ENERGY FROM THE DESERT

Executive Summary

Very Large Scale Photovoltaic Systems: Socio-economic, Financial, Technical and Environmental Aspects

Edited by Keiichi Komoto
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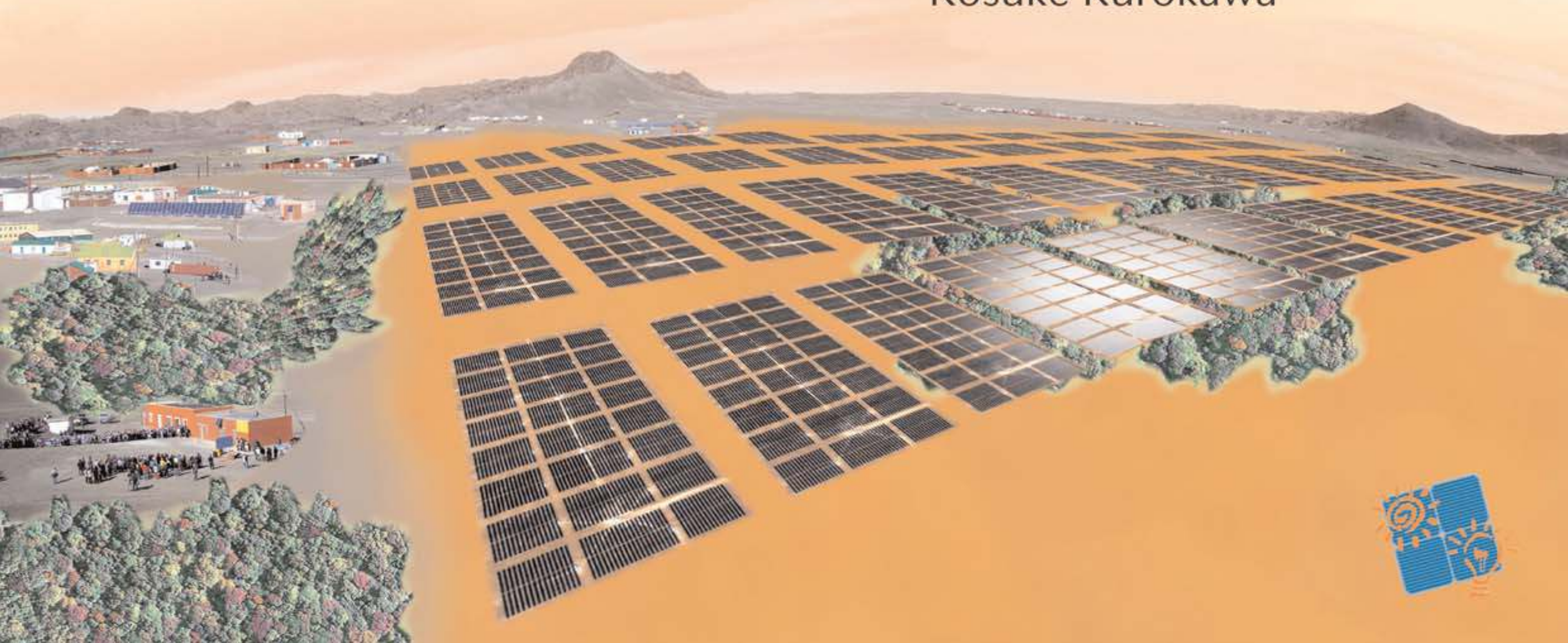

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Foreword

During 2008, the International Energy Agency (IEA) published the Energy Technologies Perspectives (ETP) publication which forms the response to the G8 call on the IEA to provide guidance for decision-makers on how to bridge the gap between what is happening and what needs to be done in order to build a clean, clever and competitive energy future. The message from ETP 2008 is very clear: what is needed in order to meet the challenges the world is facing is nothing less than a global revolution in ways that energy is supplied and used. ETP 2008 provides an analysis of different scenarios showing how the energy sector will need to be transformed over the next decades. According to the most advanced (BLUE Map) scenario, which corresponds to IPCC emission reduction targets, renewable energy, by 2050, will account for 46 % of the global electricity power. Among the renewable energy technologies, photovoltaics will play a major role.

When the International Energy Agency's Photovoltaic Programme IEA PVPS Task 8 – Study on Very Large-Scale Photovoltaic Generation Systems – was set up in 1999, very large-scale photovoltaic systems were seen as a futuristic concept with little relationship to reality. However, in only ten years, the size of large ground-based photovoltaic systems has increased, with systems up to 100 MW being planned and commissioned these days. The vision of Professor K. Kurokawa, who inspired and led the work of IEA PVPS Task 8, has become closer to reality far quicker than many would have predicted.

Building on the work of IEA PVPS Task 8 over the past 10 years, this book is one step further towards the realization of very large scale photovoltaic systems. The focus of this book lies in the description of key generic aspects concerning technological, socio-economic and environmental issues of such systems. I am confident that, through its comprehensive approach, this book can serve as a reference document as well as a basis for decision-making for future projects and initiatives.

This book will serve its purpose if it can provide a sound basis for assessment of the different issues to be considered when addressing the subject of very large scale photovoltaic systems. I would like to thank Professors K. Kurokawa and K. Komoto for their foresight, leadership and commitment, and the whole Task 8 expert team for their dedicated contributions and critical reviews in making this publication possible. As we learn from history, only the future will tell us where visions have ultimately become true. But having visions is the crucial condition for changes to happen.

Stefan Nowak
Chairman, IEA PVPS
May 2009

Preface

The scope of Task 8 is to examine and evaluate the potential of very large-scale photovoltaic (VLS-PV) power generation systems that have a capacity ranging from several megawatts (MW) to gigawatts (GW) and to develop practical project proposals for implementing the VLS-PV systems in the future.

The work first started under the umbrella of the International Energy Agency's Photovoltaic Power Systems Programme (IEA PVPS) Task 6 in 1998. The new task – Task 8: 'Study on Very Large-Scale PV Power Generation Systems' – was set up in 1999.

In May 2003 and January 2007, we published two volumes of our extensive reports, both of which are also entitled 'Energy from the Desert', concerning VLS-PV systems in deserts. The books show that the VLS-PV is not a simple dream but is becoming increasingly realistic and well-known all over the world, especially in desert countries. Some countries and regions use the books as a reference for developing their vision of photovoltaic (PV) deployment.

From 2006 to 2008, an extended number of specialists have joined the task and have studied and discussed VLS-PV systems in great detail. This new report contains new, in-depth knowledge about how to implement VLS-PV systems in the desert. We have come to the conclusion that desert regions contain an abundant and inexhaustible source of clean energy and that very large-scale solar electricity generation provides economic, social and environmental benefits, security of electricity supply and fair access to affordable and sustainable energy solutions.

Since the first half of the 2000s, the installation of MW-scale PV systems has been rising substantially year on year, and so too is the capacity of MW-scale PV systems expanding. The capacity could reach 100 MW in the near term, and then GW-scale PV plants consisting of several 100 MW-scale PV systems could be realized towards the middle of the 21st century.

'It might be a dream, but…' was a motive for Task 8 when established. Now we have become confident that VLS-PV systems must be one of the promising options for large-scale deployment of PV systems.

Professor Kosuke Kurokawa
Operating Agent, Task 8

Keiichi Komoto
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II

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A.1 Introduction and overview

A.1.1 Objectives

The purpose of this study is to examine and evaluate the potential of very large-scale photovoltaic power generation (VLS-PV) systems that have capacities ranging from several megawatts (MW) to gigawatts (GW), and to develop practical project proposals for implementing the VLS-PV systems in desert regions (see Figure A.1).

Our study has achieved a comprehensive analysis of all major issues involved in such large-scale applications based on the latest scientific and technological developments and by means of close international cooperation with experts from different countries.[1, 2]

The key factors enabling the feasibility of the VLS-PV systems have been identified and the benefits of the systems' applications for neighbouring regions have been clarified. The study also describes the potential contribution of system application to global environmental protection and long-term renewable energy utilization. In addition, various subjects such as electricity transmission and storage, water pumping, water desalination, irrigation, agriculture, community development and socio-economic development have been discussed. The study concludes that desert regions contain an abundant and inexhaustible source of clean energy and that very large-scale solar electricity generation provides economic, social and environmental benefits, security of electricity supply and fair access to affordable and sustainable energy solutions.

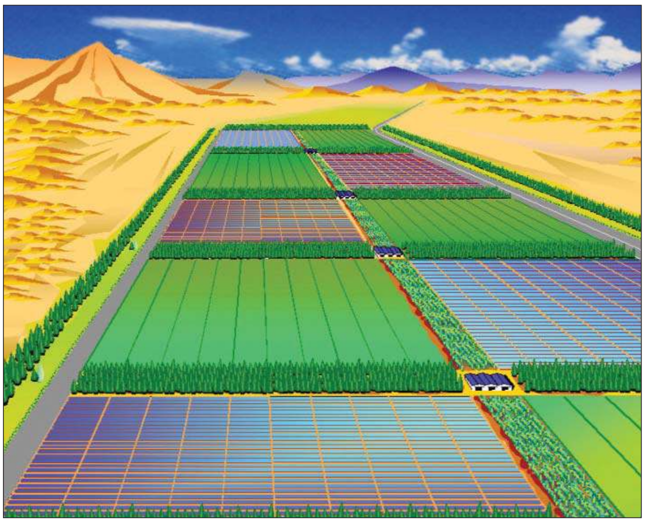


Figure A.1 An image of a VLS-PV system in a desert area

From the perspective of the global energy situation, global warming and other environmental issues, it is apparent that VLS-PV systems can:

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

PV systems with a capacity of more than 10 MW have already been constructed and operated, for example in Spain and Germany. This demonstrates that VLS-PV systems are already feasible.

However, to further deploy these systems and to implement real VLS-PV projects, the main challenge is to propose excellent projects and to convince local governments, energy companies and financing institutions to become positively involved in realizing ambitious projects for the large-scale generation of solar electricity.

This report shows the feasibility and the impact of VLS-PV projects, offering huge potential for socio-economic, financial, technical and environmental factors. We also present a VLS-PV roadmap and recommendations for implementing VLS-PV projects in the near future.

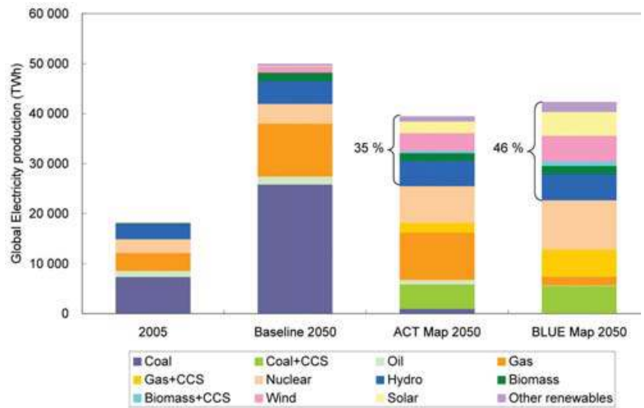
A.1.2 VLS-PV for a sustainable future

Since the Industrial Revolution, human beings have achieved dramatic economic growth and life has become more convenient and comfortable. Total energy consumption has increased along with economic and population growth and, at the same time, various environmental problems associated with human activities have become increasingly serious. In order to achieve the goals of sustainable development, it is essential to minimize the consumption of finite natural resources and to mitigate the environmental burden to within nature's restorative capacity.

Greenhouse gas (GHG) emissions in the future and their impact are expected to be at far from acceptable levels, even in alternative scenarios, and drastic change in economies, societies and technologies will be needed to achieve a sustainable future.

The International Energy Agency (IEA) has analysed the possible contribution of technologies in order to fill the gap between the need for mitigation of climate change and global energy demand.[3] The new scenarios developed show the importance of renewable energy technologies as well as energy-efficient technologies. The scenarios developed are called the Baseline scenario, ACT scenario and BLUE scenario. The Baseline scenario is consistent with the World Energy Outlook 2007 Reference scenario until 2030,[4] and the trends are extended to estimate the energy profile in 2050. The ACT scenario assumes that global energy-related carbon dioxide (CO_2) emissions in 2050 will be at the same level of that in 2005; by contrast, the BLUE scenario targets half of the ACT scenario in 2050. From the perspective of temperature increase, the BLUE scenario is roughly equivalent to 2–3 degrees Celsius (°C) increase from the pre-industrial level.

In the BLUE scenario, the renewable energy contributes to 21 % of the CO_2 reduction from the Baseline scenario. The power generation sector is one sector that enjoys the benefit of renewable energy. The electricity generated from renewable energy sources reaches 35 % in the ACT scenario and 46 % in the BLUE scenario, as shown in Figure A.2. Solar power generation includes photovoltaic (PV) and CSP (concentrated solar power) generation, and both are expected to play an important role in the two scenarios.



Source: IEA, 2008

Figure A.2 Contribution of renewable energy to power generation in the ACT and BLUE scenarios

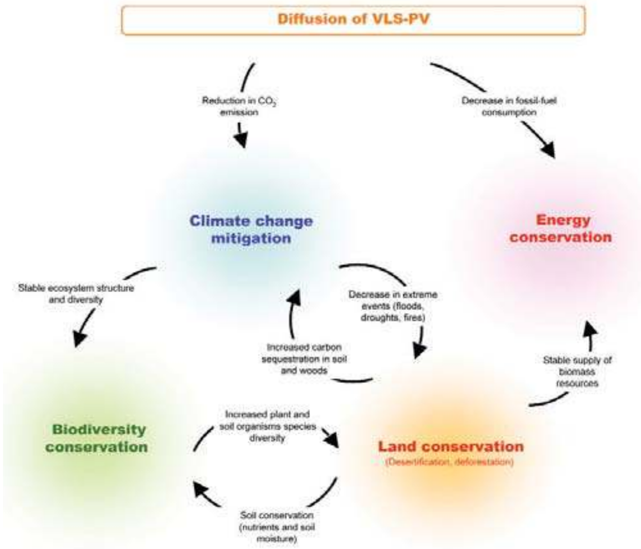


Figure A.3 A virtuous circle of environmental issues

VLS-PV systems have great potential to contribute to overcoming global issues. Because VLS-PV can generate large amounts of power without emitting GHGs during operation, it is expected to be a powerful solution to overcome both climate change and energy issues. Additionally, a number of applications are possible for VLS-PV, including application in desert areas and generating power for water supply (desalination) or other productive uses (agriculture, hydrogen production and so on). It can reasonably be concluded that VLS-PV systems have great potential to turn the vicious circle of environmental issues into a virtuous circle (see Figure A.3) and solve the problems.

A.1.3 VLS-PV and other renewable resources

It is clear that VLS-PV, by its very nature, is a technology most suited to deserts. In particular, a 1 GW plant requires in the order of 10 km^2 of land area, preferably low-cost land, and also high insolation levels to render the most favourable economics. Both of these requirements are, in general, met by the world's deserts. However, it is important to realize that VLS-PV is not the only type of renewable energy that may and should form part of a future 'green' energy mix. The two leading alternative candidates are wind and biomass. The former cannot be discussed in detail here, without over-extending the scope of the present volume. The great virtue of wind is that its random nature is not directly correlated with the cloud motion that imposes its randomness on solar energy availability. Thus, very large wind farms could be used in conjunction with VLS-PV in order to cut down on the storage requirements of the latter and, thereby, still provide a dispatchable form of energy for grid use.

Biomass, by contrast, is a far less-developed technology and one, moreover, that is fraught with controversy regarding both the amount of energy that needs to be invested in it, and its competition (for land, water and fertilizers) with food production. However, if we regard deserts as a potential source of biomass production, there is no significant competition with food, the only questionable resource, regarding availability, being water. Organisms such as microalgae may be grown using brackish or other marginal water sources of the kind that are often available in deserts, thus removing the availability of water as an obstacle. Unlike PV, however, the technology for algae production is not yet sufficiently developed to permit any kind of review within the present context.

There is an alternative, highly developed class of solar technology that must be discussed and compared to VLS-PV, namely technology for the production of solar-thermal power (CSP). The present-day advantages of CSP versus VLS-PV have been emphasized for several reasons. First, CSP is a mature technology (at least in its parabolic trough form) that is already here, whereas VLS-PV is not. Second, again at the present stage, CSP is a lower-cost technology than PV. Third, CSP technology lends itself to grid integration more readily than does VLS-PV (there being no need for a direct current/alternating current (DC/AC) inverter). However, it has been argued that in the long run, VLS-PV will outperform CSP, both in cost and land productivity.

However, it has also been argued that the deserts are large enough for a wide mix of alternative energy technologies in future. Indeed, the wider the mix the better, because the more technologies whose respective intermittent power outputs are not correlated to one another, the smoother and more dispatchable their combined effect will be. Therefore if CSP costs can also be reduced in future, it will enjoy an 'honourable sister' relationship with VLS-PV, wind and perhaps biomass as well.

A.2 SOCIO-ECONOMIC ASPECTS

A.2.1 Potential benefits for desert countries

Deserts can be viewed as large areas with inhospitable surfaces, underground wealth, sunny and windy climate conditions and severe living conditions for inhabitants. A more challenging and realistic way of looking at deserts is as regions with abundant and inexhaustible sources of clean energy and fresh water, offering a solid basis for socio-economic development.

The main driving force for such socio-economic development would be a VLS-PV power generation policy, which would create a sustainable market for solar electricity, PV system components, installations and clean development mechanism (CDM) credits. This development would also create many jobs and would involve technology transfer from industrialized countries to desert countries. The generated electricity could be used for lighting, communication, entertainment, industrial and education purposes, but also for providing potable water, irrigation, agriculture and industrial purposes. VLS-PV plants will contribute to energy security, provide fair access to energy for everybody and reduce the threat of climate change.

The potential benefits of VLS-PV for desert countries are summarized in Table A.1.

Table A.1 Potential benefits of VLS-PV for desert countries

Economic benefits	Introducing a solid strategy for the introduction of very large-scale PV solar electricity generation will create a large and sustainable local market for solar panels and other system components and materials, including installation and maintenance. In addition, CDM credits will be generated. The generated electricity can be distributed in the local market as well as in the export market and the CDM credits can be sold in the international market.
Social benefits	The sustainable local market that will be created by the adoption of a solid long-term strategy for solar electricity generation allows for national and international investments in local production of solar panels, solar cells, silicon material and other basic materials such as glass, metals, concrete and others. This will create significant additional employment in desert regions. For the introduction of state-of-the-art technology, international cooperation and technology transfer will be needed.
Security of energy supply	Because a lot of sunshine is and will always be available in desert regions, this is the most secure source of energy; sunshine is available to everybody. Because the components and systems for converting sunshine into electricity will become cheaper with technology evolution, very large, as well as very small, systems will become cost-effective in the near future.
Environmental issues	For reducing the effects of climate change, international agreements for reducing GHG emissions have been and will be concluded. By generating solar electricity instead of conventional electricity, GHG emissions will be significantly reduced.
Peace/poverty alleviation	The abundant availability of solar energy (sunshine) in desert regions provides fair access by everybody to affordable and sustainable energy solutions. This is an important condition for preventing wars over energy. Moreover, the availability of solar electricity will stimulate economic development in desert regions.
International recognition	By the introduction of a sustainable energy strategy based on solar electricity, an example will be created that will generate international recognition and this example will be followed by many other countries.

A.2.2 Creation of local markets and industries

In industrialized countries, a strong trend towards larger systems can be observed. These systems are normally connected to a transmission line and incorporated in a national or international electricity distribution grid. Electricity prices are, in fact, directly dependent on the amount of sunshine. This means that electricity prices will potentially be the lowest in desert regions. This will allow for the export of solar electricity to the international market.

With a solid strategy for implementing very large-scale photovoltaic solar systems, the local market will create enough need to justify local manufacturing of solar system components such as:

- assembly of PV solar panels;
- manufacturing of solar cells;
- manufacturing of silicon;
- installation, building and services.

In addition, various kinds of knowledge and experiences have to be transferred.

- Transfer of system and application know-how – system and application know-how should mainly be transferred to and extended at renewable energy institutes, utilities and energy companies.
- Transfer of technology – in order to keep track of worldwide technology developments, technology exchange between universities and scientific institutes in industrialized countries and in desert regions has to be organized or improved.
- Transfer of policy matters – it may also be wise to transfer policy matters from countries that already have more experience with financing, installation and maintenance of very large photovoltaic systems. In this case, local decision-makers should be involved.

To obtain a good acceptance of solar electricity systems, it will be necessary to make people aware of the advantages and the potential of solar electricity generation in desert regions. Such awareness creation is necessary at all levels in local communities.

The roles of major stakeholders such as renewable energy institutes, energy companies, government institutions, financial institutions and educational institutes, are significant.

A.2.3 Sustainable community development

The introduction of VLS-PV systems in desert regions may have quite a large impact on the development of present and future inhabitants of deserts. Other impor-

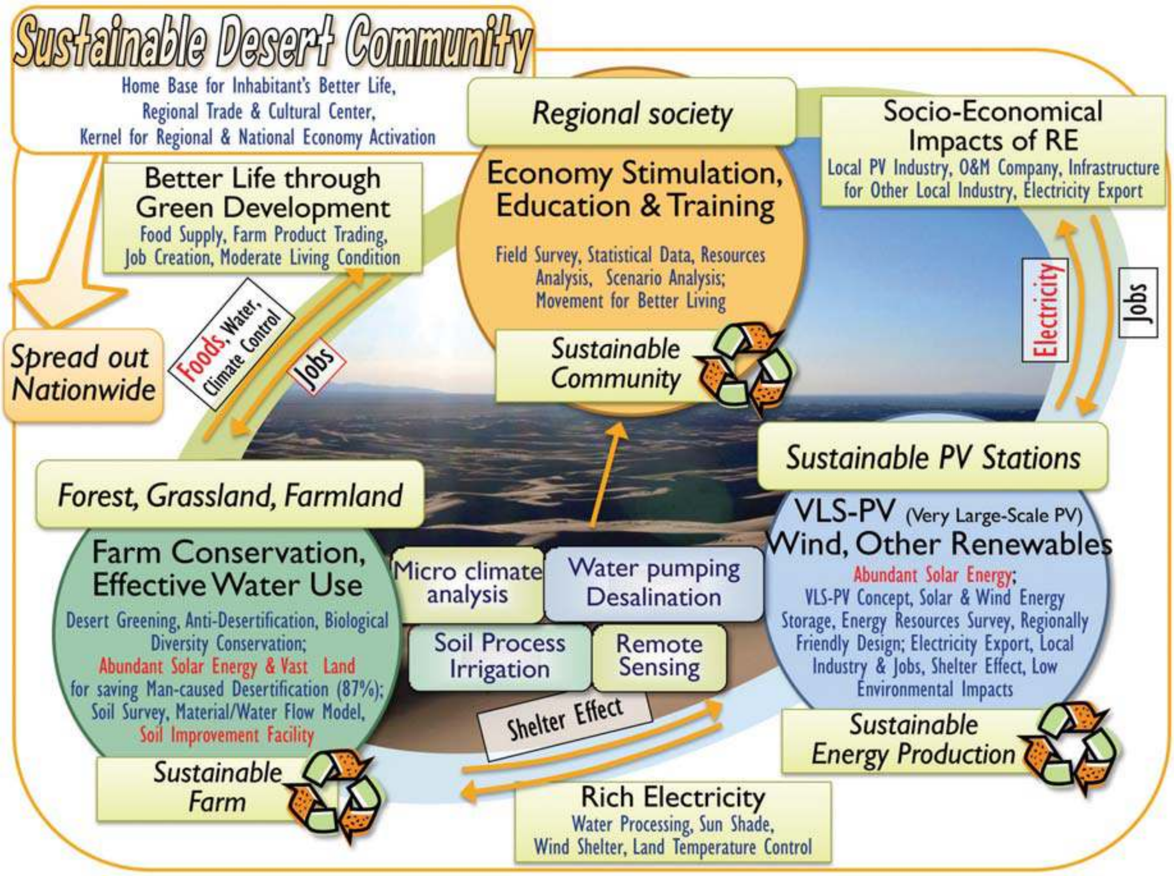


Figure A.4 Concept map of a sustainable desert community tant subjects such as irrigation, agriculture water pumping and desalination have to be considered in connection with the large-scale generation of solar electricity. This means that sustainable community development is important. Figure A.4 shows a concept map of a sustainable desert community based on VLS-PV development.

In many countries, the majority of available water resources are used for agricultural purposes. The efficiency of most irrigation systems is still very low and inefficient irrigation often leads to soil degradation. Using PV solar power in combination with modern irrigation and desalination techniques will lead to more efficient irrigation systems. Lower amounts of precious water are spoiled and salinity in the soil is prevented. Therefore, more efficient agricultural development can take place.

In order to prevent further desertification, which could have disastrous effects for the earth's inhabitants, planting trees in desert regions would be a good solution. Sustainable greening would help to prevent further desertification.

A.2.4 Agricultural development

Agriculture is often the largest economic sector in developing regions. Employment is very important to sustaining and extending the self-reliance of local communities. To improve and strengthen agriculture is a first step in developing arid and semi-arid regions.

Agriculture is the largest user of water in the world. The situation will get worse as the population increases because the use of fresh water is roughly proportional to population. Salt accumulation and accompanying desertification that stems from improper irrigation under arid and semi-arid climates is a serious problem. High-quality deep ground water is not rechargeable and is thus rather similar to fossil resources such as oil. At this time, desalinated sea water and brackish rechargeable shallow ground water may be alternative water resources. Secondary treated water from municipal sewage is another choice. Water desalination requires energy and thus costs money. The energy source for this process may be the most important issue in the future. It is not wise to utilize fossil energy to drive desalination plants. Running desalination plants with renewable energy such as PV systems would satisfy the requirements of sustainability.

Local and traditional agricultural technologies in developing regions are often well-adapted to tough natural conditions; however, they are neither cost nor labour efficient. Replacing the local and traditional technology with exotic and state-of-the-art technology often does not work effectively. It is crucial to set a target to introduce 'intermediate technology' between traditional and modern technology. PV systems may be beneficial for this purpose because they have flexibility regarding size and placement.

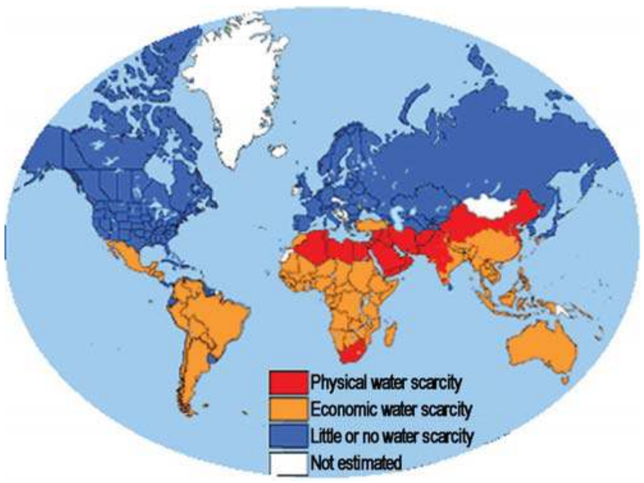
Irrigation technologies (i.e. border, furrow and drip irrigation as well as leaching of soluble salt) have been studied for more than three decades and water-saving irrigation is well established. A case study suggests that if enough water is available, farmers can afford to pay the cost of irrigation by combining traditional crops and new cash crops. PV systems based on desalinized water have the potential to improve the sustainability of traditional agricultural systems in semi-arid regions, and might also improve the local community's economic situation. The choice of proper irrigation practices and introducing additional cash crops to earn money may be an incentive for introducing a system of sustainable production and the cash crop itself would help to improve the economic situation in developing regions.

A.2.5 Desalination

The need for water is increasing in many parts of the world due to domestic, agricultural, industrial and tourist pressures. The exponential growth of the world's population can be found mainly in the dry regions of the world (Africa, India), which leads to an increase in food demand, causing additional intensive stress on water resources that are already scarce. In many of the regions, the groundwater level is falling by several metres every year, leading to water shortfalls or high salt intrusion, thereby making the water unfit for consumption. Additionally, rapid industrialization, especially in some parts of Asia, leads to excessive pollution of rivers and aquifers due to unsustainable use of available resources.

Figure A.5 shows the prediction of a global water shortage for the year 2025. In many countries, potable water is already a scarce resource and this shortage will rise dramatically in the near future. Most diseases and fatalities in developing countries are directly related to a lack of clean water. The availability of clean water is a basic element of human life. Furthermore, the quantity of available water is one of the most important boundary conditions for the development of agriculture, manufacturing, industry, trade and overall socio-economic development of society.

One option for creating new fresh water resources is desalinated seawater, which is effectively an inexhaustible source. A lack of energy sources complicates the use of standard desalination technologies in these regions. However, in arid and semi-arid regions the lack of drinkable water often corresponds with high solar insolation, enabling solar energy to be used as the driving force for water treatment systems. Thus, one very promising option is to generate the energy necessary for large-scale desalination by conversion of solar



Source: Bayot, 2007

Figure A.5 Predicted water scarcity for the year 2025[5]

radiation. Figure A.6 provides an overview of thermally- and electrically-driven desalination technologies and the approach to solar energy supply.

The generation of energy from solar radiation by solar-thermal or large-scale PV power plants becomes increasingly economically competitive due to increasing energy costs with conventional plants and the rising problems of CO_2 emissions resulting from the burning of fossil fuels.

Today, reverse osmosis (RO) systems may offer the best solution for desalination, when powered by (solar) electricity. Part of the electricity from PV power generation can be used to operate an RO plant. The cost of desalination systems is expected to be reduced further by the introduction of innovative desalination technologies, such as those using solar energy to save fuel.

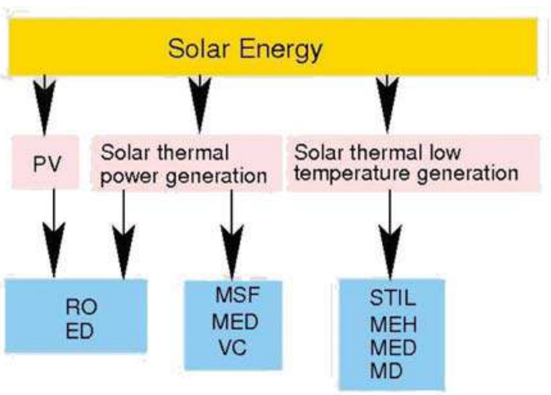


Figure A.6 Approaches to the use of solar energy for desalination

A.3 FINANCIAL ASPECTS

A.3.1 The cost of VLS-PV generation

To understand the cost of a VLS-PV system, a generation cost of the system that assumes current technologies was analysed from the viewpoint of lifecycle. Generation cost can be calculated by dividing annual expenses, including capital cost, by annual power generation. Because annual power generation and costs for materials and labour would depend on the regions used as VLS-PV installation sites, eight different regions, such as the cold Gobi desert, the hot Sahara desert and the moderate region in Negev, were assumed.

The annual expenses for a VLS-PV system were calculated by considering the interest rate, salvage value rate and capital recovery factor. In this analysis, the currency value was assumed to be the average price in 2006, and the exchange rate was assumed to be JP¥120 per US$1. Other economic indicators were assumed as follows: the interest rate was 3 %, the salvage value rate was 10 %, the property tax rate was 1.4 % per year, the overhead expense rate was 5 % per year, and the depreciation period was 30 years. Here, the lifetime of a VLS-PV system was assumed to be 30 years, while that of an inverter was 15 years. The annual power generation was analysed by considering the system performance ratio (PR), which is a result of a calculation that include an annual module temperature increase, cell temperature factor, soil degradation factor, annual mean degradation ratio, degradation factor, array circuit factor, array mismatch factor and inverter efficiency.

Maintenance costs were calculated based on experience with an actual PV plant. In this analysis, it was assumed that the costs for repair parts were 0,084 % per year of the total construction cost, including equipment cost and that of labour for maintenance involving one person per year. Concerning system construction, the construction period was assumed to be one year, or 240 working days. Land transport was assumed to be 600 kilometres (km), and marine transport was assumed to be 1 000 km. A land cost was not included, although costs for the materials for array supports were considered. An electric transmission system was assumed to involve 100 km, two channels and 110 kilovolts (kV) for connecting to existing transmission facilities. Additionally, the transmission loss was assumed to comprise cable losses, transformer losses and transmission losses and to be approximately 5 % of PV power generation in total.

Figure A.7 shows the results of the generation cost of a VLS-PV system with 1 GW capacity and a 100km transmission line. The generation cost was around $0,18–0,22 per kilowatt-hour (kWh) at a $4 per watt (W) PV module price. If the module price is reduced to $1/W, the generation cost is reduced to $0,0–0,11/kWh.

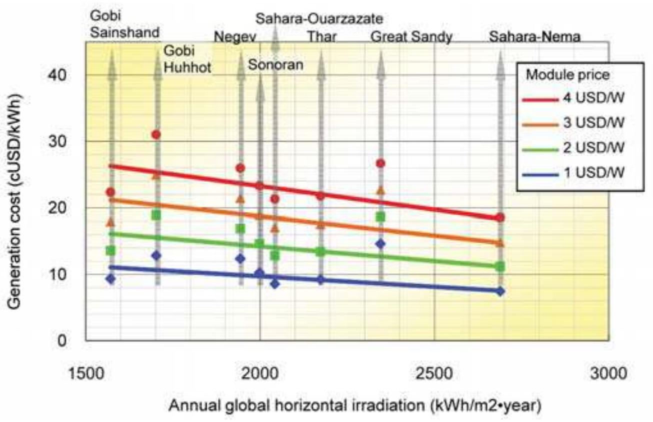


Figure A.7 Generation cost of VLS-PV systems, assuming installation in eight regions

A.3.2 VLS-PV financing requirements

As a source of power generation, a PV plant is highly capital-intensive. The supply and cost of capital are a key consideration in the feasibility of large-scale PV power plants. Availability of capital is a function of perceived risk and not just cost. It is also, to some extent, dependent on the state of financial markets, and therefore on how the intended investment is positioned in the economic cycle. During periods of credit restriction and flight to quality, non-domestic capital may simply not be available for investment in some emerging markets at any price.

There are several possible project structures, each of which demands a different financing approach. A first important distinction is whether the asset is considered individually, or belongs to a corporate or state entity, or is a mix of public and private initiatives. A second distinction is that of the arrangements under which the project sells its output, which may consist of electricity alone, but also of emission reduction certificates or services to the grid. A third distinction is the support mechanisms. Key distinctions help establish the main 'risk universes' that will impact on access to capital and its cost, depending on the location of the project. Table A.2 summarizes these concepts.

Several structures could be used to ease the financing of VLS-PV in countries where creditworthy long-term contracts or support mechanisms are not in place; most require the involvement of the public sector or a multilateral institution, which are the entities most suitable to lengthen the time horizon for investors and lenders. An important role could also be played by sovereign funds from countries with a dynamic renewable energy policy, or by those intent on ensuring that the country does not miss out on the major industrial shift that energy transition will represent.

A more general constraint applies to limited recourse financing of VLS-PV, and that is the difficulty of using good practice financing structures that require that sponsors or contractors guarantee the performance of the plant upon completion. This guarantee may be structured in a number of ways, from a full completion guarantee to a performance ratio guarantee, but it ultimately relies on the credit of: first, the owner of the facility, or second, the purchaser of electricity (which must in this case start making payments on a certain date, irrespective of the actual performance or even the physical existence of the facility), or third, the general contractor, or fourth, jointly or severally, a limited number of contractors linked by some supervising or coordinating agreement. The issue is that very few suppliers or contractors in the PV sector are sufficiently creditworthy to back a guarantee commensurate with an investment worth $500 million or more. Unless this question is addressed from the outset in the contractual structuring of the project, such financing may prove difficult to obtain.

A.3.3 Proposal for a VLS-PV business model

The business model of a VLS-PV system consists of calculating all the financial outputs throughout the life of the system in order to draw up the financial statements on a six-monthly basis. The outputs are calculated based on macro-economic, technical and financial hypotheses specified for a given project. Using a transparent methodology to build the business model is important to all the different participants in the

Table A.2 Project structure and risk matrix

	Power Purchase Agreement	Tax incentive	Feed-in tariff	Market-based
State/state agency	No additional support usually provided to the agency.		Credit and political risk.	
Private corporate	Can be used as collateral if credit risk is below investment grade.	Reduces risk to borrower.	Reduces risk to borrower.	Limited improvement on credit.
Mixed (private–public partnership)	As above. Risk to lenders is mainly the supplier during construction, the operator for technical performance, and the state for rents.			
Private: Single asset	Credit risk of offtaker. Usually coupled with tax incentives. Political risk if offtaker is public.	Renders plant competitive or close to competitive. Limited credit risk on sales.	Macroeconomic and political risk.	Political risk and high risk on the future value of certificates.

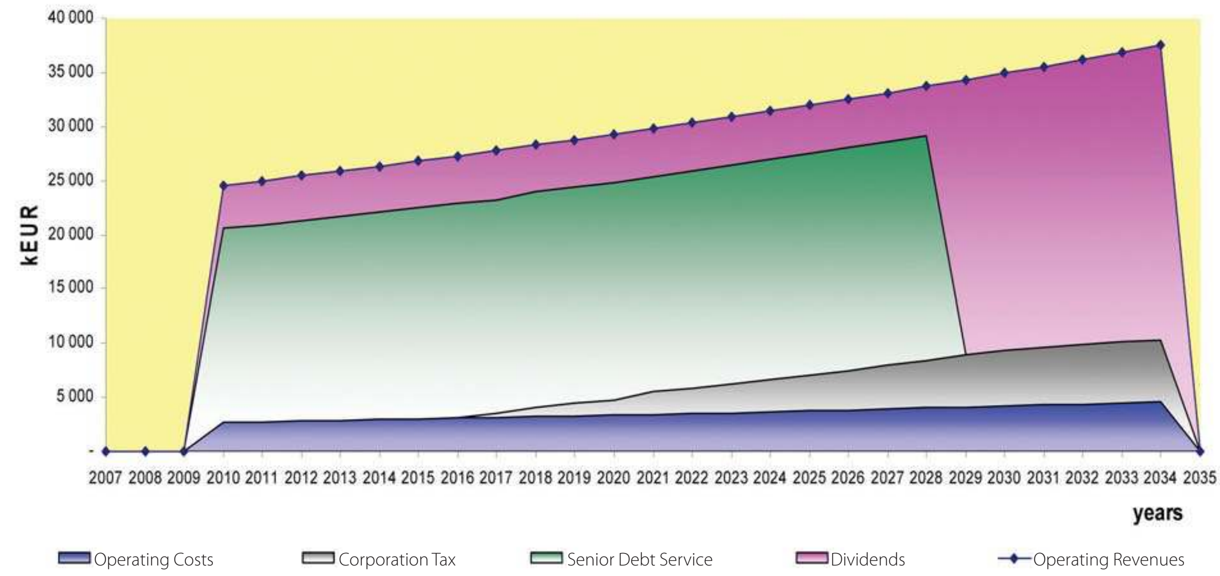


Figure A.8 The cash account of 25 years of operation of a 100 MW VLS-PV system

project. It helps the investors to evaluate their expected return under different scenarios, the banks to estimate their risks and calculate the amount of debt and equity required for the financing and the developers to calculate an electricity selling price that will ensure the sustainability of the project.

Initially, the technical design of the VLS-PV system leads to an estimation of the costs of the materials, the transportation costs, the civil works costs, the labour costs and the grid connection costs. These costs have been defined as the **technical investment costs**. In order to ensure correct management of the construction of the systems and the implementation of all the processes linked to the project, a consortium of several companies, including constructors, banks and investors will be constituted. All of them will request or provide several guarantees, the constitution of a sound insurance programme, a completion guarantee and a letter of credit, among other things. It is important to note that the overall transaction costs vary from one operation to another depending mostly on macroeconomic and market factors: interest rates, country risks and confidence in the technology.

The operating costs have to be split again between pure technical costs and management costs of the transaction. The **technical operating costs** include preventive maintenance and corrective maintenance, including the price of spare parts. The other costs are insurance premiums, security, local tax and management of the project including accounting, reporting and other management functions. Local tax varies drastically from one country to another. A corporate tax should also be added to the operating costs. As this element varies from one country to another, it is necessary to undertake a thorough fiscal and accounting analysis before engaging in any simulation.

Eventually, the generation cost should be equal to the generation price, because the latter includes all the costs of the transaction, including the investors' return. The generation price, calculated with the methodology, is the minimum price that enables the transaction. Indeed, if the price is lower, the investors will not reach their target internal rate of return (IRR) and will decide not to invest in the project. The following steps are necessary to calculate the electricity generation price:

- Estimation of the construction and operating costs (financial costs excluded);
- Estimation of annual electricity production;
- Definition of the accounting and fiscal structure;
- Definition of the macroeconomic environment: market interest rates (without the bank margin) and inflation;
- Definition of the main terms and conditions of the loan (especially the debt service coverage ratios, the maturity and the margins);
- Definition of the target investors' IRR;
- Calculation of an electricity price that will ensure the target IRR.

Figure A.8 shows an example of a cash account of a 100 MW VLS-PV system. Its operation would start at the beginning of 2009, run for 25 years and be financed with equity and a 19-year loan. It is intentionally simplified in order to understand the methodology.

For any electricity price, the model will calculate the amount of debt supported by the project, the amount of equity required and as a consequence, the IRR. The electricity generation price is the minimum price that allows the investors to reach their target IRR.

The financial structure, the terms and conditions of the loan and the cost of capital (the target IRR) also have a huge impact on the project and on the electricity generation costs. It is possible to prepare different cost scenarios with the business model and calculate the corresponding electricity generation costs, hence validating the choice of PV in the energy mix and the research and development (R&D) roadmap. Therefore, various case studies will help the entire PV sector to have a better idea of the real electricity generation costs of PV and identify the main factors that could increase the development of PV.

A.4 TECHNICAL ASPECTS

A.4.1 Technology overview

A variety of PV cell and module technologies are available for current and future VLS-PV applications, in particular thin film, crystalline silicon wafer-based and concentrator cell technologies.

Crystalline silicon wafer-based cells and modules are best proven in mass production and will soon be produced at a GW scale by several companies. Significant cost reduction can be achieved by applying thin film solar cell technology. In this case, very thin layers of semiconductor materials are deposited on glass, metal or plastic substrates and electrical connections are made by advanced laser structuring methods. Basically, three different semiconductor materials can be used, notably thin film silicon and compounds of cadmium telluride (CdTe) or copper indium gallium diselenide/sulphide (CIGS) materials. Manufacturers of thin film panels in each technology are rapidly expanding their production capacities in order to utilize their potential economies of manufacturing scale.

For PV system and electricity generation costs, no dominance of one technology has been seen so far because a lower production cost of thin film modules can be offset by higher balance of system (BOS) costs due to lower efficiencies. The cost reduction potential of all technologies is still significant, resulting mainly from technological advancements and economy of scale accompanying mass production. PV generation cost is expected to intersect with utility prices in the relatively short term, firstly in high-insolation regions, which is an important prerequisite for the widespread commercial implementation of VLS-PV in general, but also in desert regions.

Another way of obtaining lower system costs and, consequently, lower electricity costs, is the use of concentration. In this case, the sunlight is concentrated by lenses or mirrors and concentration factors of 500 to 1000 are relatively easily achieved. By concentration, expensive semiconductor material can be partly replaced by comprehensively cheap glass or plastic material for lenses and metal for cooling. Concentration systems need to be placed in direct sunlight and need to follow the sun. Therefore, they are only effective in locations with a lot of direct sunshine and they need to be placed on sun-tracking systems. One of the attractive options for using concentrating solar panels in desert regions is that a major part of the panels can be produced locally.

A.4.2 The progress of MW-scale PV systems installation

Since the beginning of the 21st century, installation of MW-scale PV systems has been increasing substantially year by year, especially in Germany and Spain. Nowadays, more than 800 MW-scale PV systems are being operated, and the capacity of such MW-scale PV systems is expanding continually (see Figure A.9). Compared with all PV applications installed in IEA-PVPS countries, the ratio of annually installed MW-scale PV systems reached about 18 % of all PV applications in 2007 (2.26 GW/year). As for cumulative installed capacity, the ratio of MW-scale PV systems increased to about 10 % of all PV applications by the end of 2007 (7.84 GW).

Including MW-scale PV systems installed by the end of 2008, the total capacity of MW-scale PV systems installed has already reached about 3 GW.

It is obvious that MW-scale PV systems are already a major PV application. Because the capacity of MW-scale PV systems is expanding year by year, the capacity will reach 100 MW in the near future (a few years). After this stage, GW-scale PV plants consisting of several 100 MW-scale PV systems should be realized toward the middle of the 21st century. For the PV industry worldwide, MW-scale systems are increasingly becoming the basis of production capacity. This is true for cell producers as well as for module, inverter and other original equipment manufacturing (OEM) producers.

Thus, MW-scale and VLS-PV systems are promising options for large-scale deployment of PV systems. In the future, VLS-PV systems should be a viable option for many large remote desert regions around the world where conventional power plants can never be built.

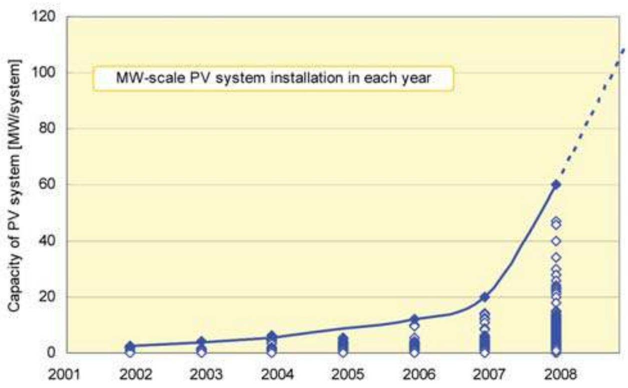


Figure A.9 Trend in MW-scale PV system installations

A.4.3 Advanced technology for VLS-PV systems

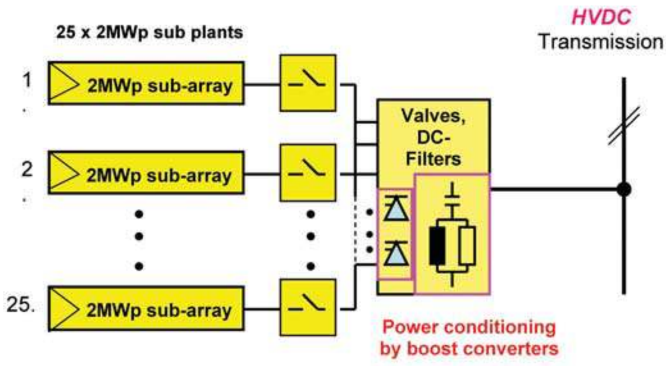
PV systems have the benefit of being modular up to the multi-megawatt range. As ground-mounted installations, PV plants do not disturb the ground below and so can use parts of the country that are not suitable for farming or agriculture. Furthermore, PV plants use robust components, have a technical lifetime of several decades and maintenance needs are very low.

Despite the relatively short development phase of multi-megawatt techniques, these large PV installations constitute sound operating plants. Most of the installations are working very reliably and producing the power expected by investors. In addition to their everyday business, it is time to review the typical issues they face and what features such projects have or should have. The aim is for PV plants to be accepted as industrial power plants, being comparable with other mature industrial power generation installations. In addition to the capital investment cost, the economic success of VLS-PV is strongly dependent on operating costs. The investment costs can be determined quite easily, but for operational costs, many factors of the individual plant have to be taken into account.

Looking into future, which may not be as far away as many expect, the plant architecture will become feasible for VLS-PV applications on the scale of 50–100 MW installations. Dimensions like this will be realized by early and close coordination with grid owners in special regions, concerning grid conditions to be considered in the design of the VLS-PV. Power transmission from remote areas to which PV may expand in the future will involve grid extensions or new construction. A promising solution is high voltage direct current (HVDC) power transmission, which has the benefit of lower transmission losses. Figure A.10 shows an example of the replacement of many AC power conditioners (inverters) by a central DC power-conditioning unit.

Because a stable market for VLS-PV has been established, a new type of module, called a ‘MW module’, especially designed for this application, has to be developed. The module must suit the special conditions of multi-megawatt plant operation, and so their electrical, as well as mechanical, design is modified accordingly. These modifications and effects on electrical plant design result in lower cost per watt.

The cost of setting up a huge number of PV modules can be very high. New module support structures can reduce these costs remarkably by allowing very quick tacking and easy installation of modules. Normally, concrete foundations may be replaced by earth screws. A new approach that reduces cost is the static structure design, based on the wind-scale effect. Applying this effect requires a special evaluation of the dynamic wind loads and static calculations, which differ from common static calculations.



Source: ©PVconsult

Figure A.10 Example of advanced 50 MW VLS-PV unit at a HVDC grid)

A well-designed VLS-PV plant is clearly arranged. The right choice of inverter system can contribute to this. Inverter development must focus on even more robust types in remote areas, extensive remote control, longer-lasting electronic components and calculated redundancy. Reliability with low maintenance will become increasingly important and will build confidence in the success of VLS-PV plants. In order to secure high availability of machines and plant operation, besides remote control, a service contract of over 20 years or longer is necessary. Within these contracts, the replacements components are guaranteed over the entire lifespan.

The operation of a VLS-PV plant is greatly influenced by the quality of the monitoring system. The system should be like those used for common industrial process control, using standard components. A higher investment in a more detailed monitoring system may eventually pay off by saving time by identifying causes of abnormal operating conditions, etc. In the near future, the generation of relevant grid information by the monitoring system will facilitate the process of communicating with grid owners.

A professional VLS-PV must be designed with excellent electrical security. Like all other professional industrial installations/plant, it should also have a complete lightning protection system. This is not only for insurance reasons, but also increases the availability of the plants. It is usual for industrial complexes that have a high risk of theft to have a security service; this would ensure the protection of VLS-PV plants. In parallel, a software-integrated signalling system can inform the operator immediately about any critical incidents. Such a service structure also has to be established locally.

A.4.4 Future technical options

A.4.4.1 Matching to grid requirements

A well-balanced utility will have fixed the base-load part of its daily output so as to produce as little surplus power as possible, and will have designed a system that follows the actual changing load requirements so as to regulate the spinning reserve as efficiently as possible. As the input to the grid from PV systems becomes larger and larger, the probability increases that there will be moments when the PV input to the grid exceeds the output of the spinning reserve at that moment. At such times, the PV system would be generating more power than could be used by the grid, and this power would be wasted unless some kind of storage facility exists.

Unless the amount of such storage is sufficiently large, a VLS-PV plant would, therefore, inevitably need to dump some of its power generation. However, by optimizing the amount of storage capacity, the latter could be employed for solarizing some of the base-load generation. Accordingly, some form of trade-off between the cost and efficiency of storage on the one hand, and the value of the electricity it would save on the other, is necessary before a definite conclusion can be drawn about the optimal size of storage that is required if VLS-PV is to be incorporated into existing grid systems. This emphasizes a third important reason for storage, in addition to those of smoothing the effect of passing clouds and of enabling nocturnal solar availability: namely, to overcome the inflexibility of conventional generating methods employed by existing power grids.

A.4.4.2 Energy storage

Electricity storage is an important ingredient in the operation of large-scale PV systems, both for nocturnal utilization and for smoothing out differences between supply and demand caused by passing clouds. For accurate simulation of the temporal variation of stored energy, the regular hourly and annual variation of insolation and the load, as well as the random fluctuations of these quantities around the regular variation, need to be taken into account. However, a much simpler analysis is possible if the regular temporal variation of both insolation and load can be replaced by their averages, around which these quantities fluctuate randomly. This is an approximation that provides rough estimates of quantities of practical interest, such as the averages of the required backup energy and of the dumped energy.

The approach recognizes the finite size of storage media, and balances the need to provide backup energy with the need to dump surplus PV production. Perhaps the most important finding is the fact that, in all situations for which the regular temporal behaviour of the principal variables (solar generation and load requirements) can be replaced by their long-term average, the probability distribution for the stochastic variations about the average is exponential in the battery storage level. This mathematically simple result permits the calculation of many properties of storage that are of critical importance for system designers.

A.4.4.3 Solar hydrogen

Hydrogen could be the ideal replacement fuel for hydrocarbons. First, it could be produced via the electrolysis of water, using DC electricity generated by VLS-PV plants. In this way, and in contrast to the conventional methods of producing industrial hydrogen from hydrocarbons, its production would leave no carbon footprint. Second, when hydrogen is burned or used as a power source in a fuel cell, the only waste product is water vapour; again a carbon-free process. Third, with an energy density of 142 megajoules per kilogramme (MJ/kg), compared to 47 MJ/kg for gasoline, it may seem strange that hydrogen engines were not developed long ago.

The reasons why the world has not hitherto availed itself of a hydrogen economy are governed by simple chemistry and physics. It has become a convention to add two more aspects to these two fundamental problems: first, hydrogen is produced, as it presently is, from fossil fuel and so has neither a low carbon footprint nor a low energy cost; second, renewable energies such as solar or wind are presently too expensive to enable them to improve the economics of hydrogen production.

There is nothing fundamental about the energetic cost of oil, other than the fact that it is rising in monetary terms and will continue to rise as that commodity becomes ever scarcer. By contrast, the energetic cost of solar energy is easier to quantify, and as solar hardware costs decrease towards a situation in which revenues have paid off the initial capital investment then the cost of producing the energy becomes the O&M cost of the system. At that stage the energetic cost of hydrogen from electrolysis becomes equivalent to gasoline at 72 US cents per litre.

The present approach will take the various hurdles purely as challenges, motivated by the fact that electric power from VLS-PV will ultimately be so low in cost and environmentally clean that its availability will force a fresh approach to hydrogen that will almost certainly overcome all of today's problems. VLS-PV will be able to provide a low-cost, carbon-free energy source for the generation of hydrogen gas.

A.4.4.4 Cloud prediction

Apart from the nocturnal absence of solar radiation, shading of the sun by clouds constitutes the major reason for the low capacity factors of ground-based solar power producing systems. Cloud shading is responsible for the stochastic component of solar power intermittence. It leads to lower power quality and system instability, considerably reducing the performance characteristics and economy of large-scale solar power plants.

A system for predicting shading has to become a part of a knowledge-based expert system for the operation of large-scale solar power plants. The principles of a system would be capable of tracking clouds in the sky in angular proximity to the sun and of predicting the moment of shading, thereby giving the control system of a power plant enough time to prepare for, and to soften the dynamic reaction to the on–off effects of sun shading. The method is suitable for tracking the sporadic clouds that are associated with good weather, and for the more complex case of intermediate cloudiness – both of which conditions coincide with those encountered during the operation of solar power plants.

A.5 ENVIRONMENTAL ASPECTS AND VLS-PV POTENTIAL

A.5.1 The energy payback time and CO_2 emission rate of VLS-PV

The lifecycle analysis (LCA) methodology is an appropriate means of evaluating the potential of environmental impacts. As indices, energy payback time (EPT) and CO_2 emission rate were analysed. EPT means years to recover for primary energy consumption throughout its lifecycle, by means of its own energy production. The CO_2 emission rate is a useful index to calculate the effectiveness of the PV system for global warming.

The VLS-PV systems evaluated would have a capacity of 1GW and, as PV modules used for the VLS-PV system, six kinds of PV modules were supposed: single-crystalline silicon (sc-Si), multi-crystalline silicon (mc-Si), amorphous silicon/single crystalline silicon hetero junction (a-Si/sc-Si), amorphous silicon/micro crystalline thin-film silicon (thin-film Si), copper indium di-selenide (CIS), and cadmium telluride (CdTe). The array structures assumed are conventional structures with concrete foundations. However, for comparison, a new array structure called an 'earth-screw' is also discussed.

The installation site was assumed to be in Hohhot in the Gobi desert in Inner Mongolia, China. Annual irradiation there was assumed to be 1 702 $kWh{\cdot}m^{-2}yr^{-1}$ and in-plain irradiation at a 30 degree tilt angle was 2 017 $kWh{\cdot}m^{-2}yr^{-1}$. The annual average ambient temperature is 5.8°C. Most of the equipment for the VLS-PV system was assumed to have been manufactured in Japan and transported by cargo ship. However, the foundation and steel for the array structure were assumed to have been produced in China. For these materials, land transport was assumed to be 600 km, and marine transport was assumed to be 1 000 km.

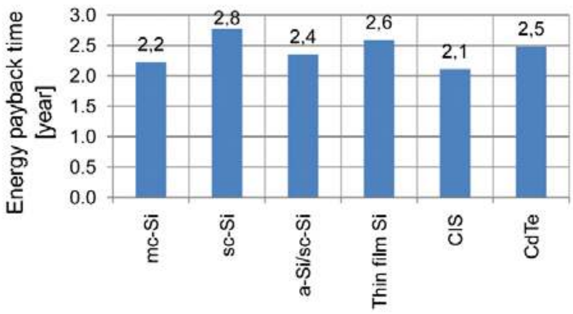


Figure A.11 Energy payback time of VLS-PV systems

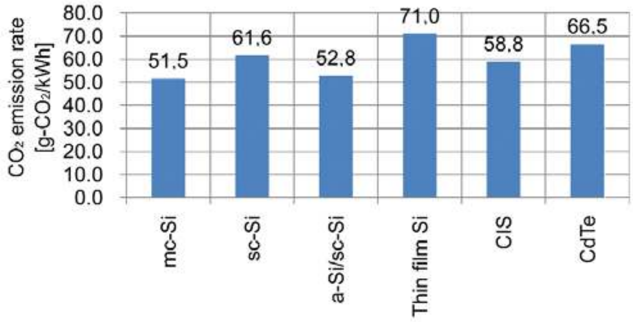


Figure A.12 CO_2 emissions rate of VLS-PV systems

The lifetime of the VLS-PV system was assumed to be 30 years, while that of the inverter was 15 years. It is assumed that after the end of the equipment's lifespan all equipment will be transported to a wrecking yard and transported for reclamation.

Figure A.11 and A.12 show the EPT and CO_2 emissions rate of the VLS-PV system. It was calculated that the EPT of the VLS-PV system would be 2,1–2,8 years, and the CO_2 emissions rate would be 51–71 g-CO_2/kWh. This means that the VLS-PV would be able to recover its energy consumption in the lifecycle within three years and provide actual clean energy for a long time. Furthermore, the CO_2 emissions rate of the VLS-PV system would be much smaller than that of a fossil-fuel fired plant. In particular, a PV system generates during the day when fossil-fuel fired plant are also operational.

A.5.2 The ecological impact of VLS-PV development

VLS-PV development can truly contribute to sustainable development for our future. The concept of ecological footprint and the ecological footprint analysis are methods of evaluating its potential from viewpoints of the ecological sustainability.

The ecological footprint (EF) is a largely heuristic tool that has been widely used in sustainability analyses for over a decade now. The EF is, for example, defined as a measure of how much biologically productive area an individual, a country or humanity uses to produce resources and absorb the waste. While the EF by itself tells us little about sustainable resource usage and is simply a measure that increases or decreases as our demands on the environment increase or decrease, without telling us whether or not those demands are sustainable, the ecological footprint analysis (EFA) compares the EF with available biological capacity (BC). The BC means the appreciable extent of natural resources and services on the earth within the context of sustainability.

Because VLS-PV systems have a huge potential for generating clean power, VLS-PV development will contribute to improve the ecological balance on earth. In this study, the possible ecological impact of the VLS-PV development in the Gobi desert was estimated by using the following indices:

- The potential for reducing CO_2 emission by substituting existing electricity generation with VLS-PV systems;
- The potential of changing the EF by reducing CO_2 emission with the VLS-PV project;
- The potential of changing the BC with the VLS-PV project, including a desert development

The CO_2 emissions reductions of 100, 500 and 1 000 GW VLS-PV projects were estimated to be 173,863 and 1 726 million tons (t) of CO_2/year, respectively. These correspond to about 3 %, 17 % and 34 % of the amount of annual CO_2 emissions in China in 2005. As shown in Figure A.13, a 100 GW VLS-PV development would slightly decrease the EF from 12,5 to 11,9 global hectare (gha) per capita. In the case of a 500 GW VLS-PV development, the EF would decrease to 9,5 and the ecological balance would improve significantly, although still overshooting the BC. Furthermore, in the case of a 1 000 GW VLS-PV project, the EF would decrease to 6,4 gha/capita; overshooting the BC is resolved and the ecological balance would be drastically improved. Additionally, if the analysed area is extended to Mongolia and South Korea, a significant improvement in the ecological balance could be expected due to development of the 1 000 GW VLS-PV.

In addition, the global potential for the possible impact of a 10 000 GW VLS-PV development is estimated as follows. The reduction in CO_2 emissions is estimated to be 8 162 million t-CO_2/year, which would be 31 % of the global annual CO_2 emissions in 2005. The change in EF per capita is estimated to be 5,89 gha/capita, and the EF would be decreased from 21,9 to 16,0 gha/capita. Because the change in BC due to the project is negligible compared with the current condition, for example 15,7 gha/capita, overshooting the BC by EF is almost resolved and the ecological balance will also be greatly improved.

It is concluded that a VLS-PV development in a suitable area of the Gobi desert could improve the ecological balance and that the area influenced would expand from local, national, to global, depending upon its capacity. Furthermore, the VLS-PV development would include desert development such as afforestation and agricultural development. Although the ecological impact of this development has not yet been analysed, the development would help increase the BC at a regional or global level, in addition to curbing the EF by reducing CO_2 emissions.

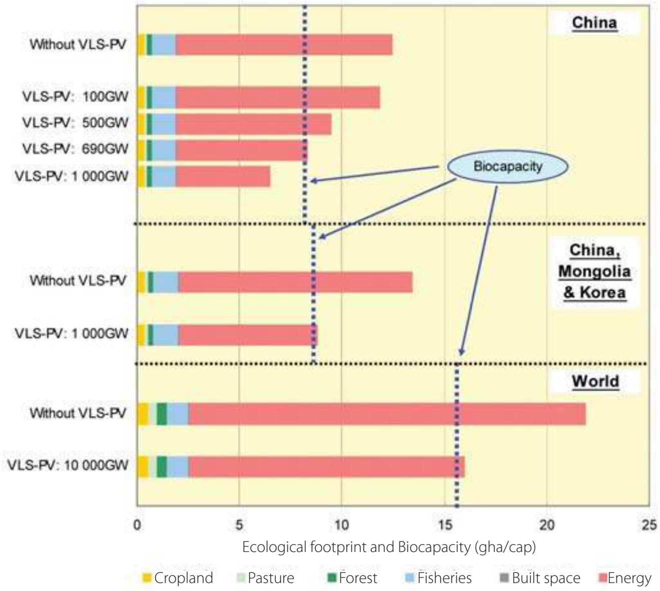


Figure A.13 The possible ecological impact of the VLS-PV project on the Gobi desert

A.5.3 Analysis of global potential

It is assumed that VLS-PV systems will be installed in desert regions. However, land conditions are important for stable operation of VLS-PV systems. Installation on a sand dune may be difficult, but a gravel desert is a good location because of its stable, flat land conditions: the hard ground consists of small rocks and sand. In this study, a gravel desert was considered to be a suitable area for VLS-PV installation, and a method for identifying such regions and evaluating their potential was developed.

The method uses remote sensing with satellite images. Satellite images taken by LANDSAT-7 are first converted by using a reflection ratio, for classifying ground cover and undulating hills. The ground cover classification is done by using the maximum likelihood estimation, which is a statistical method. The undulating hills classification is done by using a Laplacian filter to find the edges of sand dunes and mountains. A third analysis is done by a vegetation index, which is provided by the NDVI data set from NOAA's satellite images. By using this method, the solar energy potential of the Gobi, Sahara, Great Sandy, Thar, Sonora and Negev deserts was analysed.

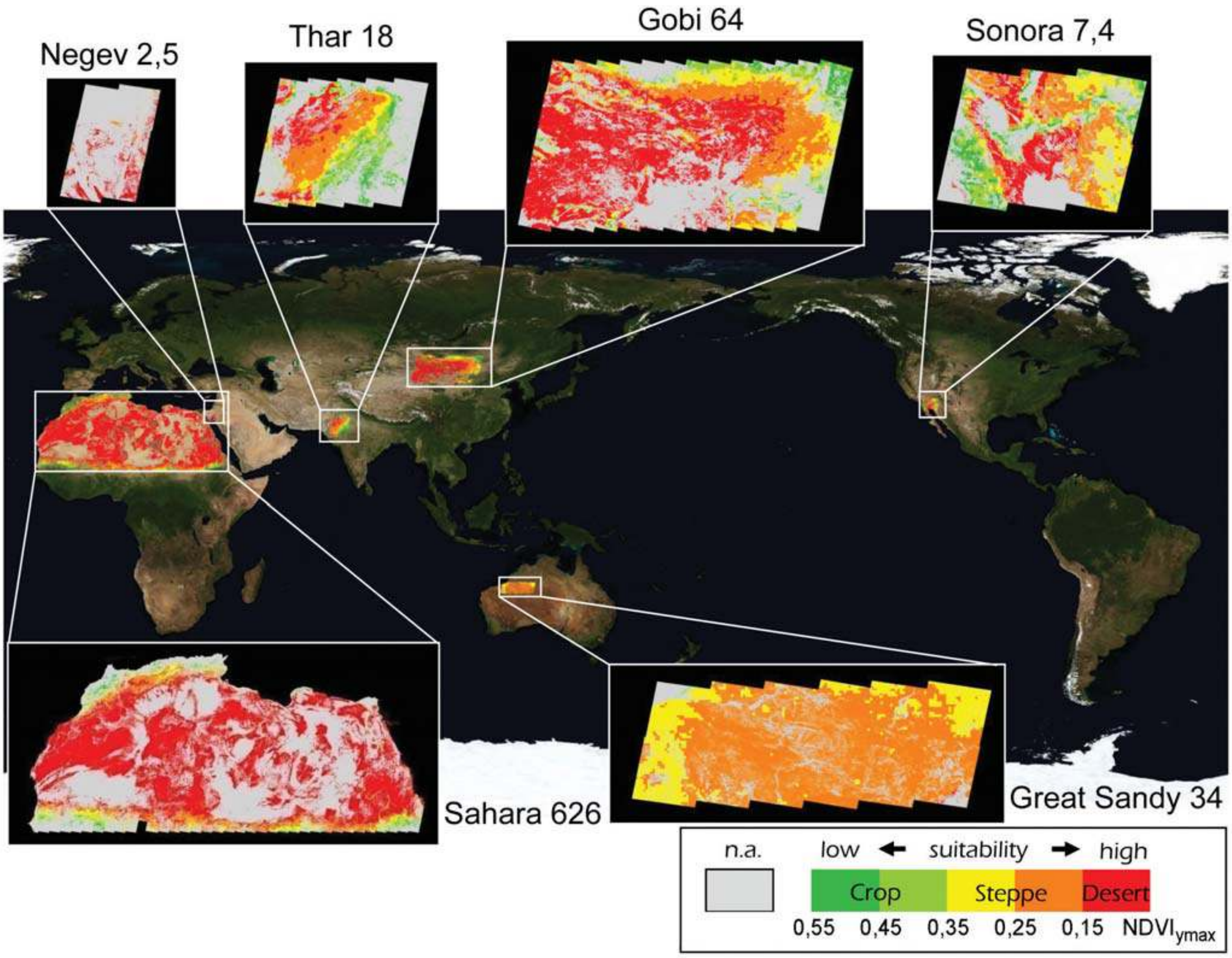


Figure A.14 Annual generation of the world's arid areas by PV resource analysis (PWh/year)

Figure A.14 shows the results of the evaluation. White areas correspond to unsuitable areas, and coloured areas indicate suitable areas. Red means a more arid area and green means more vegetation. Therefore, the red areas are more suitable for VLS-PV than green areas. In the case of the Gobi desert, the rating of area suitability, for example crop level, was 54 %. It was also observed that the Sahara desert is very dry, whereas the Great Sandy desert has some vegetation in the entire region.

In Figure A.14, numeric values next to the desert's name indicate the amount of annual PV generation. In the case of the steppe level and below, the potential annual generation by VLS-PV would be 752 petawatt hours (PWh), which would be equivalent to 2707 exajoule (EJ) and be five times the world's energy demand in 2010. It was shown that the Sahara desert has the largest potential and could generate twice the world's current energy demand, and that the Gobi desert also has large potential.

A.6 CASE STUDIES

A.6.1 A case study on the Sahara Desert

The Sahara is by far the largest desert in the world with the biggest potential for generating VLS-PV solar electricity. Moreover, the Sahara desert is located relatively close to big energy users in Africa, as well as to potential regions for export of the generated electricity, notably southern Europe.

A.6.1.1 Country studies

To review the state-of-the-art potential for VLS-PV in the Sahara region, country studies on Northern Africa were first carried out. The countries selected were Morocco, Algeria, Tunisia, Libya and Egypt. The status of PV development and installation, the potential for PV application and VLS-PV were reviewed for these countries.

The state-of-the-art technology in the different countries shows a lot of variety, but the main conclusions are common: desert countries have huge potential for harvesting the benefits of the sun. However, it was also revealed that much work remains to be done and decision-makers should be made aware of the huge potential of a VLS-PV strategy.

A.6.1.2 CPV in the Sahara

As part of the country studies, a top-down study for Northern African countries, focusing on concentrator photovoltaics (CPV), was performed. For the various countries in North Africa, it was proposed that each country would construct VLS-PV plants, *one per year*, but this time sized only large enough to enable their existing electricity production to keep pace with expected population growth. Such a top-down programme, if adopted as national policy, would enable a country to effectively freeze its fossil-fuel consumption at the level it would have reached when the first VLS-PV plant goes on line, approximately five years after the decision to go ahead. Thereafter, all additional electricity needs would be provided by solar energy.

As for the electricity tariff, this was fixed in a manner that would just permit so-called *type-3 sustainability*. In this context: *Type-1 sustainability* was defined as a situation in which electricity revenues cover all accrued costs within the lifetime of the first VLS-PV plant (assumed to be 30 years); *Type-2 sustainability* was defined as a situation in which revenues from electricity sales suffice to permit the continued annual construction of VLS-PV plants without the need for additional external investment; *Type-3 sustainability* was defined as a situation in which, from year 35 onward, revenues from electricity sales suffice to permit the construction of *two* VLS-PV plants per year without the need for any external investment – one plant to continue the ever-increasing need for electricity due to population growth, and the other to replace a 30-year-old (assumed worthless) VLS-PV plant.

The analyses add a significant number of North African states to the list of desert countries for which VLS-PV, of the CPV variety, may be expected to be a thoroughly cost-effective venture. In all of these cases, *type-2 sustainability* can be expected after approximately 20 years. At this time, the entire initial infrastructure costs would be fully paid off, including interest, *and* a situation would exist in which electricity revenue from the previously-constructed VLS-PV plants would cover the entire cost of continued annual plant construction without the need for further external investment. Furthermore, in all of these case studies, *type-3 sustainability* would also set in after 34 years, namely, at that time the revenues from all previously-constructed plants would suffice to construct *two* new VLS-PV plants each year: one to satisfy the demands of continued population growth and the other to replace a 30-year-old-plant at the end of its expected lifetime.

A sensitivity study shows that all assumptions that have any bearing on economics are extremely robust – particularly in that it largely ignores technology improvements that will certainly take place during the coming 20 years, and which will render the economics of the scheme even more cost effective than it already clearly is.

Finally, it should be emphasized that after the VLS-PV plants have paid themselves off via electricity revenues, the effective cost of electricity production would become a mere 0,5 US cents/kWh. This is an order of magnitude lower than present-day fossil-fuel electricity generation costs. At such a low production cost, many new uses for electricity such as hydrogen production would become cost-effective.

A.6.1.3 Developing projects

The technologies for converting solar irradiation into electricity and for transportation and storage of electricity are widely available. We also believe that financing can be made available for excellent project proposals. Therefore, the main challenge is to make these excellent project proposals and to convince governments, energy companies and financing institutions to become positively involved in realizing ambitious projects for the large-scale generation of solar electricity. Connected issues, such as (sea)water desalination, irrigation, agriculture, community development and socio-economic development should be covered as well. We should focus on proven technology with substantial cost reduction potential and on a step-by-step development, with relatively low initial investment and modular growth in conjunction with decreasing costs. For these reasons, we will focus on electricity generation by converting solar irradiation directly into electricity (PV systems).

For developing realistic projects, we want to cooperate with influential local institutions that have sufficient expertise and a powerful network. The target size of the projects should be in the order of 1 GW, to be extended to 10 GW over time. In order to make maximum use of the foreseeable price decreases, the first GW installation should be built in steps during a time frame of, for example, 10 to 15 years.

Community development should take place in parallel to the growth of the PV power plant. Such long-term planning will allow the creation of a sustainable local industry for all required materials, components and services.

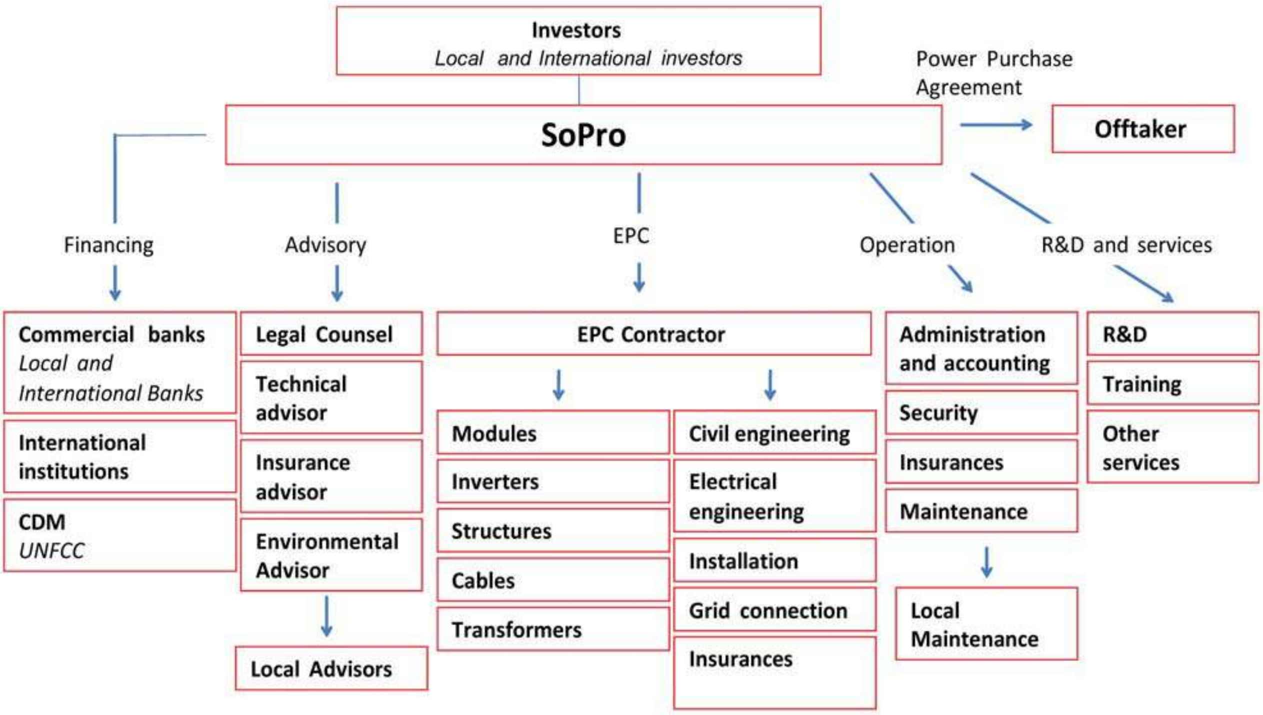


Figure A.15 Contractual structure

A.6.2 Case study on the Gobi Desert

As a case study on the Gobi desert, a financial aspect and a possible installation site was initially discussed and actual examples of PV installation in the Gobi desert were introduced.

A.6.2.1 Financial aspect

The costs to society of constructing and operating a 1 GW VLS-PV system in the Gobi desert were discussed. The contractual scheme shown in Figure A.15 was supposed for the analysis. It was assumed that a consortium of companies, both local and international, would ensure the development, the construction and the operation of the project. All the main contracts, such as land lease, insurances, the power purchase agreement (PPA) and the loan agreement will be negotiated and signed by the Consortium.

It was concluded that if the PV electricity price can largely compete with other sources of energy, it remains in the upper cost range and, therefore, should be appreciated in the context of CO_2 emission reduction mechanisms, increasing energy commodity prices and the huge potential of cost reductions in the sector.

A.6.2.2 Possible installation site in the Gobi Desert

Because deserts are large, it might be difficult to supply electricity generated for the nearest demand immediately and it seems difficult to identify an appropriate installation site even if a suitable gravel area can be found. However, if there is a suitable area with a transmission line already constructed nearby, it would become easier to supply electricity.

Figure A.16 shows the integrated results of remote sensing analysis on the Gobi desert with a Geographical Information System (GIS) around the Gobi desert covering China and Mongolia. Red dots on the figure show suitable areas that were analysed by remote sensing analysis, brown dots show other desert areas, and blue lines show transmission lines. It was initially concluded that the southeast part of the Gobi desert might facilitate connection of a VLS-PV system to existing transmission lines.

A.6.2.3 A preliminary test of PV power systems installed in Naran Soum and Tibet

Korea has implemented two joint projects for the installation of PV systems in Mongolia and China, which have deserts that are adequate for PV power generation. The preliminary test project for PV systems for future installation of VLS-PV in deserts has been carried out in Naran Soum in Mongolia and Tibet in China, which are semi-desert areas with abundant solar radiation. The power capacity of PV systems installed in Naran Soum and Tibet are 5 kilowatts (kW) and 100 kW, respectively.

By using the operational results of a 100 kW system, the EPT and CO_2 emission rates were calculated. Considering annual generation capacity and a system lifetime of 20 years, it was estimated that the EPT and CO_2 emission rates of the system were six years and 20,3 g-C/kWh, respectively.

The preliminary testing of PV systems in Naran Soum and Tibet has been carried out successfully.

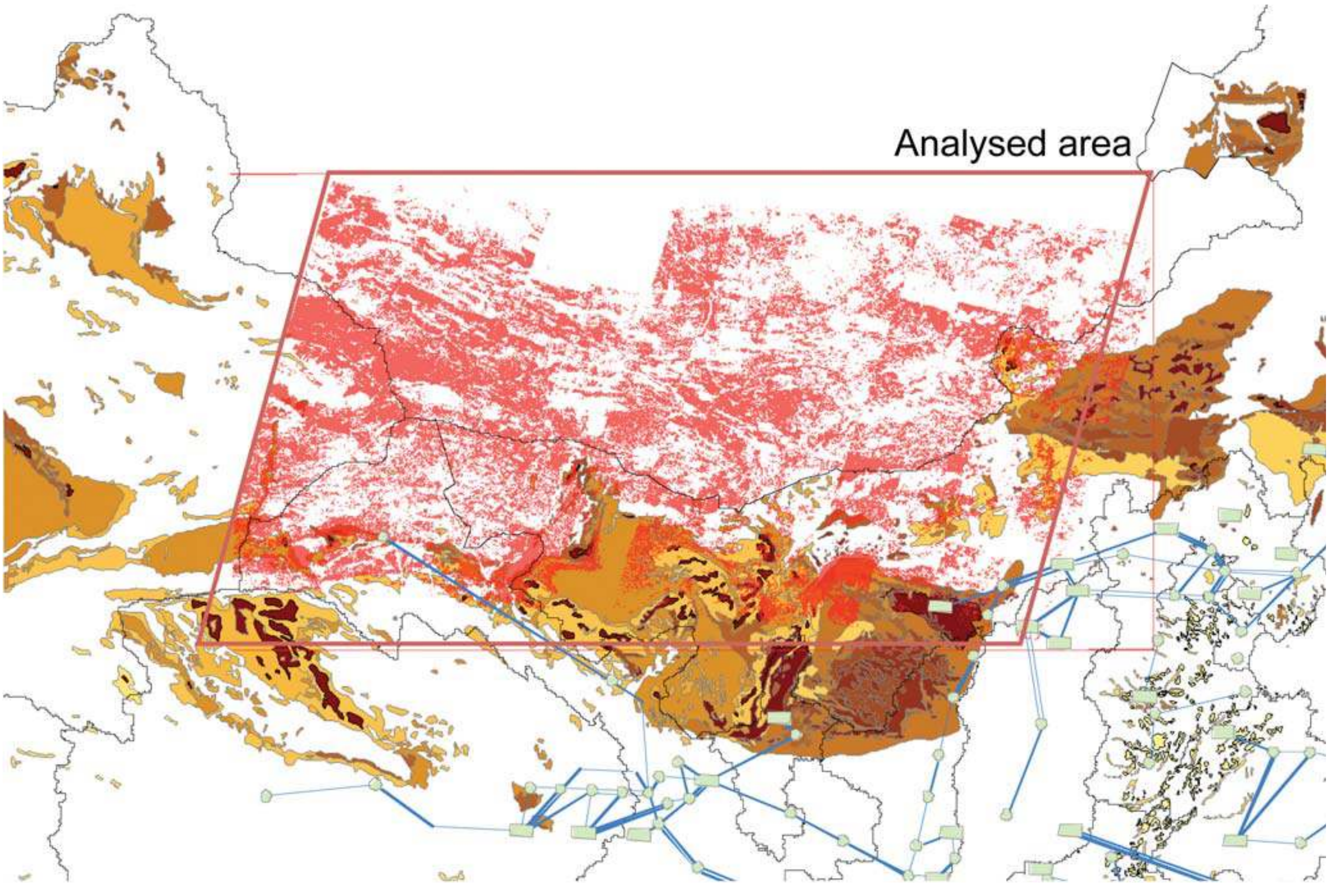


Figure A.16 GIS showing transmission lines, desert and suitable land for VLS-PV by remote sensing

Various results from these tests will be useful as fundamental data for the future installation of a VLS-PV system in a desert region. Further studies are continuing to examine the reliability of a VLS-PV system in the desert.

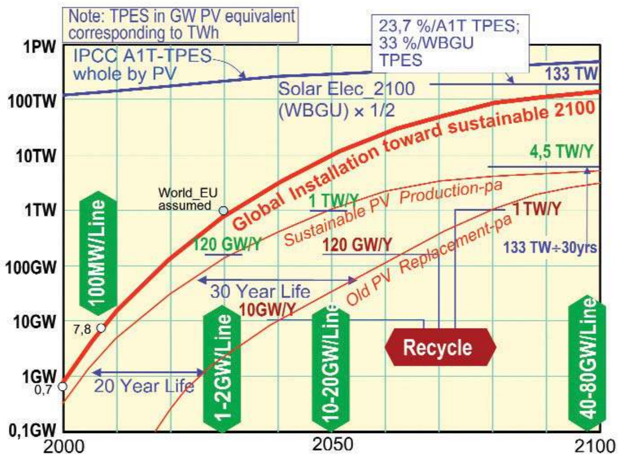
A.7 VLS-PV ROADMAP

A.7.1 Future directions

The top line in Figure A.17[6] shows the projection of world's total primary energy supply (TPES) up to 2100, given as an Intergovernmental Panel on Climate Change (IPCC) SRES-A1T scenario[7] and its interpolation by the IEA.[8] TPES is denoted by GW-pve (photovoltaic electricity), which means that 1 GW-pve is equivalent to 1 TWh of energy, considering an annual PV yield of 1 000 hours. This also converted to 3,6 petajoules (PJ). The second curve corresponds to the world's cumulative installation of PV modules, starting from the present level, i.e. 0,7 GW in 2000 and 7,8 GW in 2007.[9] This reaches a stable level of 133 terawatts (TW) in 2100, which corresponds to 23,7 % of the SRES-A1T TPES, and 33 % of the German Advisory Council on Global Change's (WBGU)[10] TPES or 50 % of solar electricity. Thus, intermediate values are given 10 TW in 2050, 10 TW in 2050 and 75 TW in 2075, respectively.

Based on the cumulative curve and with the assumption that annual PV production becomes stable in 2100, the third curve gradually reaches the 4,5 TW/year (2100 stock (133 TW) divided by module lifetime of 30 years). This means that all the expired modules are replaced by new produced modules. Intermediate values are 120 GW/year in 2030 and 1 TW/year in 2050.

The module replacement curve is shown as the fourth curve, assuming a 20-year lifetime in the beginning and 30 years after 2030 or so. Therefore, recycling



Source: Adapted from Kurokawa, 2007

Figure A.17 Proposed long-term sustainable scenario or waste management should consider 10 GW/year in 2040, 100 GW/year in 2060 and finally 4,5 TW/year in 2100.

Furthermore, because an annual module production scale is given in this figure, the required production speed can be specified by supposing that the number of production lines in the world is 50 to 100 lines. Presently, a typical PV module fabrication line may be in the range of 100 MW/year/line. This will become 1–2 GW/year/line in 2030, 10–20 GW/year/line in 2050 and 40–80 GW/year/line in 2100. For a 1 GW/year/line and a 10 GW/year/line respectively, the necessary line speeds for PV cells, modules and power conditioners have been studied elsewhere. See Figure A.17.

A.7.2 Scenarios on major technology streams

To consider the needs and potential for the long-term deployment of PV mentioned above, the authors suggest a technology development roadmap, as shown in Figure A.18.

It is essential to substantially improve PV energy conversion efficiency and to raise production speed and yield according to production volume expansion, decade by decade. The final targeted electricity cost should at least be lower than the wholesale price. It is also necessary to develop a total system approach to accommodate the huge number of distributed PV clusters in many types of regions in the world in order to realize truly sustainable societies.

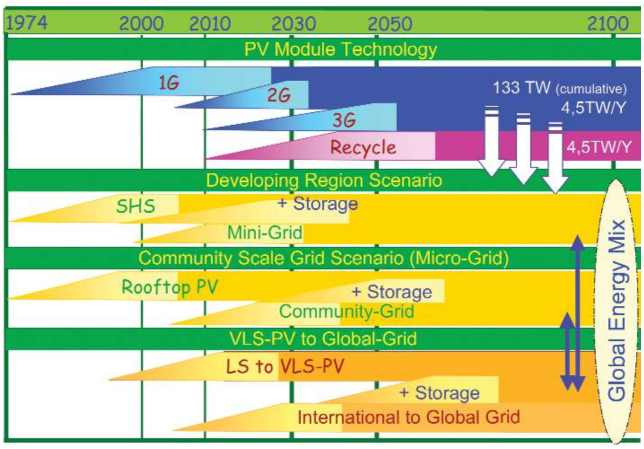
As illustrated in Figure A.18, four major streams are specified as described in clause:

1 PV technology stream
- PV materials and device processes such as present commercial processes for the first generation; ongoing major R&D may be categorized as the second generation, such as the Japanese PV2030[10] for the longer-term future, fundamental research on third generation concepts expects breakthroughs beyond 2030.
- Replacement/waste issues of old modules arising after 2015 to 2020, considering the 20-year lifetime; the necessities of recycling/waste management technologies growing decade by decade.

2 Developing region deployment
- Solar home systems (SHSs) as an initial stage of small-scale rural PV electrification.
- Village electrification by medium-size PV station with mini-grids; finally extended to a larger network to connect villages each other. Locally available renewable energy resources can be also combined.

3 Urban community grids
- Annual-base residential PV potential is sufficient to supply 80 % of household energy presently; 100 % for completely electrified houses by 22 % efficiency module (as specified by the target of Japanese PV2030.[11]
- Expanded to an urban community grid concept, applied to residential PV community or solar PV town/city.
- The necessity of power electronics to follow autonomous and dispersed logics, entirely different from the present power grids; advanced power devices such as silicon carbide (SiC) and power integrated circuit (IC).

4 VLS-PV to global grids
- Large-scale PV (LS-PV) plants of the order of multi-10 MW are already appearing; PV plants larger than 100 MW will soon be realistic, especially for desert areas; VLS-PV up to GW class originally proposed by IEA PVPS/Task 8 studies.
- VLS-PV, including concentrator photovoltaics (CPV), utilized for developing desert areas and for other regions through transmission lines; desert countries able to export abundant electricity by the interregional link infrastructure.
- Asynchronous power routing functions make it easier to realize wide-area and global network by means of localized power control.



Source: Adapted from Kurokawa, 2007

Figure A.18 The assumed outlined scenarios towards 2030–2050 and beyond

Furthermore, according to recent technological development on advanced battery storage, the degree of freedom in PV system planning is expected to increase as follows.

5 Energy storage function
- For mini-grid applications in remote areas, if sufficient auxiliary power sources are not available, applications have to be made autonomous by using a storage battery facility, even today.
- Essential for raising the autonomy of larger PV aggregation to be harmonized with the operation

of upstream power grids; expecting advanced storage technologies such as lithium-ion batteries; at least three days capacity for adjusting load/demand gap within a micro-grid; storage energy management by introducing weather forecasting, raising its value remarkably.
- When the future share of PV energy is extended to broader regions, the necessity of a storage function becomes obvious in principle to balance PV power generation and regional load needs.
- If many types of renewable sources can be combined through regional grids, and if the fluctuation of various loads can be equalized also through the grid, the necessary total capacity of regional energy storages tends to be reduced as covered areas are extended and broadened. Present HVDC transmission is matured for connecting 3 000 km or longer distances very easily. Links among global networks may be one solution in the longer term.

A.7.3 VLS-PV roadmap proposal

A proposed VLS-PV roadmap is shown in Table A.3 and is summarized below (see also Figures A.19–A.24).

- Global trends
  - Following a tendency in a proposed long-term sustainable scenario, world total cumulative PV capacity will reach 133 TW in 2100.
  - The share of community application will reach the maximum share of world's total PV capacity in an early stage. Rural and mini-grid applications will have the second largest share until 2075. Large and very large applications are growing gradually from a low-percentage share in 2010 to 20 % in the 2050. Finally, in the second half of the 21st century, the share of large and very large applications will rapidly increase and attain a major position in world energy supply, i.e. roughly 50 % in 2100.
  - It is assumed that the average system cost will gradually descend from 4,50 USD/W in 2010 to a stable value of 0,75 USD/W in 2100, most likely regardless of system type.
  - Annual world PV installation is expected to be about 120 GW/year in 2030, 1 000 GW/year in 2050 and finally level off at 4,5 TW/year in 2100. Then, the world PV market will expand to 56 USD billion/year in 2020, 160 USD billion/year in 2030, 0,9 USD trillion/year in 2050 and stabilize at 3,4 USD trillion/year in 2100.
- VLS-PV trends
  - The cumulative capacity of VLS-PV installed in the world will increase to 100 GW in 2030, 2 TW in 2050, 30 TW in 2075, and will reach 67 TW in 2010 corresponding to a 50 % share of world total cumulative PV capacity.
  - Annual VLS-PV installation is expected to be about 2,2 GW/year in 2020, then will increase 17 GW/year in 2030, to 236 GW in 2050 and finally level off at 2,2 TW/year in 2075 and beyond.
  - The VLS-PV market will expand to 5,1 USD billion/year in 2020, 23,2 USD billion/year in 2030, 214 USD billion/year in 2050, and stabi-

Table A.3 Proposed VLS-PV roadmap

Year	2010	2020	2030	2050	2075	2100
World PV (cumulative)	~20 GW	140 GW	800 GW	10 TW	75 TW	133 TW
Rural and mini-grid	~10 %	20 % 15 GW	35 % 160 GW	40 % 3,5 TW	30 % 30 TW	40 TW
Urban and community Grids		~83 % 115 GW	67.5 % 540 GW	45 % 4,5 TW	20 % 15 TW	20 % 26.6 TW
LS-PV to VLS-PV	4 % 0,8 GW	7 % 10 GW	12.5 % 100 GW	20 % 2 TW	40 % 30 TW	50 % 67 TW
Developed regions	0,8 GW	6 GW	63 GW	1,7 TW	12 TW	20 TW
Developing regions	-	4 GW	36 GW	0,3 TW	18 TW	47 TW
System cost (USD/W)	4,50	2,34	1,33	0,91	0,78	0,75
Annual world PV installation	4,4 GW	24 GW	120 GW	1 TW	4,4 TW	4,5 TW
World PV market size (USD million/year)	19,6	55,7	162	908	3408	3388
Annual VLS-PV installation	0,2 GW	2,2 GW	17 GW	236 GW	2,2 TW	2,25 TW
Developed region	0,2 GW	1,7 GW	8,5 GW	210 GW	0,65 TW	0,67 TW
Developing region	-	0,5 GW	8,9 GW	26 GW	1,55 TW	1,58 TW
VLS-PV market size including replacement (USD billion/year)	0,9	5,1	23,2	214	1726	1685
Annual expenditure for VLS-PV (USD billion/year)	0,2	2,3	13,8	181	2252	4761
Generation cost (USD/kWh)	0,208	0,108	0,062	0,042	0,036	0,035

Note: VLS-PV will include concentrator photovoltaics (CPV)

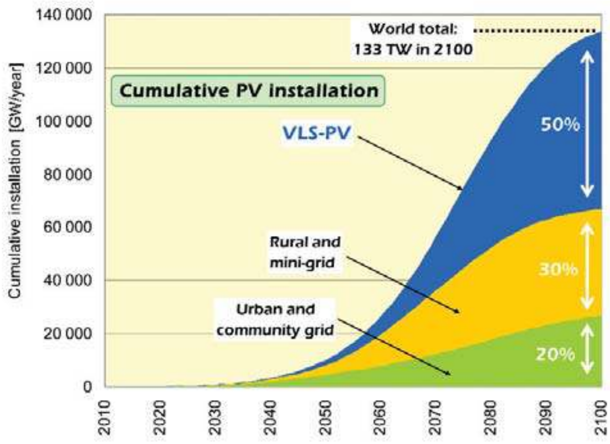


Figure A.19 Cumulative installation by PV application (GW)

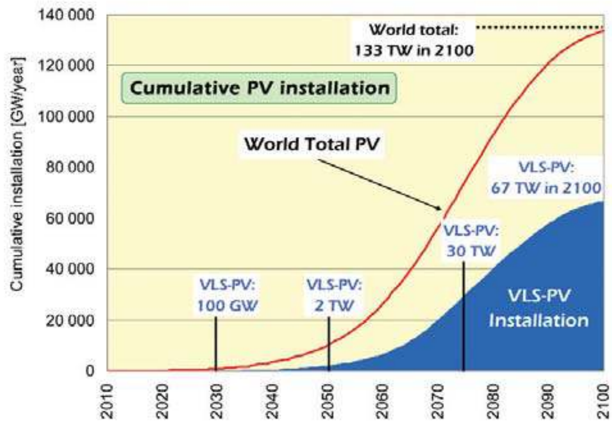


Figure A.20 Cumulative VLS-PV installation (GW)

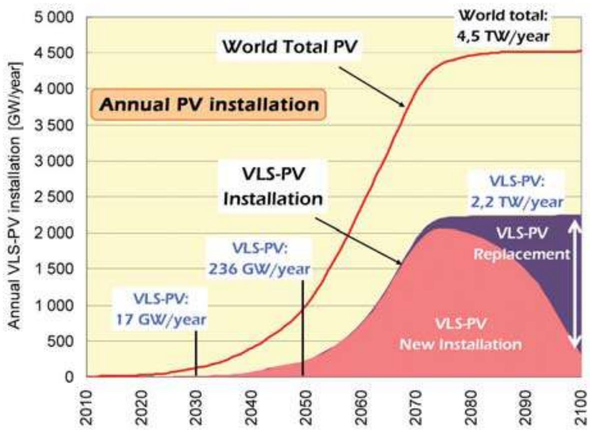


Figure A.21 Annual net installation and replacement of VLS-PV (GW/year)

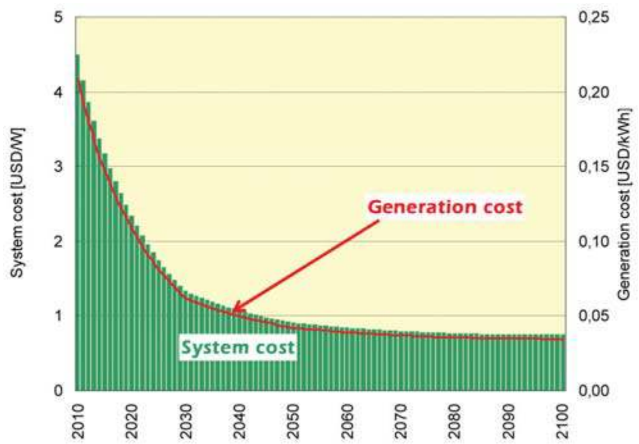


Figure A.22 Assumed system cost and generation cost

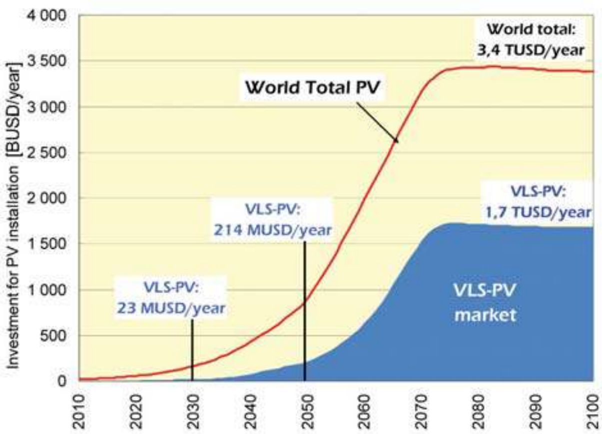


Figure A.23 Investment for VLS-PV installation ($ billions/year)

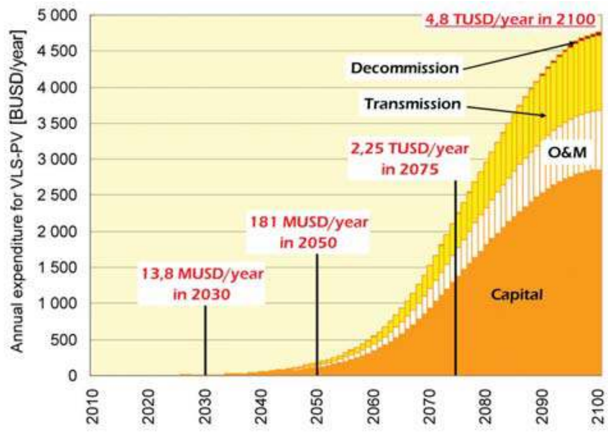


Figure A.24 Annual expenditure for VLS-PV (including replacement) ($ billions/year)

lize at 1,7 USD trillion/year in 2075 and beyond.

- Annual expenditure for VLS-PV will grow to 2,3 USD billion/year in 2020, 13,8 USD billion/year in 2030, 181 USD billion/year in 2050, 2,25 USD trillion/year in 2075 and 4,76 USD trillion/year in 2100.
- In developed regions, after a few decades, mainstream PV installation will move to VLS-PV. In 2050, an annual installation of VLS-PV in developed region will be around 200 GW/year and its cumulative capacity in developed region will be 1,7 TW. Thereafter, the cumulative VLS-PV installation will reach 20 TW in 2100.
- In developing regions in a second half of the century, PV installation will shift to VLS-PV systems. VLS-PV installation in 2075 and 2100 will greatly exceed the developed regions and will reach 18 TW in 2075 and 47 GW in 2100.

A.8 CONCLUSIONS AND RECOMMENDATIONS

A.8.1 Conclusions

Solar energy resources, PV technologies and renewable energy will help to realize important economic, environmental and social objectives in the 21st century and will be a critical element for achieving sustainable development.

In order to advance the transition to a global energy system for sustainable development, it is very important to orient substantial and increasing investments towards the introduction of renewable energy. If investments continue with business as usual, mostly in conventional energy, societies will be further locked into an energy system incompatible with sustainable development and one that further increases the risks of climate change. In order to promote renewable energy, the diversity of challenges and resource opportunities, as well as financing and market conditions among and within regions and countries, indicate that different approaches are required. Establishing policies for developing markets, expanding financing options and developing the capacity required have been indicated in order to adopt policy changes and incorporate the goals of sustainable development into these policies.

Box A.1 Statements by world-recognized institutions

Observatoire Méditerranéen de l'Energie[12]

- Independent organization, a Euro-Mediterranean association of energy companies
- Reference point for all questions concerning energy in the Mediterranean
- Regards energy as having prime importance for socio-economic development
- Link between the industrialists and the political decision-makers
- Recognized for its statistics and long-term scenarios and for its assessment of infrastructure
- Developed expertise on issues related to investment, market regulation, renewable energy and Kyoto mechanisms

HRH Prince Hassan bin Talal[13]

- Energy is the indispensable fundament required for socio-economic development and a basic ingredient in the recipe for peace
- It is a basic right that all societies and human beings should have fair access to energy markets, bearing in mind that energy production and consumption must be sustainable for future generations
- We need a concerted effort to increase energy efficiency and we must move our dependency to renewable energy sources
- Solutions are needed for:
  - lack of energy, which is the most pressing threat to the world economy
  - lack of water, the most pressing threat to physical survival
  - climate change, the most pressing threat to our living conditions on earth
  - access to clean energy and water, which is at the core of survival, development, security and peace
- Every day, the deserts of North Africa and Middle East receive over 2000 times more energy than is currently employed by all mankind
- The sunbelt and technology belt, when coupled together, can turn deserts into clean and inexhaustible powerhouses for the world
- Another challenge to the sunbelt is the severe shortage of drinking water. The long desert shorelines of arid countries have the potential to house waterworks powered by solar energy
- Clean power for Europe and fresh water for the Middle East and North Africa (MENA) region would be a win–win situation and a solution for all of us
- Look at our deserts through new eyes as an overabundant and inexhaustible source of clean energy and fresh water!

Global Network for Renewable Energy Approaches in Desert Regions[14]

- Deserts represent large lands with cruel surfaces, underground wealth, sunny and windy climate conditions and severe living conditions
- Deserts have an abundance of renewable energy and a high shortage of water
- The level of groundwater in the aquifers in the MENA region and southern European is dropping due to large water pumping programmes. More energy is needed to future pumping
- The salinity of groundwater in these regions is increasing; more energy is needed for desalination.

Energy Declaration 'Amman 2006'[15]

- Current and future increases in world energy demand results in:
  - conflicts for limited fossil resources
  - climate changes and other environmental degradation
- The desert regions of the world are scarce in water but rich in renewable energy resources; within six hours they receive more energy from the sun than the world uses in one year
- The high rate of groundwater extraction in the MENA and southern European countries is unsustainable, leading to depletion of aquifers, to the decrease of their levels and to the increase of their salinity. Hence more energy is demanded for desalination and pumping.

The IEA set up international task groups. In PVPS Task 8 we investigated the potential for very large power generation systems in desert regions. The purpose of our work has been to examine the possibilities for solving the world's problems concerning fair access to clean energy for everybody. We started the first phase in 1999 and concluded this phase with our book *Energy from the Desert: Feasibility of Very Large Scale Photovoltaic Power Generation Systems* in 2003. Our main focus was on technical feasibility and life cycle assessment. In the second phase, which concluded with our book *Energy from the Desert: Practical Proposals for Very Large Scale Photovoltaic Systems* in 2007, we mainly focused on the feasibility of projects. Both reports generated a lot of useful information for people who want to prepare and execute VLS-PV system projects in desert regions.

During the third phase, which was concluded by the end of 2008, we had a strong focus on socio-economic issues. Therefore we received useful inputs from, among many other experts, bankers, investors, project companies, module manufacturers, university professors and scientists.

It was also noticed that several renowned institutions stated the importance of renewable energy and the potential of solar energy in deserts,[12, 13, 14, 15] as shown in Box A.1. Having studied the justification for these statements in depth and having discussed the relevant issues on a global level, we came to the inescapable conclusion that: desert regions contain abundant and inexhaustible sources of clean energy and fresh water, offering a huge potential for socio-economic development

A.8.2 Recommendations

Deserts can be looked at as large lands with cruel surfaces, underground wealth, sunny and windy climate conditions and severe living conditions for inhabitants. However, it is necessary to find a more challenging and realistic way of looking at them.

The main driver for socio-economic development would be a VLS-PV power generation concept including concentrator photovoltaics (CPV), which would provide a sustainable market for solar electricity, PV and system components, installations and CDM credits. This development would also create massive employment opportunities and would involve technology transfer from industrialized countries to desert countries. The generated electricity can be used for lighting, communication, entertainment and education purposes, but also for providing potable water, for irrigation, agriculture and for industrial applications. VLS PV power generation plants will contribute significantly to energy security, provide fair access to energy for everybody and reduce the threat of climate change.

The technologies for converting solar irradiation into electricity and for transport and storage of electricity are widely available. We also believe that financing can be made available for excellent project proposals. Therefore, the main challenge is to make such project proposals and to convince governments, energy companies and financing institutions to become positively involved in realizing ambitious projects for the large-scale generation of solar electricity. Related subjects, such as (sea)water desalination, irrigation, agriculture, greening, community development and socio-economic development should be covered as well. We will focus on proven technology with substantial cost reduction potential and on a step-by-step development, with relatively low initial investment and modular growth in conjunction with decreasing costs.

For developing realistic projects, we want to cooperate with influential local institutions that have sufficient expertise and a powerful network. The target size of the projects should be in the order of 1 GW, to be extended to 10 GW in time. In order to make maximum use of the foreseeable price decreases, the first GW should be built in steps during a timeframe of ten years, for example. Community development should take place in parallel to the growth of the PV power plant. Such long-term planning will allow for the creation of sustainable local industries for all required materials, components and services.

The main target audience for our message are decision-makers for VLS-PV strategies in desert regions, which may include policy-makers from governments, utilities, industries, investors, banks, renewable energy institutes and NGOs.

We want to inform decision-makers in and around desert regions of the opportunities for exploitation of these deserts in a sustainable and rewarding way. In addition, we would be prepared to assist institutions in desert regions with implementing strategies for exploiting their mostly hidden wealth.

To this end, we intend to start the fourth phase of our study, which will focus on implementation of VLS-PV strategies in desert regions, as indicated in Box A.2. This implementation will be performed in close cooperation with local people and local institutions.

Box A.2 Proposed activities for implementing VLS-PV

Vision:
Deserts contain abundant and inexhaustible sources of clean energy, offering huge potential for socio-economic development.

Mission:
Evaluate opportunities and implement strategies for the exploitation of solar energy in desert regions.

Main activity:
Support for the preparation and execution of strategies for implementing VLS-PV systems in desert regions.

Organization:
Create a company or foundation consisting of experts with project, financial and/or organizational as well as other skills.

Business cases:
Different business cases will be developed for different types of regions:

- industrialized countries such as the US, Australia and southern Europe
- oil/gas/coal exploring countries such as UAE, Kuwait, Libya and Algeria
- developing countries in Africa, Latin America and Asia.

Network approach:
In the initial phase, we intend to reach decision-makers via existing networks such as IEA, OME, E8, G8, development banks, UN, European Commission, Club of Rome, the Global Network for Renewable Energy Approaches in Desert Regions and so on.

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