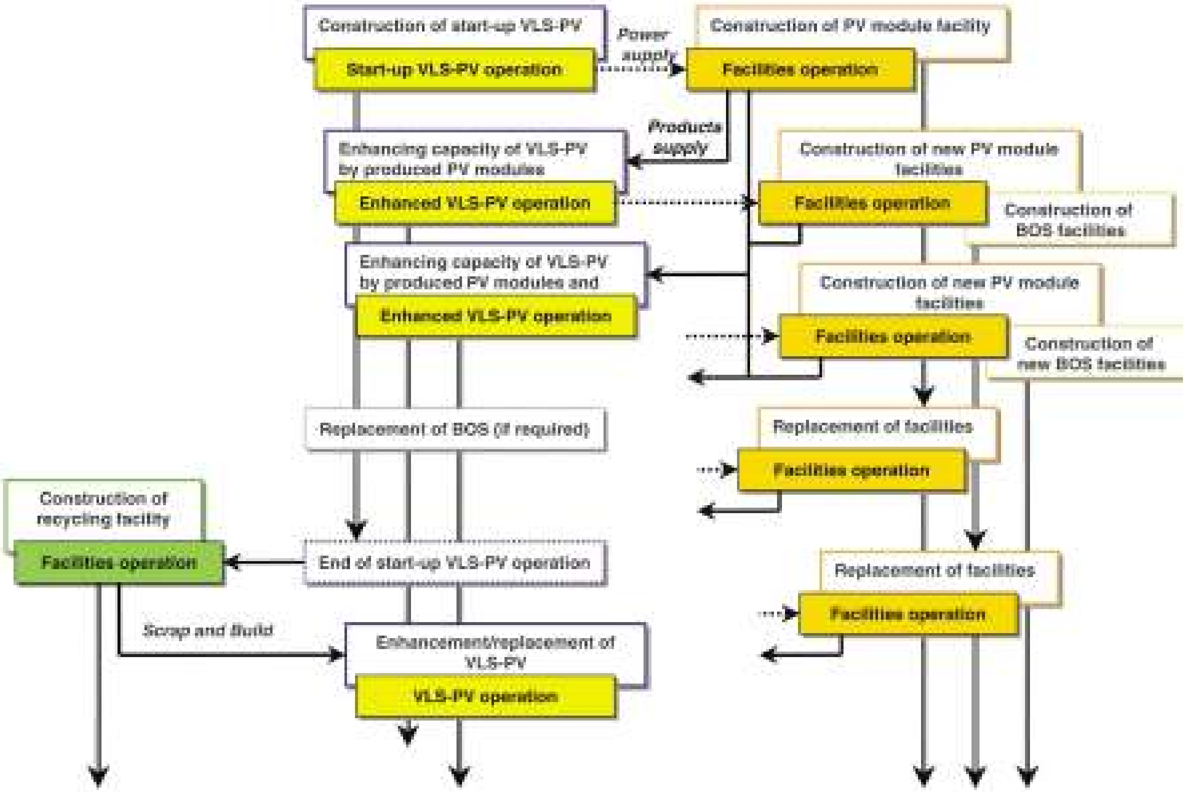


Figure C.3 Example of a concept for sustainable growth of VLS-PV

C.2 POSSIBLE APPROACHES FOR THE FUTURE

The VLS-PV scheme will be a project that has not been experienced before. Therefore, to realize VLS-PV it is necessary to identify issues that should be solved and to discuss a practical development scenario. Focusing on the technical development, a basic concept for VLS-PV development, which consisted of the following four stages, was proposed. Although the capacity of the first PV system was set at 25 MW, *R&D stage (S-0)* was assumed as the first stage to verify the basic characteristics of the PV system.

- S-0: R&D stage (four years)
  - PV system: 5 × 500 kW research system
  - Price of PV module: 4 USD/W

  - PV module: import from overseas
  - Inverter: import from overseas
- S-1: Pilot stage (three years)
  - PV system: 25 MW pilot system
  - Price of PV module: 3 USD/W
  - PV module: import from overseas
  - Inverter: import from overseas
- S-2: Demonstration stage (three years)
  - PV system: 100 MW large-scale system
  - Price of PV module: 2 USD/W
  - PV module: domestic/regional production
  - Inverter: import from overseas
- S-3: Deployment stage (five years)
  - PV system: around 1 GW VLS-PV system with energy network
  - Price of PV module: 1 USD/W
  - PV module: domestic/regional production
  - Inverter: domestic/regional production

To develop VLS-PV, there are many technical and non-technical aspects that should be considered in each stage. These are summarized in Table C.1.

S-0: R&D stage (four years)
Five 500 kW PV systems will be constructed and operated to verify the basic characteristics of the PV system in a desert area. The reliability of VLS-PV in a desert area and the requirements for grid connection will be mainly examined and investigated as technical issues. Conditions for site selection, planning of co-operation frameworks, including training engineers, and funding schemes will be investigated as non-technical issues.

S-1: Pilot stage (three years)
A 25 MW PV system will be constructed and operated to evaluate and verify preliminary characteristics of a large-scale PV system. Technical issues here are of a higher level and shift to concentrated and grid-connected PV systems, for building VLS-PV technical standards. PV module facilities will be constructed and operated although the PV modules constructed would be imported. PV module production will be introduced in the next stage. Further, development for preventing desertification, such as vegetation and plantations, will also be started at this stage.

S-2: Demonstration stage (three years)
A 100 MW PV system will be constructed and operated to research methods of grid-connected operation and maintenance when VLS-PV actually takes on part of the local power supply. The knowledge, on connecting VLS-PV to the existing grid line, obtained at this stage will be technical standards for deploying VLS-PV. Non-technical issues will also advance for industrialization. Mass production of PV modules will be carried out and BOS production on-site will be started towards a deployment stage.

S-3: Deployment stage (five years)
A 1 GW PV system will be operated to verify the capability of VLS-PV as a power source. Although the technologies for generating and supplying electricity will be nearly completed, for deployment of VLS-PV in the future, some options such as demand control, electricity storage and component recycling will be required. These will contribute to building the concept of the *solar breeder*, which is similar to 'scrap and build' shown in Figure C.3, and some business plans for VLS-PV will be proposed.

The implementation of VLS-PV will activate the world PV industries in a wide range of technologies involving a vast range from solar-cell production to system construction. However, to achieve the final stage, the previous stages from S-0 to S-2 are important, and the developments in each stage should be carried out steadily.

Table C.1 Summary of the VLS-PV development scenario

		Sub-stage	
		Technical issues	Non-technical issues
S-0: R&D stage	Scale of system: 5 x 500 MW Module cost: 4 USD/W Module: import from overseas Inverter: import from overseas	• Examination of the reliability of a PV system in a desert area • Examination of the required ability of a PV system for grid connection	• Site selection for VLS-PV based on various conditions • Project planning, including training engineers and funding
S-1: pilot stage	Scale of system: 25 MW Module cost: 3 USD/W Module: import from overseas Inverter: import from overseas	• Development of the methods of O&M for VLS-PV • Examination of the control of power supply from a PV system to grid line	• Development of the area around VLS-PV to prevent desertification • Training engineers for PV module production on-site
S-2: demonstration stage	Scale of system: 100 MW Module cost: 2 USD/W Module: domestic/regional production Inverter: import from overseas	• Development of the technical standards for O&M of VLS-PV, including grid connection	• Training engineers for mass production of PV modules and for BOS production on-site • Preparation for industrialization by private investment
S-3: deployment stage	Scale of system: 1 GW Module cost: 1 USD/W Module: domestic/regional production Inverter: domestic/regional production	• Building the concept of 'solar breeder' from the viewpoint of technical and non-technical issues	

C.3 FINANCIAL AND ORGANIZATIONAL SUSTAINABILITY

The proposed scenario for the development and introduction of very large-scale PV systems in deserts has basically four stages: R&D, pilot, demonstration and deployment (commercial) stages. The characteristics of these stages range from theoretical to technical, i.e. through the techno-economic, socio-economic and purely commercial characteristics. Each stage of growth has its own characteristics and cost structure.

From a viewpoint of the financial scenario, the feasibility stage should be settled before the R&D stage. The estimated investment levels for these phases range from 1–2 MUSD for the feasibility stage to 4 000 MUSD for the commercial stage.

An indicative portfolio of funding sources for each stage is identified. Since the first two stages are not supposed to be commercial, but are theoretical and experimental, no further exploitation or return on investment (ROI) calculation is undertaken. At this moment, the costs and funding arrangements of the commercial stage can only be estimated. The third stage (the demonstration stage) should generate cost and income details for a full investment proposal for such a large plant.

There are six potential sources of financing the investment. In Table C.2, a first estimate of possible contributions from these sources is given:

- Direct subsidies may be provided for demonstration, experimental, export promotion, or development co-operation reasons by governmental bodies. The closer a given situation is to being commercial, the lower the direct subsidies that are expected to be granted.
- The provision of soft loans and green money may be driven by similar motives, but they can also be provided by private capital. The loan money should increase as the project becomes more commercial to leverage the ROI for the shareholders.
- Equity and in-kind contributions are investments by the shareholders of the project. Examples of in-kind contributions are office housing and free management services.
- Import duties may be exempted or reduced to stimulate the uptake of new or renewable energy technologies in a particular country.
- Green certificate buy-off may constitute an up-front contribution of a utility that subsidizes the project and receives green certificates in return.
- Other instances may be profit tax advantages of investors regarding the project.

Basically, all net investment costs, interest and profits should be recovered through exploitation of the plant. The net investment is the investment after subtracting subsidies and fiscal advantages. There are four recognized sources of income during the exploitation stage:

- electricity power sales
- opportunity costs, to be explained later
- green certificates, not to be double-counted with a possible up-front investment
- tax incentives, such as reduced VAT and exemption from pollution taxes.

In Table C.3, an overview of the income and recurring costs from the exploitation is given.

The feasibility stage is easily supported when applying to national or multinational governmental organizations. The size and novelty of the project is expected to gear sufficient interest to achieve the involvement of the World Bank, the EU, and the respective national governments of interested OECD countries. There are no exploitation costs or income at this stage. At a cost of around 30–40 MUSD, this R&D/pilot project would be a project of a relatively large size for individual governments to bear, but not for two or more governments or multilateral organizations. As

Table C.2 Example of contribution towards investment by various sources of co-funding in the different stages of the introduction of VLS-PV

Source Stage	Direct subsidies	(Soft) loans including green money	Equity and in-kind	Import duty reduction	Green certificate buy-off and JI funds	Others, such as profit tax advantages	Total[a]
1. Feasibility	75 %	0 %	15 %	–	–	10 %	100 %
2. R&D/pilot	50 %	30 %	10 %	10 %	–	–	100 %
3. Demonstration	25 %	30 %	15 %	10 %	15 %	10 %	>100 %
4. Deployment/ commercial	5 %	65 %	15 %	10 %	10 %	10 %	>100 %

[a] *Redundancy of funding is necessary to reduce risks.*

Table C.3 Estimated income as a percentage of total recurring costs after subsidy of the different stages of the introduction of VLS-PV

Source of funding Stage	Electricity	Opportunity costs	Green certificates	Tax incentives	Others	Total
1. Feasibility	–	–	–	–	–	–
2. R&D/pilot	50 %	–	30 %	20 %	–	100 %
3. Demonstration	30–50 %	0–17 %	18 %	0–30 %	–	48–115 %
4. Deployment/ commercial	50 %	10 %	20 %	20 %	–	100 %

it has interesting technical and social aspects, there will be multiple instruments to apply for funding. The strongly reduced investment by heavy subsidies will enable the electrical power to be sold favourably. Thus electricity accounts for 50 % in the income of the plant. Other sources of income are green certificate values and tax incentives. The subsidy for the cost and financing of a 100 MW demonstration plant will be reduced. The exploitation could be economically attractive, depending on several assumptions. The first and most important are the value of green certificates and the value of so-called opportunity costs. These opportunity costs are costs avoided by certain companies or increased income for such companies, due to the existence of the VLS-PV project. The deployment/ commercial stage will have to benefit from reduced costs of PV modules and increased cost of power and of green certificates. However, it may be too early to give more details regarding such a 1 GW plant.

It is recommended to make a full-scale feasibility study for an R&D project and a 100 MW demonstration plant. This feasibility study should identify targets and location, and fully secure funding sources and electricity outlets for both stages. Without funding identified and secured for the 100 MW demonstration plant, the R&D stage should not be implemented.

C.4 RECOMMENDATIONS

As an overall conclusion of this work, recommendations are given here to realize long-term targets based upon the results of the studies performed in the IEA Task VIII. The adoption of VLS-PV will require four steps, as shown in Figure C.4:

1. Absorbing the concept of VLS-PV in a desert environment
2. Considering a long-term scenario approach
3. Positioning yourself in terms of your strategy
4. Making an action plan and allocating resources

In this report, concrete information on VLS-PV is given, so the first two steps can be taken into consideration. The generalized understandings and recommendations on a policy level give direction to those who consider the adoption process. To support those willing to consider the third and fourth steps, an initial checklist is given.

C.4.1 General understandings

Based on this report, the considered stakeholders may recognize the following valuable findings.

VLS-PV can contribute substantially to global energy needs

- The world's deserts are so large that covering 50 % of them with PV units would generate 18 times the primary energy supply of 1995.
- All global energy scenarios project solar PV energy to develop into a multi-gigawatt energy generation option in the first half of this century.

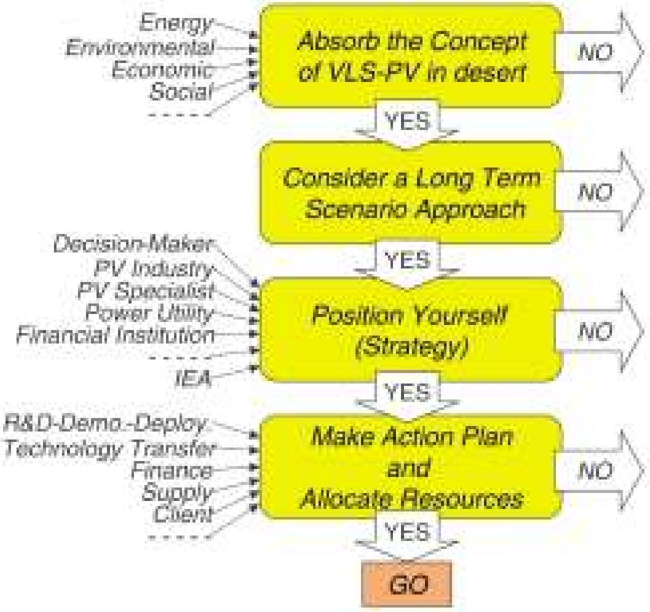


Figure C.4 Flowchart for recommendation

VLS-PV can become economically and technologically feasible

- Electricity generation costs are between 0,09 and 0,11 USD/kWh, depending mainly on annual irradiation levels (with 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 2–3 by the year 2010.
- The PV technology is maturing with increasing conversion efficiencies and decreasing prices per watt; projected prices of 1,5 USD/W around the year 2010 would enable profitable investment and operation for a 100 MW PV plant.
- Solar irradiation databases now contain detailed information on irradiation in most of the world's deserts.

VLS-PV can contribute considerably to the environment

- The life-cycle CO_2 emission is as low as 13 g-C/kWh; this is mainly due to the module production and the array support. This should be compared with the value of 200 g-C/kWh for just the fuel component of conventional fossil-burning power plants.
- The environmental issues for which VLS-PV may provide a solution are global warming, regional desertification and local land degradation.

VLS-PV can contribute considerably to socio-economic development

- Plant layouts and introduction scenarios are available in preliminary versions. I/O analysis concluded that 25 000–30 000 man-years of local jobs for PV module production will be created per 1 km^2 of VLS-PV installed.

VLS-PV development needs a long-term view and consistent policy

- To reach the level of a 1 GW system, four intermediate stages are recommended: 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, the module and system cost will go down by a factor of 4, and manufacturing will be shifted more and more to the local economy.

- In the concept of sustainable local economic growth, the first local PV module manufacturing facility has an annual output of 5 MW. This local production provides for construction of the local VLS-PV system. In subsequent years, four more 5 MW module manufacturing 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 will be replaced by a more modernized one. Thus after approximately 40 years a 1,5 GW VLS-PV power station will be in operation, and the local manufacturing facility will supply for replacement. In this way, local employment, and thus the economy, will grow sustainably.
- To realize the final commercial stage, a view to financing distribution has been 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 stage.

C.4.2 Recommendations on a policy level

From the global energy situation, global warming and other environmental issues, as well as from the case studies and scenarios, it can be concluded that VLS-PV systems will have a positive impact. To secure that contribution, a long-term scenario (10–15 years) on technological, organizational and financial issues will be necessary. Action now is necessary to unveil the giant potential of VLS-PV in deserts. In such action, involvement of many actors is welcome. In particular, the following are recommended on a policy level:

- National governments and multinational institutions adopt VLS-PV in desert areas as a viable energy generation option in global, regional and local energy scenarios.
- The IEA PVPS community continues Task VIII for expanding the study, refining the R&D and pilot stages, involving the participation by desert experts and financial experts, and collecting 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. The positive influence on local economic growth, regional anti-desertification and global warming should be recognized.

C.4.3 Checklist for specific stakeholders

To decision-makers in industrialized countries

You obviously have a long-term view of the world energy market trends and the need to provide a national energy outlook.

- Have you considered the future possibility of VLS-PV for your industries, which may become major enterprises controlling the world energy market?
- Do you have a step-by-step plan for R&D to make good use of the extensive capabilities in photovoltaic technology when the world energy problem arrives?
- Do you have a view to initiate, continue and extend bi- or multilateral international collaboration with those developing countries which have abundant solar energy?
- Do you have funds available for R&D or pilot programmes with training courses to introduce PV technology into developing regions, especially around deserts as a first stage of a consistent step-by-step approach?
- Do you have strategies in place to maintain regional sustainability and to consider a moderate technology transfer scenario when planning the further development of developing countries?
- Have you considered using your influence to mobilize multilateral institutions to stimulate VLS-PV?

To decision-makers in developing countries

You obviously are aware of the coming world energy problem in 20–30 years.

- Did you include solar PV energy as one of the most favourable renewable energy options when national master plans for energy supplies were discussed?
- Have you considered the opportunity that your country will be able to export PV energy to neighbouring regions and that new jobs will be brought to your people?
- Are you aware of the fact that PV technology has already proven itself to be a cost-competitive energy source for rural electrification and is still being improved very rapidly? In particular, are you aware that it is especially effective for stabilizing rural lives?
- Have you considered a regional development plan that utilizes abundant electricity production and vast lands?
- Have you settled on a step-by-step, long-term approach that starts with solar home systems or mini-grids as the first stage and finally reaches VLS-PV in 20–30 years?
- Do you have a plan to cultivate and gradually raise a domestic PV specialists' society from an early stage to a developed stage?
- Have you already asked for support from the variety of financial institutions you can utilize?

To decision-makers in oil-exporting countries

You obviously are aware of the fact that many oil-exporting countries around desert areas also have an everlasting natural resource: solar energy.

- Are you aware that you can export PV energy to neighbouring regions as well?
- Do you know that PV technology has already been proven as a cost-competitive energy source for rural electrification and is still being improved rapidly?
- Did you develop a long-term view of the future world energy market and your strategy including the new level of photovoltaic power plants and industries? Are you aware that it will bring you opportunities for high-tech industries and new jobs?
- Can you confirm the study results that a 100 MW PV power plant will be economically attractive in an oil-exporting country? Have you discovered good conditions in interest rates, the value of green certificates and the value of opportunity benefits from oil savings?
- Have you decided to invest in the development of the world photovoltaic business?
- Did you choose an appropriate scale for starting towards VLS-PV?

To financing institutions and banks

You are presumably aware of the fact that the market potential for VLS-PV amounts to 2 billion people worldwide.

- Are you aware of the Task VIII study results that show the size of indicative investment levels for the 100 MW demonstration stage and the 1 GW deployment stage corresponds to 500 and 4 000 MUSD respectively? Do you consider this much different from the magnitude of hydropower or infrastructure projects in a budgetary sense?
- Do you respect the following funding scenario study for a 100 MW demonstration stage and a 1 GW deployment stage? They are economically attractive in some cases, assuming that 30-65 % of total investment is met by soft loans with 4 % interest. Another portion is expected to come partially from subsidy, equity, tax reduction, etc.
- Can you positively support a full-scale feasibility study for a pilot project and for a 100 MW demonstration plant as a continuation of the Task VIII? This will identify targets and locations and will secure the funding sources and electricity outlets for both stages.
- Can you support the pilot stage and the 100 MW demonstration stage according to the results of this study?
- Could you consider a low-interest soft loan on a long-term basis for the initiation of VLS-PV system projects around desert areas?

To PV industry associations and multinational industries

You are obviously aware of possibilities for future market growth in southern countries.

- Are you aware of the future possibility of VLS-PV for PV industries? They may become major enterprises controlling the world energy market.
- Are you confident that the photovoltaic technology and market will become competitive on a worldwide level within 20 years?
- Can you ensure that the prices for solar PV energy will be reduced by a factor of a half to a quarter within the next decade?
- Can you support and invest in local industries to take off according to the technology transfer scenario?

To PV specialists and the academic community

You know that fundamental research will generate new seed technologies for VLS-PV.

- Can you confirm expected directions such as very high-efficiency PV cells, high-concentration optics, organic polymer PV cells, chemical energy transportation media like hydrogen or methanol, superconducting power transmission and so on?
- Did you formulate and assist a PV specialist society in developing countries in co-operation with top leaders in those countries?
- Will you join our continuing work, seeking the realization of VLS-PV systems? Expected work items may include more precise case studies for specific sites and funding, proposals for R&D co-operation plans, other possibilities in technological variety, resource evaluation, additional value analysis and so on.

To power utilities

You have clearly recognized that the world energy market structure will change very drastically in the near future.

- Can you confirm business opportunities in photovoltaics within the next decades?
- Can you confirm that a power transmission scenario is possible according to our study results? Additional tie-line construction of less than 100 km, for connecting VLS-PV through existing national power grids to a load centre, will raise the electricity price by less than 1 US cent/kWh. One example is a transmission operation in co-operation with coal-burning power stations located on a colliery.
- Are you ready to invest in photovoltaic industries and foster technological societies with a long-term view for the future world energy market?

To the International Energy Agency

You are clearly aware that the diversification of energy resources and the development of alternative energy are essential for overcoming the world energy problems within the next decades.

- Can you confirm our view that solar PV energy is one of the most favourable options for future electricity production?
- Can you confirm your continuous support of the IEA PVPS Implementing Agreement on the basis of the long-term world energy outlook?

- Would you support our idea about multilateral activities between IEA member countries and developing countries?
- Can you organize the higher level of IEA PVPS activities including demonstration projects for VLS-PV?
- Do you want to support a full-scale feasibility study corresponding to a pilot project and a 100 MW demonstration plant? This will identify targets and location, and fully secure funding sources and electricity outlets for both stages.
- Can you support and enhance the continuing work in the IEA PVPS Task VIII? Expected work items are to be:
  - more precise case studies for specific sites including detailed local conditions and funding sources as well as demand application,
  - proposals for the first or second stage of co-operation plans to be submitted to financial institutions,
  - comprehensive evaluation of other possibilities of a technological variety such as tracking, concentrator and advanced PV cells,
  - resource evaluation of VLS-PV by means of remote sensing technology,
  - investigation of additional effects of VLS-PV on the global environment such as global warming and desertification,
  - expansion of evaluating approaches to other types of PV mass applications in the 21st century, including value analysis in the economy, environment, socio-economy and others.

Energy from the Desert

The world's deserts are sufficiently large that, in theory, covering a fraction of their landmass with PV systems could generate many times the current primary global energy supply. Moreover, the energy produced is from solar radiation – a clean and renewable source – hence such systems would have the potential to contribute massively to the protection of the global environment.

Energy from the Desert is an extensive and high-level international study, representing the accumulated research of the world experts involved in Task VIII of the IEA PVPS Programme. This Summary highlights the principal findings of the full report (available separately).

To date, the market focus for photovoltaics has been on small to medium, stand-alone or building-integrated power systems, which have proven, but as yet not realized, the great potential of this technology. Energy from the Desert evaluates the feasibility, potential and global benefits of very large scale photovoltaic power generation (VLS-PV) systems deployed in desert areas and each generating from 10MW to several gigawatts.

The study details the background and concept of VLS-PV, maps out a development path towards the realization of VLS-PV systems, and provides firm recommendations to achieve long-term targets, based on the findings of the IEA Task VIII experts. Critical aspects examined are:

- photovoltaic technologies, systems design and plant operation
- finance, cost-benefits and profitability
- impact on and benefit to global, regional and local environment
- policy-level and investment issues

Energy from the Desert is the first study to provide a concrete set of answers to the questions that must be addressed in order to secure and exploit the potential for VLS-PV technology and its global benefits. It will be invaluable to government, energy planners, policy makers, utilities and international organizations assessing the potential for this technology, PV systems manufacturers and infrastructure providers wishing to develop this new market and consultants, scientists, researchers and engineers involved in the field.

THE EDITOR

Energy from the Desert is edited by Professor Kosuke Kurokawa, Operating Agent-Alternate, IEA Task VIII with contributions from a panel of fourteen acknowledged international experts from eight countries. Professor Kurokawa has 30 years' experience in energy systems technology including HVDC transmission and solar photovoltaics. He is currently engaged in researching a wide variety of photovoltaics systems concepts from small AC modules to very large scale PV systems at the Tokyo University of Agriculture and Technology (TUAT).

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