IEA INTERNATIONAL ENERGY AGENCY

Executive Summary

Energy from the Desert: Very Large Scale PV Power Plants for Shifting to Renewable Energy Future

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T8-01:2015

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAM

Energy from the Desert: Very Large Scale PV Power Plants for Shifting to Renewable Energy Future

Executive Summary

IEA PVPS Task8
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<Photos of cover>

- *Top* : *Topaz Solar Farm, San Luis Obispo County, CA, USA (courtesy of First Solar, Inc.)*
- *Bottom* : *Longyangxia Hydropower PV station, Gonghe, Qinghai, China (courtesy of Yellow River Hydropower Company)*

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Foreword

It is already known that the world’s very large deserts present a substantial amount of energy-supplying potential. Given the demands on world energy in the 21st century, and when considering global environmental issues, the potential for harnessing this energy is of huge import and has formed the backbone and motive for our work.

The work on very large scale photovoltaic power generation (VLS-PV) systems first began under the umbrella of the IEA PVPS Task6 in 1998. After that, the new Task8 – Study on Very Large Scale Photovoltaic power generation (VLS-PV) systems was established in 1999.

The scope of Task8 is to examine and evaluate the potential of VLS-PV systems, which have a capacity ranging from several megawatts to gigawatts, and to develop practical project proposals for realising VLS-PV systems in the future. Issues covered reflect the many facets VLS-PV for target groups as to political and governmental organisations as well as for e.g. institutes world-wide to provide a better understanding of these issues.

Since Task8 has been established, we published our extensive reports as a series of ‘Energy from the Desert’, focusing on VLS-PV systems. The books show that the VLS-PV is not a simple dream but is becoming realistic and well-know all over the world.

During our works, large scale PV systems increasingly count as a realistic energy option and have started to appear around the world in the 2000s, and have been rising substantially year on year. Now 500 MW scale PV systems are becoming reality.

Here, we compile the final Task8 report, entitled ‘Energy from the Desert’ as well. This report presents comprehensively results coming from our 15-years activity, and also includes the brand-new topics on VLS-PV, e.g. PV power plants.

We have recognized 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.

‘It might be a dream, however ---‘. It was a motivation when Task8 was established in 1999.

Now, we recognise that VLS-PV, e.g. PV power plant, has become one of the feasible options for large scale deployment of PV systems and renewable energy technologies.

河本 桂 一

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Very Large Scale PV Power Plants for Shifting to Renewable Energy Future - Executive Summary -

A. Expectations and potential for PV power plants: Why VLS-PV?

Global energy consumption has been increasing since the Industrial Revolution and is expected to increase for the coming decades. In order to meet the environmental challenge in the 21st Century, certainly, renewable energy must play an important role. Solar energy is one of the most promising renewable energy sources and a photovoltaic (PV) is the representative technology for utilising solar energy. It may no exaggeration to say that we're now coming to the stage of energy transition by PV power plants.

A.1 World energy and environmental issues

World economic growth in the 20th century was strongly driven by technologies based on a mass-consumption of fossil energy. On the other hand, drastic increase in energy consumption has led to global environmental issues including climate change. Although historical energy consumptions and carbon emissions are mainly attributed to developed countries, the impacts of some emerging countries on those issues have been increasing in a drastic manner. The importance of transition to a low carbon society has been widely recognised internationally. The global actions are essential to achieve the goal of low carbon society with sustainable energy supply.

According to the World Energy Outlook[1)] by the International Energy Agency (IEA), energy consumption and CO_2 emission are projected to increase continuously, as shown in from Fig. A.1-1 to Fig. A.1-4. It is forecasted that energy and electricity demand in Non-OECD countries will also continue to increase and that as a result CO_2 emission will continue to increase in such countries.

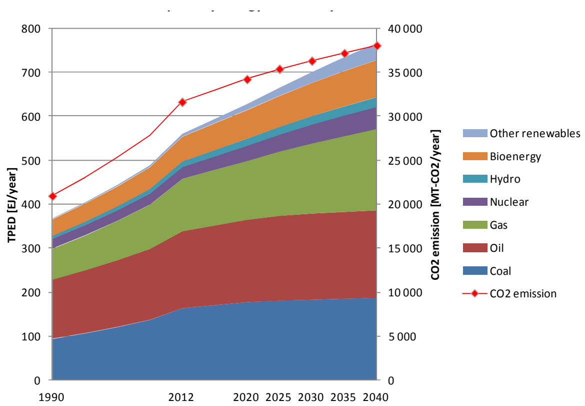

Fig. A.1-1 Primary energy demand and CO_2 emission in the world (New Policies Scenario)[1)]

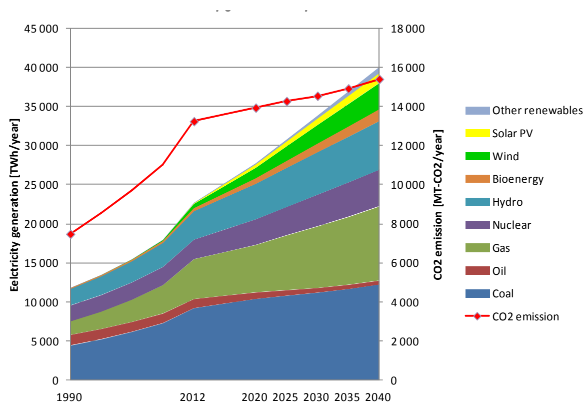

Fig. A.1-2 Electricity generation and CO_2 emission by electricity generation (New Policies Scenario)[1)]

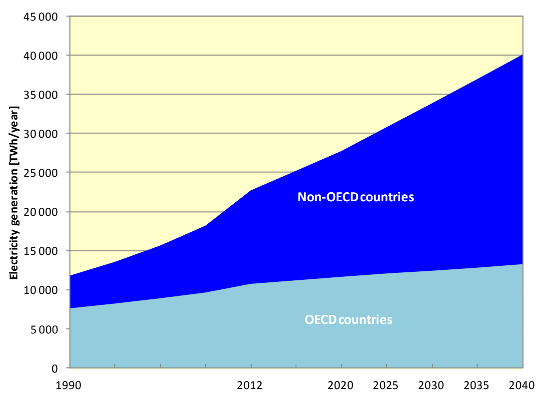

Fig. A.1-3 Electricity generation in OECD and Non-OECD countries (New Policies Scenario)[1)]

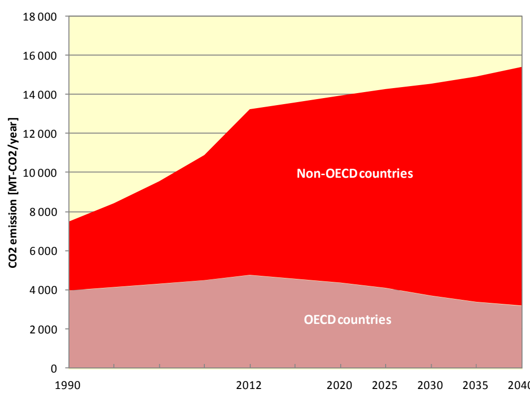

Fig. A.1-4 CO_2 emission by electricity generation in OECD and Non-OECD countries (New Policies Scenario)[1)]

The fifth assessment report from Intergovernmental Panel on Climate Change (IPCC)[2,3] concluded that climate change is mainly driven by human activity, saying that:

"Warming of the climate system is unequivocal; Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion; Direct CO_2 emissions from the energy supply sector are projected to almost double or even triple by 2050 compared to the level in 2010, unless energy intensity improvements can be significantly accelerated beyond the historical development."

On the other hand, the report also stated the possibility of renewable energy technologies including PV technology for overcoming the issues as follows:

"Decarbonising (i.e. reducing the carbon intensity of) electricity generation is a key component of cost effective mitigation strategies in achieving low-stabilization levels; Many RE technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale."

Meanwhile, discussions and directions on nuclear power, which was positioned as low-carbon base-load power, have become polarised after Fukushima accident in March 2011. One is that nuclear power is necessary for suitable electricity supply and the other is that considerable extensive risks by nuclear power should be avoided. At the IPCC 5th assessment report[3], description on nuclear power is, for example, that *"nuclear energy could make an increasing contribution to low carbon energy supply, but a variety of barriers and risks exist"*.

Energy Technology Perspectives 2014 (ETP2014) [4] from IEA, one of the representative projections in the world, developed and analysed several scenarios on future energy and electricity supply, as well as associated global temperature rise by 2100. Table A.1-1 shows major scenarios of ETP 2014.

Table A.1-1 Examples of scenarios under the ETP2014[4]

6DS (6^oC Scenario)	The 6DS is largely an extension of current trends. By 2050, energy use grows by more than two-thirds (compared with 2011) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentrations of GHGs, average global temperature rise is projected to be at least 6 ^oC in the long term.
4DS (4^oC Scenario)	The 4DS takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency, projecting a long-term temperature rise of 4 ^oC.
2DS (2^oC Scenario)	The 2DS is the main focus of ETP 2014. It describes an energy system consistent with an emissions trajectory that recent climate science research indicates would give at least a 50 % chance of limiting average global temperature increase to 2 ^oC. The 2DS also identifies changes that help ensure a secure and affordable energy system in the long run. It sets the target of cutting energy- and process-related CO_2 emissions by more than half in 2050 (compared with 2011) and ensuring that they continue to fall thereafter. Importantly, the 2DS acknowledges that transforming the energy sector is vital, but not the sole solution: the goal can be achieved only provided that CO_2 and GHG emissions in non-energy sectors are also reduced.
2DS hi-Ren (2DS-High Renewables Scenario)	The 2DS hi-Ren variant illustrates an expanded role of renewables in the power sector, based on a decreased or delayed deployment of nuclear technologies and CCS.

The 2DS is the main focus of ETP 2014 and offers a vision of a sustainable energy system with reduced greenhouse gas and CO_2 emissions[4]. It describes an energy system consistent with an emissions trajectory that recent climate science research indicates would give at least a 50 % chance of limiting average global temperature increase to 2 ^oC[4]. As shown in Fig. A.1-5, to meet 2DS targets, CO_2 emissions per unit of electricity must decrease by 90% by 2050. This reveals that a massive reversal of recent trends that have shown continued reliance on unabated fossil fuels for generation is required.

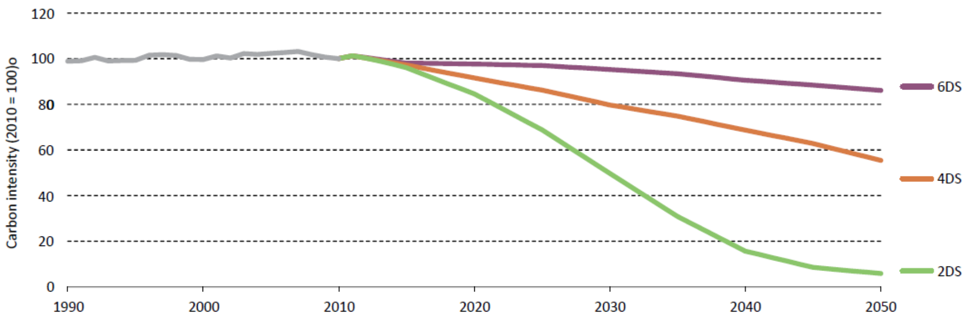

Fig. A.1-5 Electricity generation sector carbon intensity index by ETP2014[4)]
(©OECD/IEA 2014, Energy Technology Perspectives, fig. 3.3, p. 124, IEA Publishing.
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Fig. A.1-6 shows global electricity mix in various scenarios in 2050 described in ETP 2014. In the 2DS scenario, renewable energy comprises 65 % of the overall electricity demand, and the reminder 35 % is from nuclear and fossil fuel with CCS (carbon capture and storage). In 2DS-High Renewable (2DS hi-Ren) scenario, the share of the renewable energy in global power generation is even higher, and covers 79 % of the total demand[4)]. In the scenario, PV is the second largest energy sources (next to hydro) covering 16 % of the global electricity mix in 2050. The global cumulative capacity of the PV reaches to 4 626 GW.

Fig. A.1-7 shows cumulative CO_2 mitigation in the 2DS-hi Ren scenario from power sector in contrast to 6DS scenario by 2050.

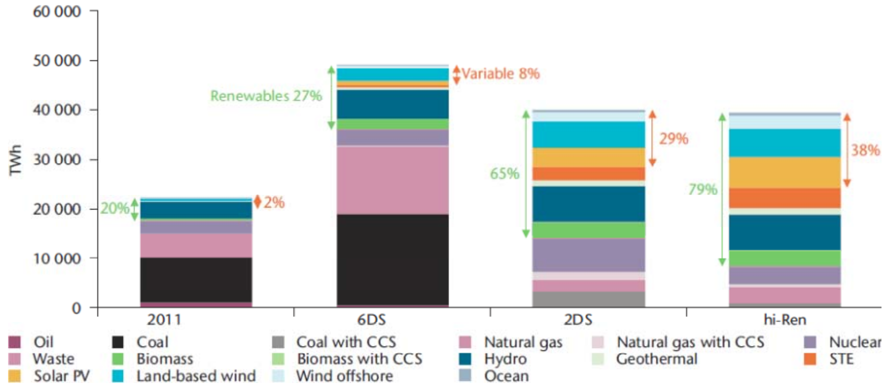

Fig. A.1-6 Global electricity mix in 2011 and in 2050 in three ETP 2014 scenarios[5)]
(©OECD/IEA 2014, Technology Roadmap: Solar Photovoltaic Energy, fig. 5, p. 18, IEA Publishing.
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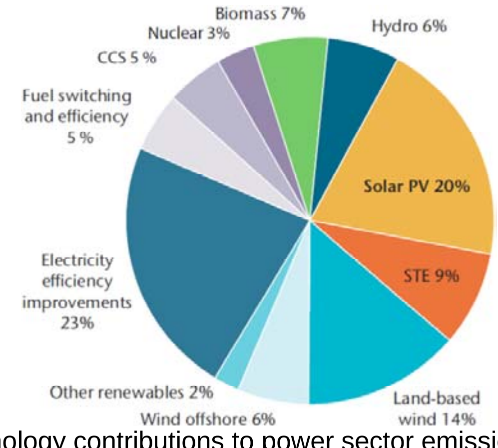

Fig. A.1-7 Cumulative technology contributions to power sector emission reductions in ETP 2014 hi-Ren Scenario relative to 6DS up to 2050[6)]
(©OECD/IEA 2014, Technology Roadmap: Solar Photovoltaic Energy, fig.6, p. 19, IEA Publishing.
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A.2 PV power in the deserts

Although, PV is expected to be one of the major energy sources in the future, the solar energy is low density energy in nature and the irradiation is unevenly distributed among the regions. In order that the solar energy becomes one of the major power sources, vast land areas with high solar irradiation are essential. The desert area which covers one-third of the land surface is clearly one of the best sites for the purpose.

Fig. A.2-1 and Table A.2-1 show world major deserts. Total area of deserts listed is approximately 1 900 million ha. It should be noted that the desert land areas have been expanding in the last few decades. Table A.2-1 also presents preliminary PV installation potential evaluation on the desert with 50 % space factor. The total electricity produced is simulated to be 2 239×10^3 TWh (=8 060 EJ), which is 14 times of the world primary energy demand 560 EJ in 2012. In other words, only 8 % of the surface area in the desert (without space factor the value becomes 4 %) is enough to provide global primary energy today. Another example is that Gobi desert area located between China and Mongolia can generate 5 times of the annual world power demand (Fig. A.2-2).

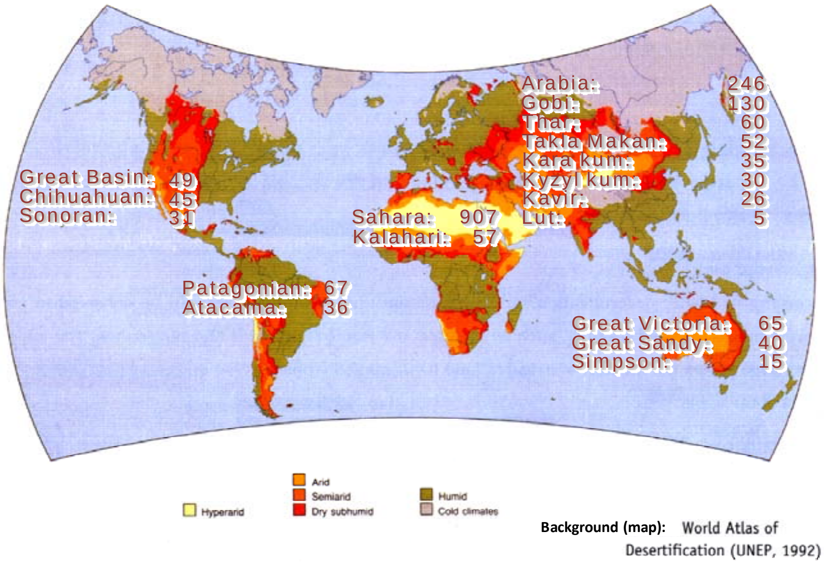

Fig. A.2-1 World desert (unit: 10^6 ha)[7)]

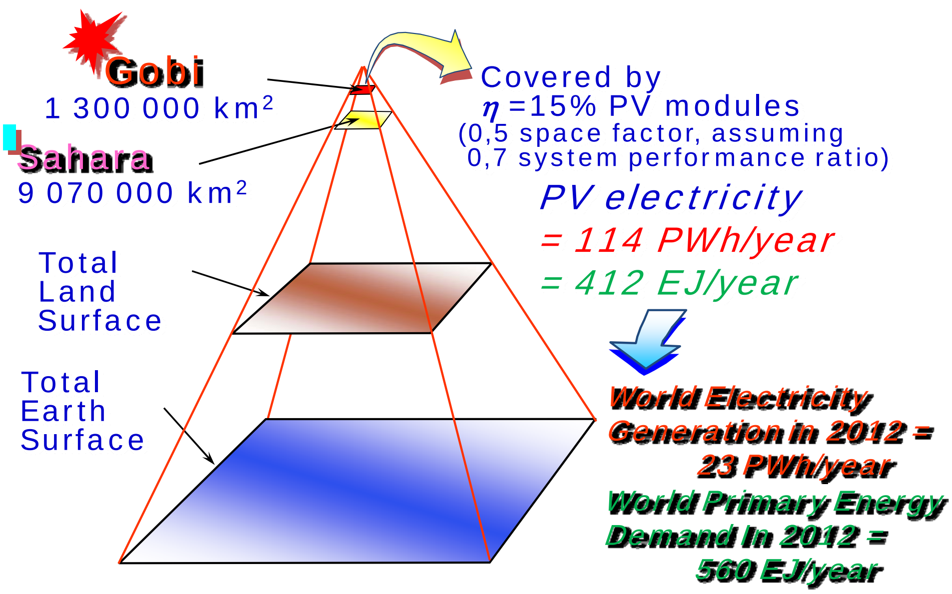

Fig. A.2-2 Solar Pyramid

Table A.2-1 World deserts and solar energy potential

Desert Name	(a) Area (10^6 ha)[7)]	(b) Annual average Irradiation ($MJ \cdot m^{-2} \cdot d^{-1}$)[8)]	(b) Annual reference Yield (h)	(d) Possible PV array Capacity (TW)	(e) Annual electricity Generation (10^3 TWh)
North America					
Great Basin	49	20,32	2 060	36,8	53,0
Chihuahuan	45	19,68	1 995	33,8	47,1
Sonoran	31	17,21	1 745	23,3	28,4
Subtotal	125			93,8	128,5
South America					
Patagonian	67	12,81	1 299	50,3	45,7
Atacama	36	22,08	2 239	27,0	42,3
Subtotal	103			77,3	88,0
Australia					
Great Victoria	65	21,57	2 187	48,8	74,6
Great Sandy	40	23,11	2 343	30,0	49,2
Simpson	15	21,57	2 187	11,3	17,2
Subtotal	120			90,0	141,1
Asia					
Arabia	246	22,24	2 255	184,5	291,2
Gobi	130	16,53	1 676	97,5	114,4
Thar	60	21,44	2 174	45,0	68,5
Takla Makan	52	16,19	1 641	39,0	44,8
Kara kum	35	16,34	1 657	26,3	30,4
Kyzyl kum	30	16,34	1 657	22,5	26,1
Kavir	26	18,33	1 858	19,5	25,4
Lut	5	21,09	2 138	3,8	5,6
Subtotal	584			438,0	606,4
Africa					
Sahara	907	23,52 26,46	2 534	680,3	1 206,5
Kalahari	57	22,54	2 285	42,8	68,4
Subtotal	964			723,0	1 274,9
Grand Total	1 896			1 422,0	2 238,9

(c) =(b) × 365d/($3{,}6 MJ \cdot m^{-2} \cdot h^{-1}$) : where $3{,}6 MJ \cdot m^{-2} \cdot h^{-1} = 1 kW \cdot m^{-2}$ is the reference irradiance.
(d) =0,14 × 1 kW/m^2 × (a) × 0,5 : where 0,15 is PV module efficiency, and 0,5 is space factor.
(e) =(d) × 0,7 × (c) : where 0,7 is system performance ratio.

The desert areas have abundant potential for PV power plants. However, not all the area is suitable for PV power plants and the site evaluation is very important. There are several unfavourable conditions for PV to be installed in the desert area. For example, a sand dune area may not be suitable for the PV power plants in terms of construction and maintenance, while a flat gravel desert is much more feasible from engineering point of view.

Another important aspect for the assessment is social and environmental impact. Even if the land is classified as desert area, there are areas which have enough rainfall and can be utilised other purposes such as agriculture or cattle breeding. In our site evaluation study, those land area is regarded as “not suitable” even if there is no technical barriers for constructing plants.

Fig. A.2-3 is the evaluation results of the suitable areas for PV power plants for selected six deserts in the world using remote sensing technology with satellite images. White areas correspond to unsuitable areas from technical, social and environmental perspectives, and coloured areas indicate suitable areas. The green coloured area is the land with vegetation, while the red coloured area is the arid land; hence, regarded as more suitable for PV. The potential annual generation by PV power plants within suitable desert area is calculated to be 752 PWh, which is approximately 5 times of the world energy demand and 33 times of world electricity generation in 2012.

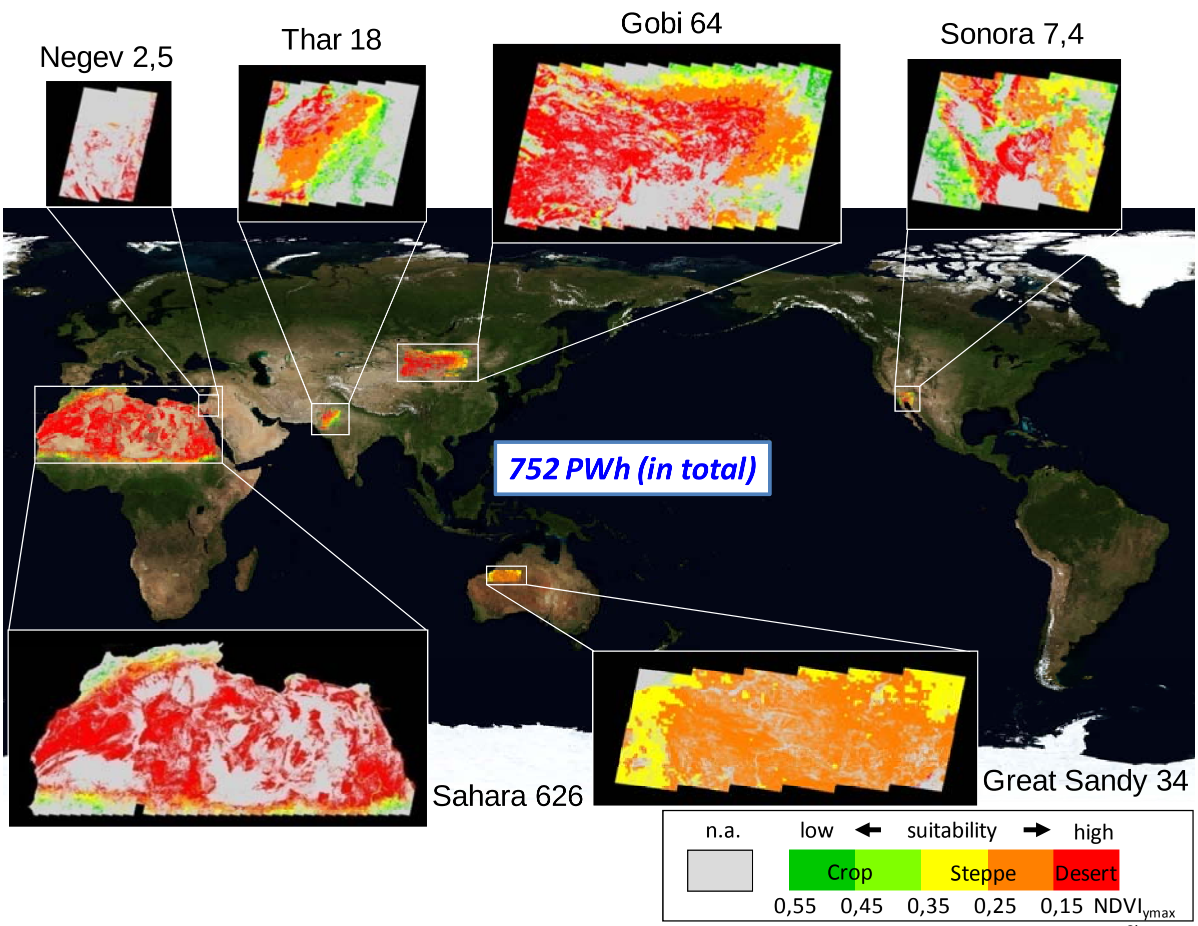

Fig. A.2-3 Expected annual electricity generation at the PV power plants in world 6 deserts[9)]

B. Technical feasibility of PV power plants: VLS-PV is already feasible!

B.1 Market trends in PV power plants

When Task8 established in 1999, cumulative capacity of PV installation in the world was less than 500 MW. Since then, PV market growth rapidly, especially in a latter half of 2000s. Cumulative PV installation in the world achieved 100 GW in 2012 and 140 GW at the end of 2013[10]. In the last few years, annual PV installation has been around 30 GW or more (see Figs. B.1-1 and B.1-2).

In 2000s, major PV market was in European region. After 2011, the major PV market shifted to USA, China and other Asian region. Especially, expansion of Chinese market is remarkable as shown in Fig. B.1-3. At the end of 2013, cumulative PV installation in China was 19,7 GW, in which 16,3 GW is large scale PV power plant. Similarly, annual PV installation in China in 2013 was 13,0 GW, in which 12,1 GW is large scale PV power plant application.

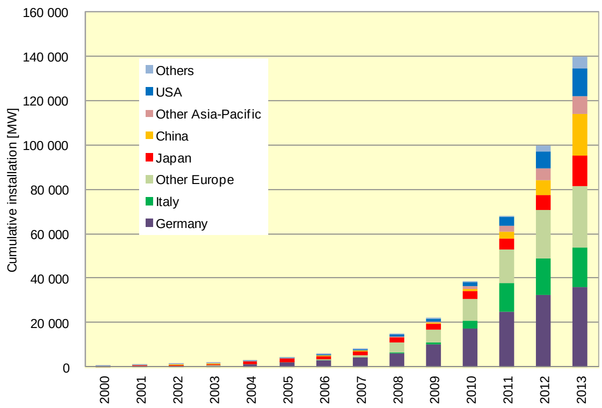

Fig. B.1-1 Cumulative PV installation in the world[10,11)]

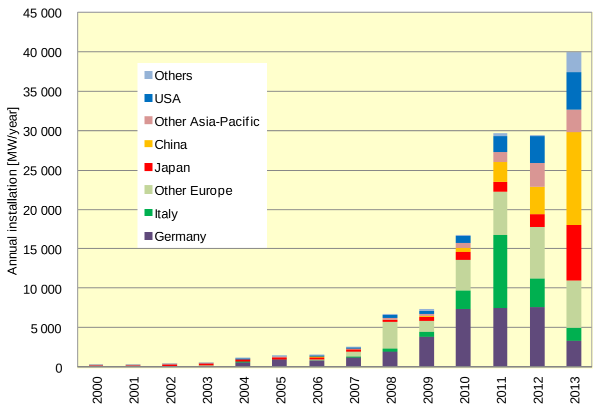

Fig. B.1-2 Annual PV installation in the world[10,11)]

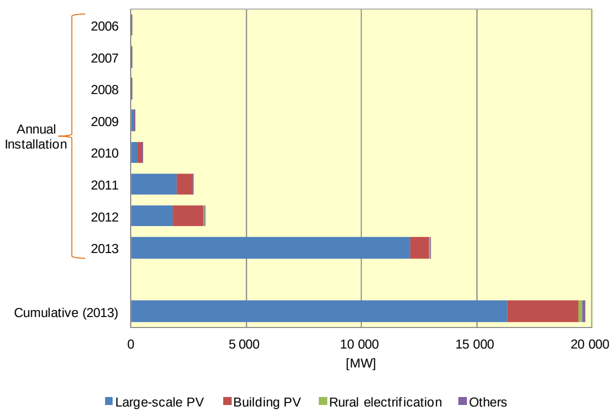

Fig. B.1-3 Trends in PV installation in China[12)]

Large scale PV power plants came on the market first in the latter half of 2000s, and many large scale PV power plants over 20 MW were installed in Europe, especially in Spain, under the Feed-in-Tariff scheme. After that, large scale PV power plants market expanded to other regions such as in USA and China for utility scale. Today, PV power plants with several tens of MW capacities are also emerged in Chile, as well as South Africa.

Fig. B.1-4 shows trends in large-scale PV installation until 2013, based on our survey. Unfortunately, there is no reliable statistics to capture all the large scale PV power plants in the world. Therefore, we've counted large scale PV power plants as much as possible, and confirmed that there are at least 170 PV power plants over 20 MW in the world as of mid-2014 and cumulative capacity of those plants exceeds 9 GW. By adding the PV power plants less than 10 MW and starting operation until 2010 on the 9 GW above, total capacity exceeds 14 GW. In addition, taking into account some external information resources regarding China (see Fig. B.1-3) and USA (7 GW in Nov. 2013)[13)], the share of large scale PV power plants is at least 10-15 % of the total PV installation in the world.

Similarly, the largest PV power plants record in the world has been broken every year, as shown in Fig. B.1-5. The number of PV power plants over 100 MW in operational is more than 20 (see Fig. B.1-6). In 2011, 200 MW PV power plant was constructed and started its operation in China. The capacity of this plant was expanded to 300 MW in 2013 and to 500 MW in late 2014. In 2012, 250 MW PV power plant started operation in Arizona, USA, and its capacity was expanded to 290 MW in 2013. In early 2013, 320 MW PV power plant emerged in China, and the plant was expanded to 520 MW in 2014. Also, in USA, Topaz Solar Farm in Arizona, and Desert Sunlight in California started operation in November 2014 and December 2014, respectively. Both plants have a capacity of 550 MW.

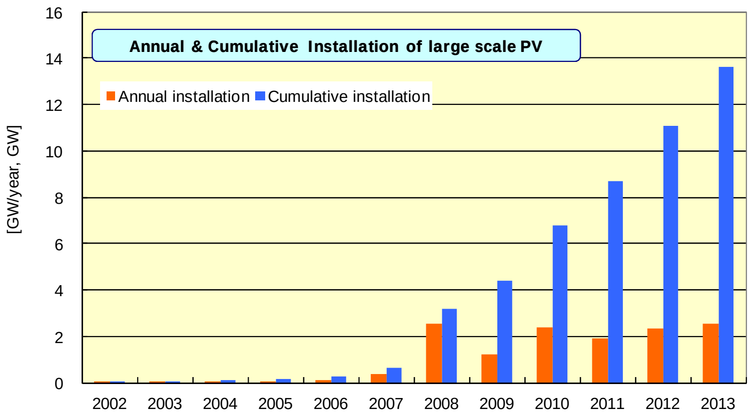

Fig. B.1-4 Trends in large-scale PV installation (based on confirmed projects)

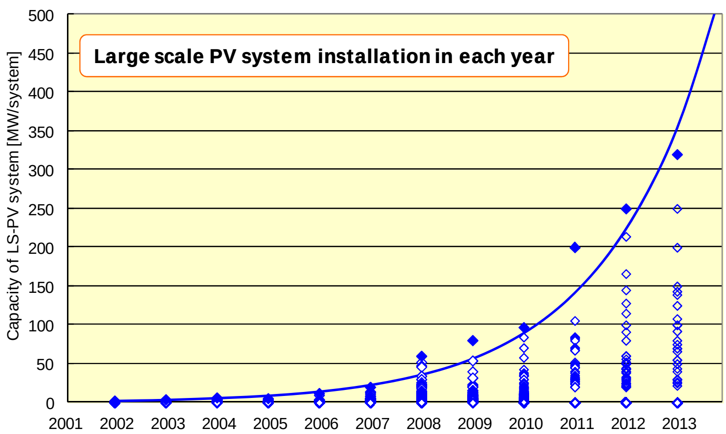

Fig. B.1-5 Expansion of capacity of large-scale PV system

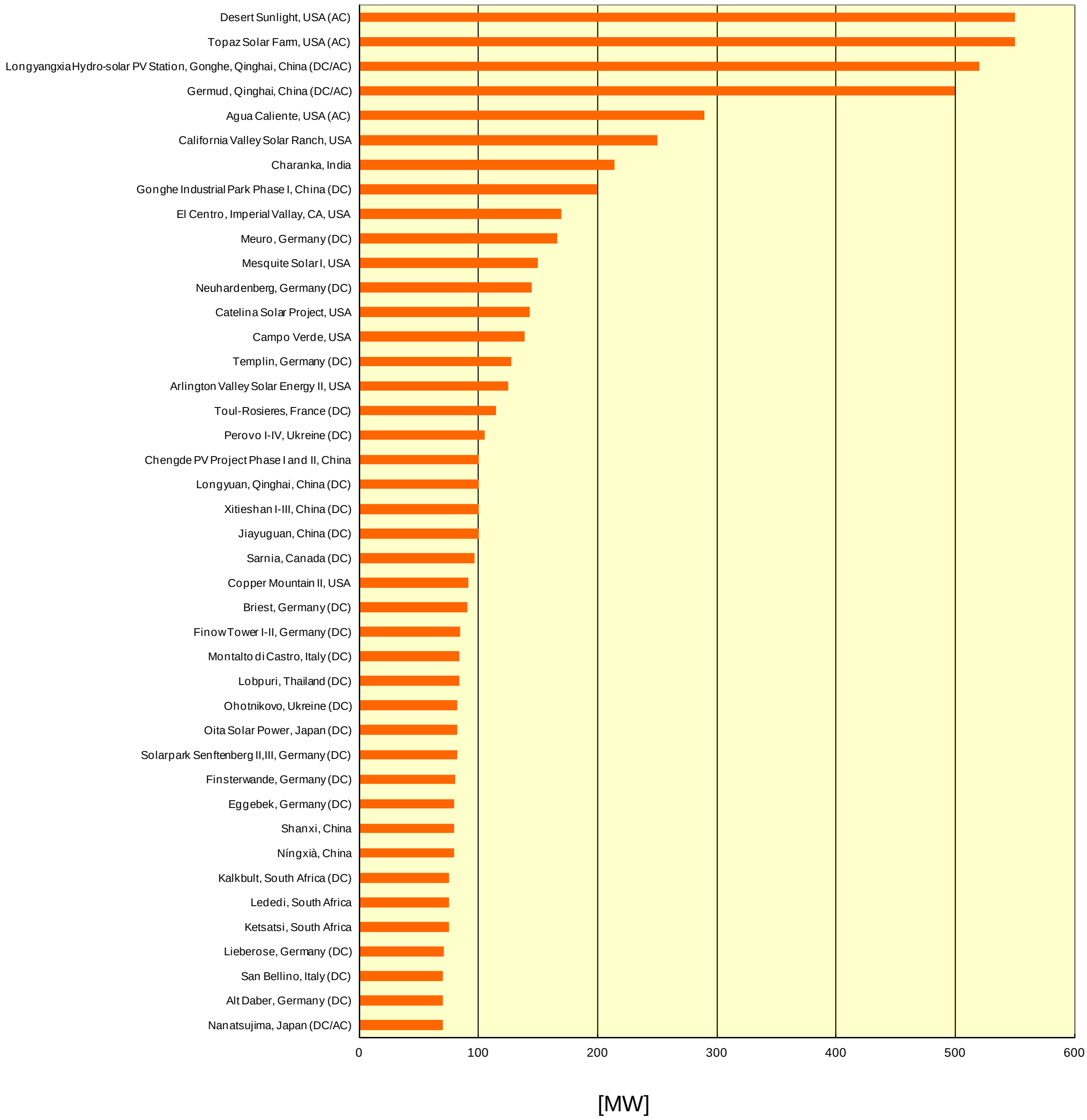

Fig. B.1-6 Examples of large-scale PV plants

As shown above, PV power plants with several hundred MW scale area already in the commercial stage and technically feasible. It may be reasonable to expect that GW-scale PV power plants will come on the market in the near future. Although it is not included in the statistics above, there are also several large scale concentrator photovoltaic (CPV) power plants which have a capacity of several tens of MW already under operation. Since high DNI (direct normal irradiance) is the prerequisite for the economic operation of the CPV technology, the desert areas are also an ideal place for CPV installations.

Fig. B.1-7 Longyangxia dam, Qinghai, China ($520MW_{DC/AC}$, c-Si) combined with 1,28 GW Hydro power

Fig. B.1-8 Germud, Qinghai, China (500 $MW_{DC/AC}$, c-Si)

Fig. B.1-9 Agua Caliente, AZ, USA (290 MW_{AC}, CdTe)

Fig. B.1-10 Osaka, Japan (12 MW, CIS) (courtesy of Solar Frontier K.K.)

Fig. B.1-11 Lobpuri, Thailand (84 MW_{DC}, TF-Si)

Fig. B.1-12 60MW HCPV in Qinghai, China

It should be noted that existing PV power plants over 100 MW may be constructed and operated under advantaged conditions, e.g. grid connection with and capacity of transmission line, operation and maintenance (O&M) including output control, etc. In order that the PV power plants to be one of the major power sources in the future, technology development such as grid integration with energy storage and long-distance electricity transmission including high voltage direct current (HVDC) will be essential. In addition, integrated energy network management with other renewable energy sources, such as wind and solar thermal generation will also become important.

B.2 PV in the desert environment

PV power plants in desert areas will have to endure severe environmental conditions. One of the most serious issues is a dust settlement (soiling). Dust accumulated on the surface of the PV modules can reduce the power output considerably.

A degree of soiling and its impact is depending upon surrounding environments and meteorological conditions of the site, as shown in Fig. B.2-1. A solution to soiling is ‘cleaning’. Cleaning option for PV plants can be justified if the cost for cleaning is lower that the income generated by the solutions. In general, a cost for cleaning is heavily depending upon the local cost of labour and water. A cost effective cleaning method will be selected by considering local conditions, as shown in Fig. B.2-2.

In case of cleaning by water, amount of water consumption will be also influenced to the cleaning cost. Table B.2-1 summarises the pros and cons of each cleaning options in China, in terms of the volume of water required, speed, quality of cleaning, as well as cost required.

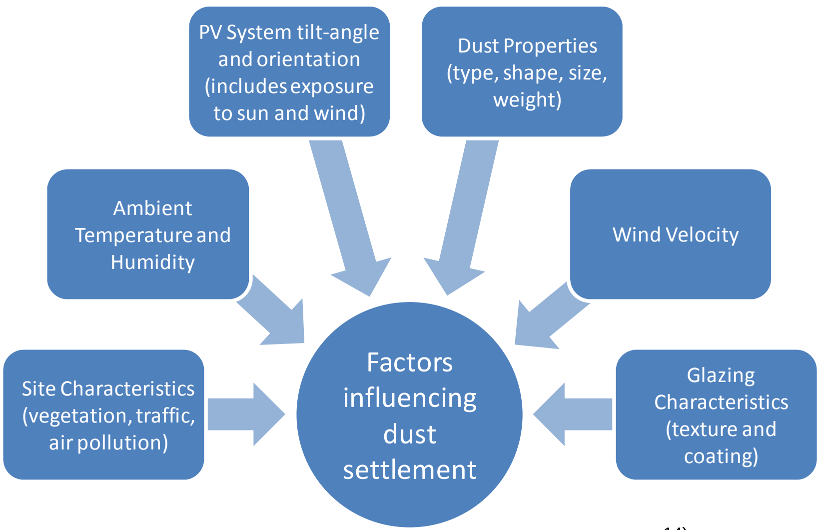

Fig. B.2-1 Factors influencing dust settlement[14)]

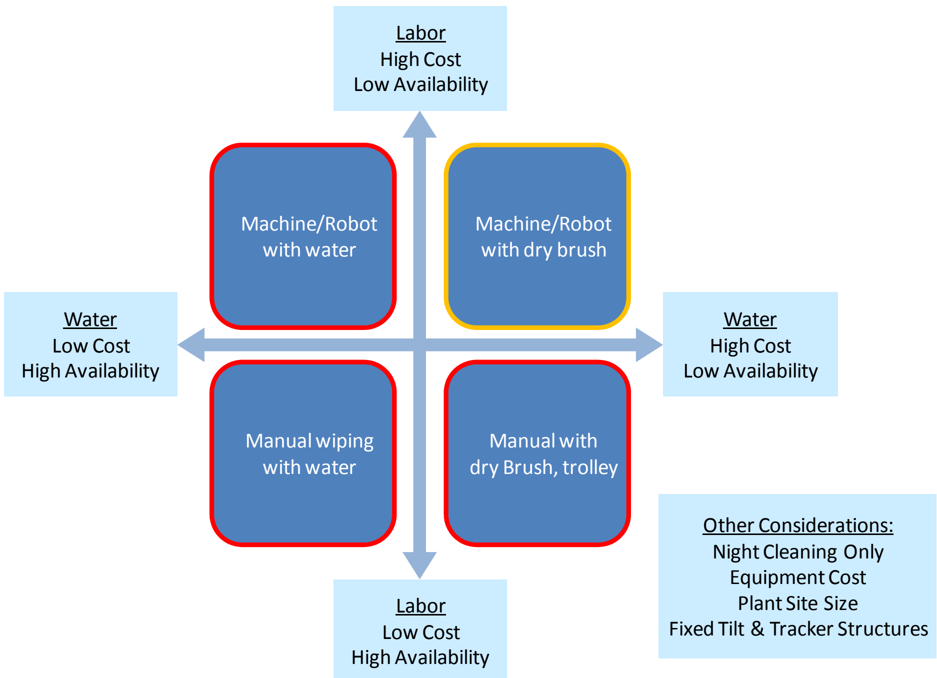

Fig. B.2-2 Classification of cleaning method[14)]

Table B.2-1 Comparing method of cleaning by water, examples in China[12)]

Methods	Cleaning equipment	Water consumption (ton/10MW/times)	Cleaning speed	Cleaning result	Cleaning cost
Wash + wipe	Water pipe installation or water transportation vehicles (water replenish)	100	Fast	Excellent	High
Spray + wipe	Water and spray pipe installation	50-60	Fast	Excellent	High
Special wash vehicle and machine	Cleaning equipment and water supply vehicles, water replenishment and equipment maintenance	30-40	Fast	Excellent	High
3-person + water	No need to pipes, vehicles and equipment	10	slow	Good	Low

Occurrence of soiling will be depending upon characteristics of sand particles, meteorological condition, etc. There are a number of academic researches on mechanisms of soiling. In the field of solar energy, e.g. not only PV and CPV, but also CSP (concentrating solar power), R&D (research and development) on countermeasures against soiling are studied and proposed[15-17)]. Recent research trends shift from 'wet' to 'dry', from 'restoration' to 'prevention', as shown in Fig. B.2-3.

In addition, a simulation tool for evaluating influences of soiling to PV power plants has been also developed[18)]. The tool requires several parameters concerning surrounding environment. It estimates degree of soiling and influence on the electricity output, and allow plant owner to develop cleaning plan before starting operation. After starting operation, by updating environmental parameters and putting actual result of electricity generation, estimation is modified to improve the accuracy and the reliability.

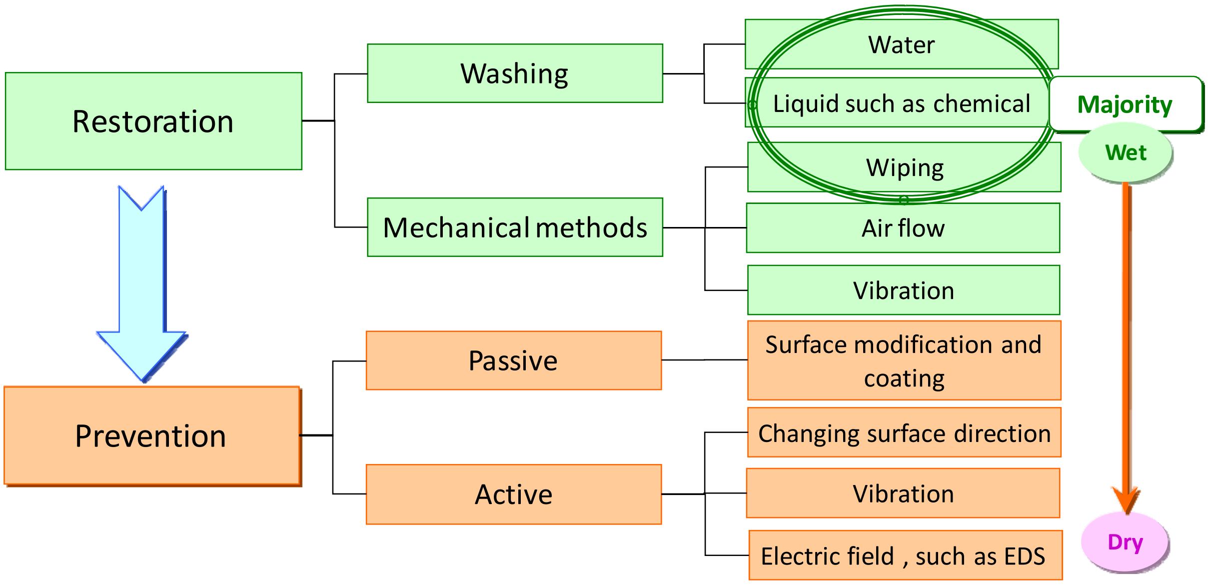

Fig. B.2-3 Examples of countermeasures for soiling

Besides soiling, sand storm and particles, high temperature and large temperature difference between day and night, exposure to intense ultraviolet irradiation, etc. are the significant and special issues for PV power plants in the deserts environment. Recently, importance and necessity of evaluating capability and performance of PV modules under the desert condition is widely accepted. Evaluation method for those issues are not standardised internationally yet, and further discussions are needed.

C. Economic feasibility of PV power plants: VLS-PV can provide low-cost electricity!

C.1 Cost trends and perspectives

Prices of PV modules are falling down rapidly. The lowest prices in recent years may be below costs. However, the costs will decline further and the IEA PV technology roadmap[19], as shown in Fig. C.1-1, is forecasting that module costs will be expected to fall to 0,3-0.4 USD/W by 2035.

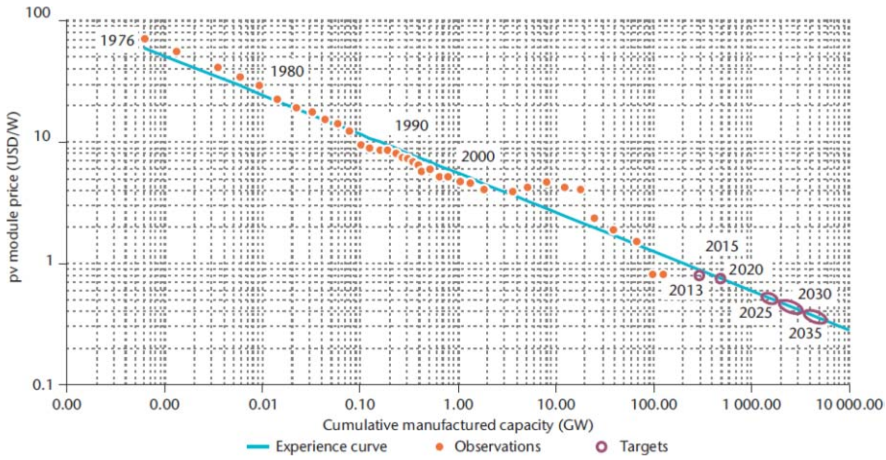

Fig. C.1-1 Past modules prices and projections to 2035 based on learning curve[19]
(©OECD/IEA 2014, Technology Roadmap: Solar Photovoltaic Energy, fig. 10, p. 23, IEA Publishing. Licence: www.iea.org/t&c/termsandconditions)

As well, initial cost for PV system installation has been decreasing with a market expansion, performance improvement, technology innovation, etc. In some regions, the levelised cost of electricity (LCOE) of PV technology is already reached to the level of residential electricity tariff.

Initial cost for PV installation per kW for the large scale PV power plants is generally lower than that of small scale PV systems. However, further cost reduction will be required for PV power plants to compete with conventional power plants.

According to the IEA PV technology roadmap[20], initial cost for utility-scale PV system will be 1,5-3 million USD (MUSD)/MW in 2015, and reached to approximately 1 MUSD/MW and 0,7 MUSD/MW in 2030 and 2050 respectively, as shown in Fig. C.1-2. If the indicated costs are achieved, the LCOE of PV power plants will be able to compete with conventional power plants.

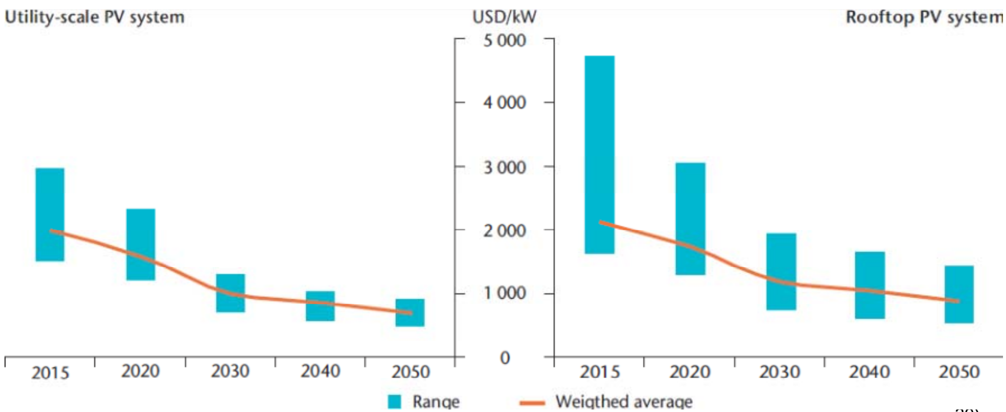

Fig. C.1-2 PV investments costs projections in the hi-Ren scenario of ETP2014[20]
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C.2 LCOE of PV power plants

Clearly, the LCOE of PV power plants are heavily dependent on the solar irradiance on site. The higher the solar irradiance, the lower the LCOE. Fig. C.2-1 represents the expected LCOE of 1 GW PV power plants assuming some desert areas, as a function of global horizontal annual irradiation. The assumptions underlying the calculation are as follows:

- Initial cost including transportation and construction cost	: 1-3 MUSD/MW
- WACC (weighted average cost of capital) for CAPEX (capital expenditure)	: 5,4 %
- Operational lifetime	: 30 years
- OPEX (operational expenditure)	: 1 % of initial cost
- Performance ratio excluding degradation rate	: 0,73-0,83 (depending upon the area)
- Ratio of soiling loss	: 5 % of overall output
- Degradation ratio	: 0,5 %/year.

The LCOE in the higher initial cost case (3 MUSD/MW), middle case (2 MUSD/MW), which is the current average level) and lower case (1 MUSD/MW), which is corresponding to the level forecasted by the IEA PV technology roadmap[20) are approximately 0,15 USD/kWh, 0,10 USD/kW and 0,05 USD/kWh respectively, although there are some differences depending on regional conditions.

Even the current level, PV power plant is economically competitive in some area, and in the near future, PV power plants will become more competitive against conventional power plants.

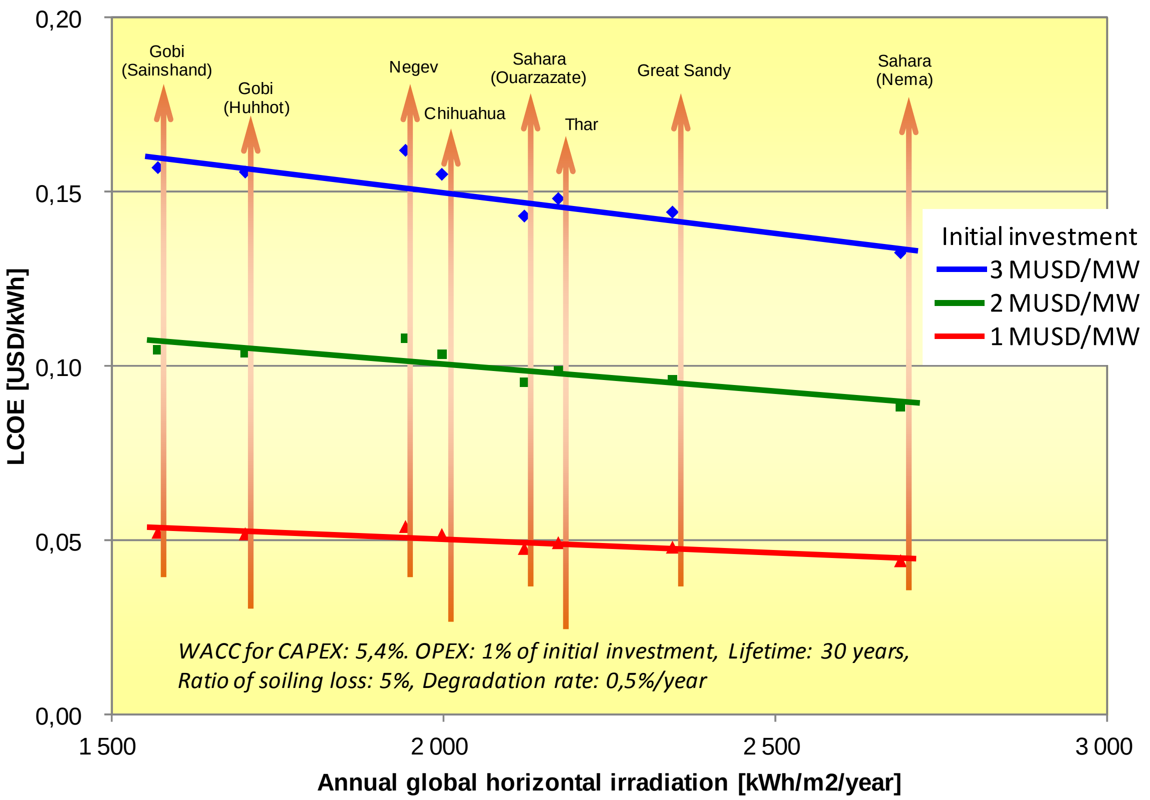

Fig. C.2-1 Expected LCOE of PV power plants

D. Environmental benefits of PV power plants: VLS-PV is a key for sustainable environment!

Technology level of the VLS-PV plants is already reached to the practical level. Economic status has been improved considerably and expected to compete with conventional power plants in the near future. Further development in technology and market will make PV technology more attractive as a major and reliable power sources. Considering its environmental value, PV is in a good position to replace the conventional power plants.

D.1 Low carbon and energy generation

The PV system is an alternative energy sources and one of the promising technologies for climate change mitigation. Life-Cycle Assessment (LCA) is a method to evaluate environmental effect quantitatively by using typical indices such as Energy Pay-back Time (EPBT) and CO_2 emission rate.

The EPBT is a year required to compensate the energy consumed throughout its lifecycle by the energy produced. After the period, the PV produces extra energy until its end-of-life. That is, PV with shorter EPBT can create larger energy and provide bigger contribution as an alternative energy.

CO_2 emission rate is CO_2 emissions of unit energy production (kWh), in other words, CO_2 emissions divided by its life-cycle energy production. The lower CO_2 emission rate is the more the technology can contribute on CO_2 emissions reduction.

The EPBT and CO_2 emission rate of the VLS-PV plants shown as Figs. D.1-1 and D.1-2 are within the ranges of 1 to 3 years and 30 to 70 g-CO_2/kWh respectively, depending on the type of PV module (efficiency mainly) and location of installation (irradiation and array manufacturing electricity mainly).

The EPBT of VLS-PV plants will be very short. Assuming 30 years life-time, the plants can produce 10 to 30 times more energy than the total energy consumed throughout the life-cycle. Similarly, the CO_2 emission rate will be very low. It is one-tenth or one-twentieth of average CO_2 emission rate in China or Africa. This means that 90 to 95 % CO_2 emissions for power generation can be reduced by substituting new fossil fired power plants with the VLS-PV plants.

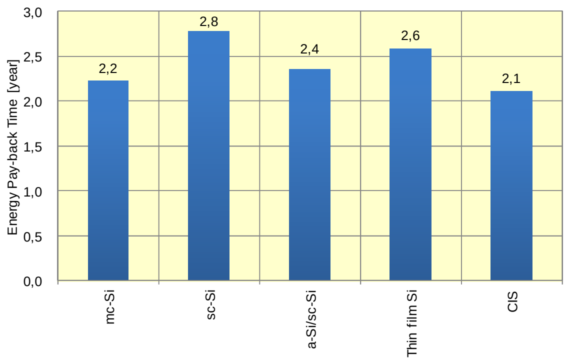

Fig. D.1-1 Energy Pay-back Time of PV power plant in the Gobi desert, China[21)]

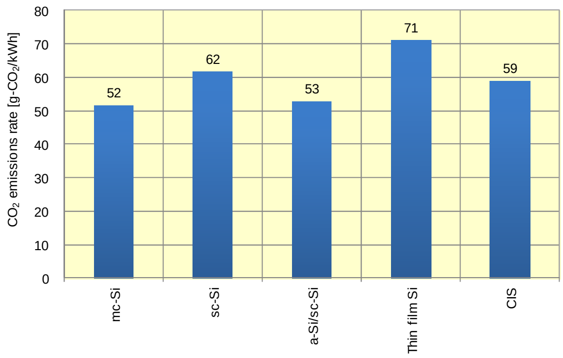

Fig. D.1-2 CO_2 emission rate of PV power plant in the Gobi desert, China[21)]

D.2 Ecological sustainability

The impacts of CO_2 emissions on global environment and the measure to mitigate the impacts are quantitatively evaluated by a number of institutions and scientists including IPCC. Ecological Footprint (EF) is one of the indicators to monitor the effects of CO_2 on the environment.

The EF is expressed by the capability of ecosystem required to purify, absorb and mitigate the impact of human activities. The unit of EF is 'gha' which is weighted area in ha. For example, the impact of

CO_2 emissions are expressed by required forest area in 'gha' to absorb them. The impact of food production is expressed by the required agricultural land area in 'gha' to produce it. The construction of the new buildings or the reclamation of the farm land on the unused land area are expressed as reduction or increase in capability of ecosystem compared to the original ecosystem. Capability of ecosystem is called bio-capacity (BC), and also expressed in 'gha'. The earth is sustainable while the EF is smaller than the BC, but if the EF is higher than the BC, the earth is regarded as unsustainable.

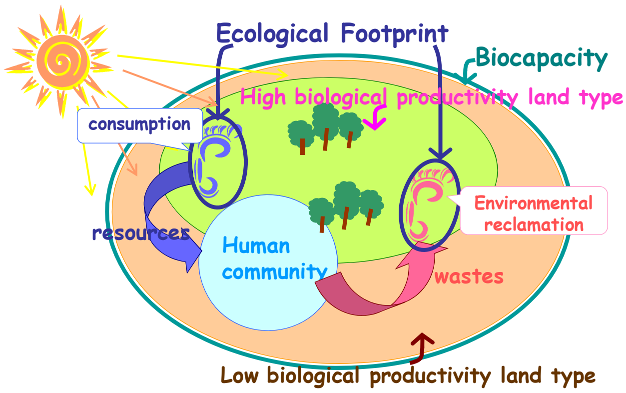

Fig. D.2-1 Conceptual image of ecological sustainability[9)]

According to the Global Footprint Network[22)], the EF of the world overshot and the world is not sustainable since 1970s. Amount of overshooting, e.g. the EF minus the BC, increases every year. This is mainly caused by the increase in CO_2 emissions from fossil fuel consumption. Therefore, CO_2 emission mitigation by the VLS-PV plants can contribute to the reduction of the EF. Although the installation of the VLS-PV plants may reduce the BC of the land, the impact will be limited if it is constructed in lower BC land such as desert. The reduction of BC will be easily compensated by the reduction in fossil fuel consumption. In addition, BC can be increased if VLS-PV plants are developed with surrounding area with afforestation or agricultural development.

For example, the EF and BC in the Northeast Asian region can be balanced by installing the 1 TW VLS-PV plants in the Gobi desert covering China and Mongolia. The area required for the VLS-PV plants is only 1 to 2 % of the Gobi desert. It should be noted that, this calculation considers the effects of CO_2 emissions reduction only. The environmental effect can be further exploited if the development is coupled with afforestation and agricultural development in the surrounding area.

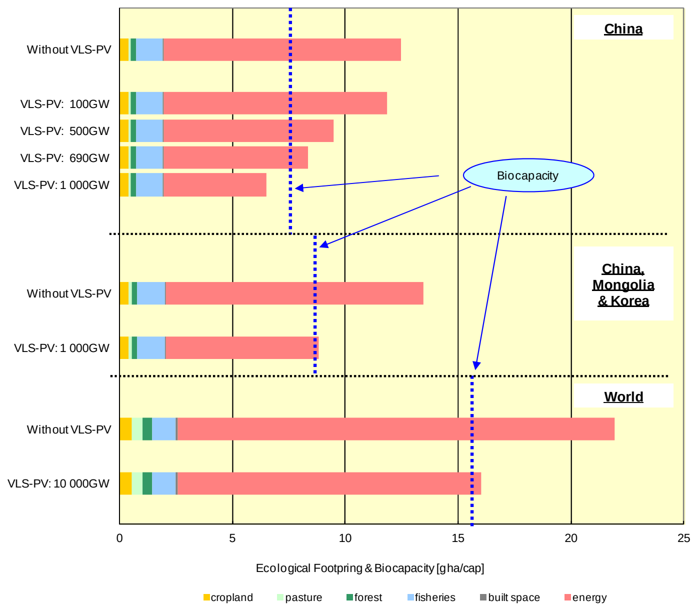

Fig. D.2-2 Ecological impacts by VLS-PV project on the Gobi desert[9)]

D.3 Saving ground water resource

Our economic and industrial activity is based on water use at various stages such as manufacturing products, producing and supplying energy, etc. On the other hand, water resources including ground water are indispensable for drinking, agriculture, etc. In some regions of the world, the ground water is used in the unsustainable manner and the situation is expected to be more serious in the future.

'Water Footprint' is an indicator which monitors the water consumption for the industrial products throughout its life cycle. Water is required for most of the power generation technologies as well.

Figs. D.3-1 and D.3-2 show example of study on life-cycle water use for electricity generation. As is shown in the figures, conventional power plants such as fossil power and nuclear power consume much water for cooling. The plants locating inland are generally using ground water. On the other hand, PV technologies consume water at the production stage to some extent, but little during their operation. Clearly, PV power plants will contribute to saving ground water use by substituting conventional power plants inland.

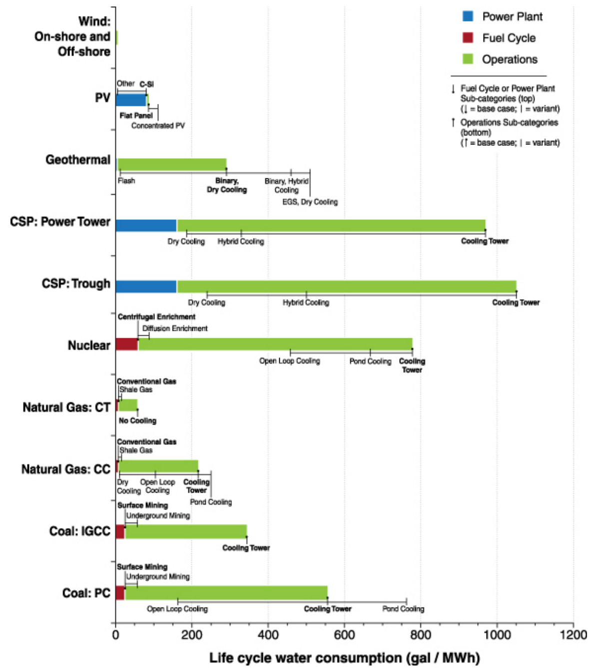

Fig. D.3-1 Life cycle water consumption[23)]

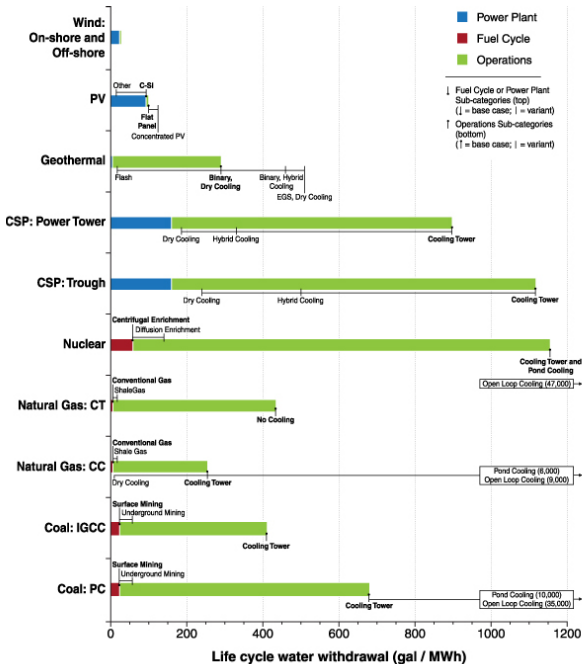

Fig. D.3-2 Life cycle water withdrawal[23)]

E. Socio-economic benefits of PV power plants: VLS-PV can contribute to sustainable social development!

E.1 Sustainable scenario for VLS-PV development

A construction of GW-scale PV power plant will create substantial and suitable demand for PV system components as well as employment for construction if the construction is managed in an appropriate manner. Below is one of our scenarios proposed for GW-scale PV plant with sustainable social development.

At the initial stage, PV plant owner installs 25 MW of PV power plant and module manufacturer constructs module factory nearby with 25 MW/year capacity. The modules are supplied for the plant construction purpose exclusively unless the production volume exceeds the demand of the construction site. The capacity of the factory is expanded every 25 MW/year every 10 years and reached 100 MW/year after 30 years.

In this scenario, a capacity of PV power plant will achieve 1 GW in 24 years and 1,5 GW in 31 years. Since then, PV modules installed in the initial stages reach to the End-of-Life (EOL), and PV module manufacturing factory provide PV modules for the replacement as well as for another PV power plants.

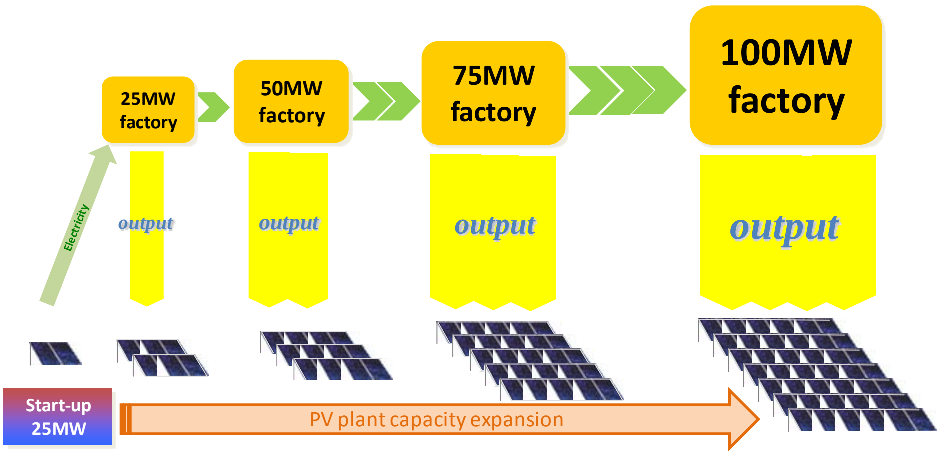

Fig. E.1-1 Conceptual view of a sustainable scheme

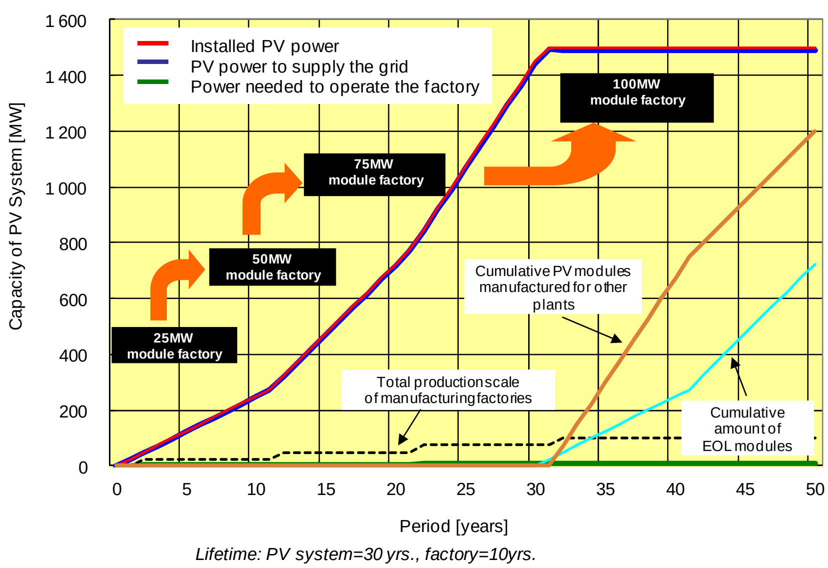

Fig. E.1-2 Sustainable scheme for VLS-PV development

The manufacturing factories near the PV power plant will create local jobs for construction and operation of the plant. Fig. E.1-3 is the estimated direct employment by a sustainable PV power plant development scheme shown in Fig. E.1-2. In the simulation, annual employment demand for PV module manufacturing, plant construction, and operation & maintenance at the initial stage are assumed to be 2 person/MW, 7,5 person/MW, and 0,5 person/MW respectively. It also includes the impact of future labour productivity improvement[24)]. During constructing 1,5 GW PV power plant, approximately 9 thousand jobs are created during the projected period, and approximately 400 stable jobs are created annually. It should be noted that, the simulation only includes direct employment. If it is coupled with indirect employment, the impact of VLS-PV on sustainable job creation can be doubled.

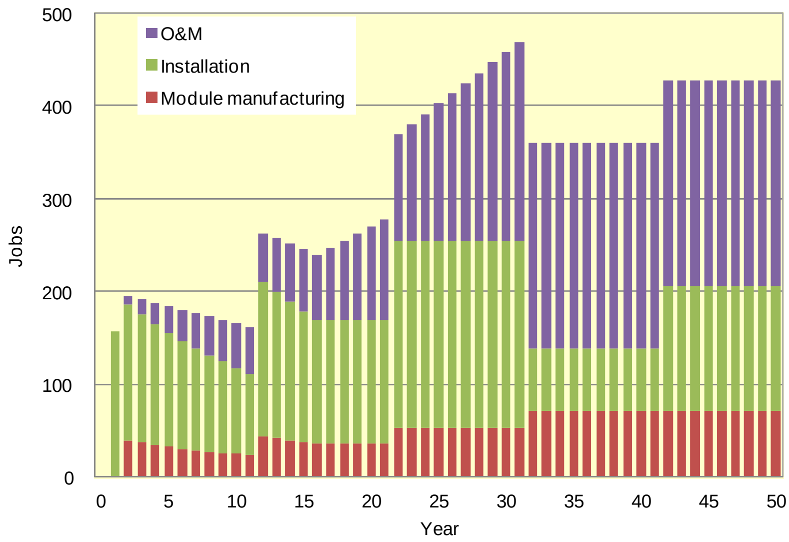

Fig. E.1-3 Expected direct employment by VLS-PV project with productivity improvement

E.2 Technology transfer

The technology transfer is the key for success of the scenario presented above. The PV module manufacturing factory near the PV power plant will be operated by experts from overseas in its initial stage. However, it is ideal to transfer the technology as much as possible to the local labours are employed to operate by themselves at certain stage. This will contribute to an intrinsic regional development with PV industry.

Difficulty level of technology transfer for PV module manufacturing is depending upon PV cell technology. In case of crystalline Si, PV module manufacturing (assembling) is relatively easy. On the other hand, PV cells manufacturing requires high technology and secured infrastructure; therefore there are many barriers to overcome for local manufacturing. In case of thin-film PV modules, the technology transfer is not straight forward since sub-module and PV module are produced through continual process.

However, considering improvement and rationalisation of manufacturing technology, technology transfer for PV cells manufacturing and thin-film PV modules production may become feasible options in near future. By localising the cell manufacturing process, the positive effects on the local economy increase considerably.

Concentrator PV modules, e.g. CPV, is another technology suitable for desert and arid areas. Although local production of super high efficiency PV cell technologies for CPV may not be a realistic option so far, local assembly of CPV modules can be attractive options. The volume of the CPV system per unit of weight is higher than that of the conventional flat plate PV modules; therefore, it can reduce transportation cost and contribute to reduction in total initial investment.

Further, if the other components of PV power plant are manufactured locally or if recycling factories of end-of-life components are introduced nearby, sustainable 'Scrap and Build' concept of the PV power plant presented in Fig. E.2-1 can be realised.

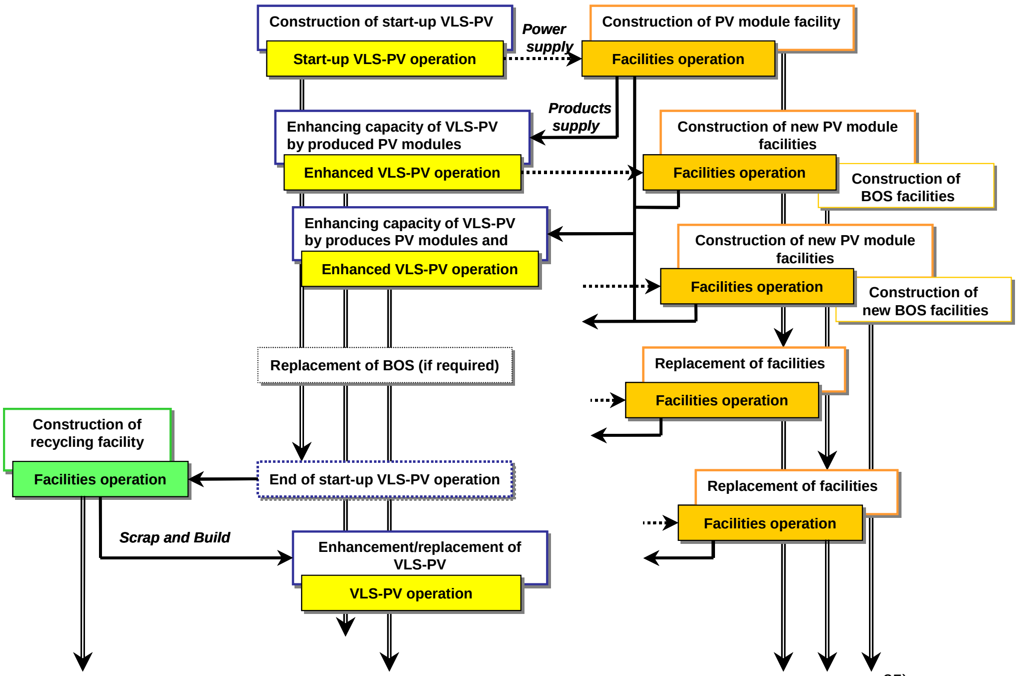

Fig. E.2-1 Example of a concept for sustainable growth of VLS-PV[25)]

E.3 Sustainable desert community development

PV power plants constructed in desert areas will provide electricity to neighbouring community or power-consuming industries through existing or newly developed transmission line. The PV power plants can be a centre of the sustainable desert community development.

Fig. E.3-1 shows our proposal on a framework of desert community development. In addition to creating PV industry based on technology transfer discussed above, various values can be created through the sustainable desert community development concept.

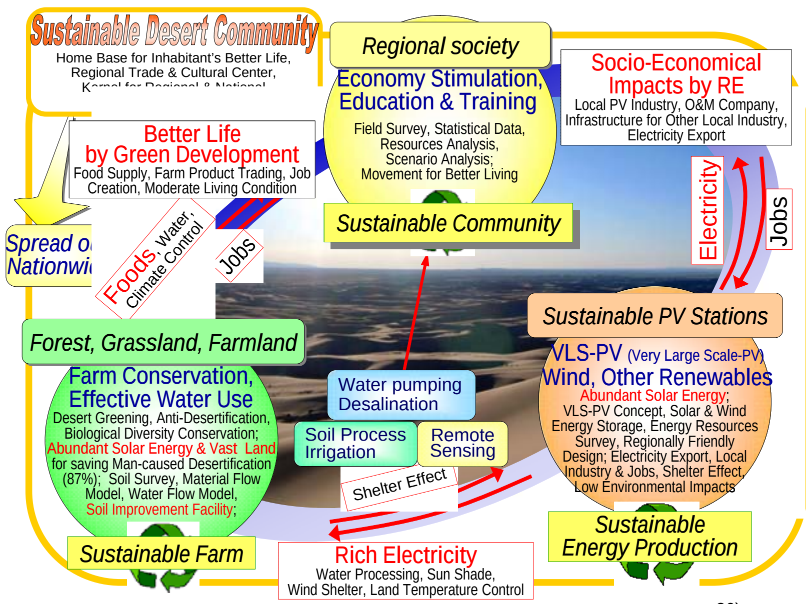

Fig. E.3-1 Framework of desert community development[26)]

The most serious problem in desert areas will be a land degradation including desertification. The degradation leads to expand in low-productivity land area: and hence, results in less income of the inhabitants. That forces residents to migrate to other regions, and accelerate land degradation even further. Examples of the possible solutions for the land degradation are afforestation and agricultural land development. The sustainability of the large scale PV development project in the desert region can be substantially improved by integrating those solutions into the whole concept.

Electricity generated from PV power plant can be used for water supply in the regions through ground water pump, desalination technologies, or irrigation systems. Comprehensive design and management of the whole regions is required for the sustainable water consumption in the regions, and the power supply from PV can contribute to those solutions. Adequate quantity of the power and water supply can be used for recovering vegetation as well as agricultural productions in the regions.

In some areas including the Middle-East, North Africa, and the South Asia, the water consumptions already exceed the renewable water resources within regions. The large-scale desalination plant is expected to be a countermeasure to secure sustainable water supply. Fortunately, in general terms, those areas have abundant solar energy and have desert or dry land close to coastal regions. A combination of PV power plant and desalination plant can provide attractive options to the regions in questions.

F. VLS-PV visions: How VLS-PV can contribute as a major power source?

The technical and economical feasibility of the large scale PV power plants are already proven, and the environmental and socio-economic benefits can make the project more attractive.

To deploy large scale PV power plants as a major power source and to realise expected benefits, in this chapter, a potential for global energy system is discussed, as well as a supply capability of PV power plants.

F.1 VLS-PV roadmap

Various scenarios, visions and forecasts projected that PV electricity plays an important role for electricity generation in the middle of 21st century. In order to set an expected target and potential of PV power plants, Task8 group has proposed a VLS-PV roadmap towards 2100, as shown in Fig. F.1-1.

The VLS-PV roadmap is based on the following assumptions; PV electricity will provide the one-third of the primary energy supply in the world; PV application will be roughly classified rural and mini-grid, urban and community grid, and the VLS-PV (PV power plants); The expected cumulative PV capacity in 2100 will be 133 TW and a half of the capacity will be PV power plants.

The roadmap was originally developed in 2009[9], and modified in 2014 by referring recent installation trends and discussion, but the target for 2100 is unchanged.

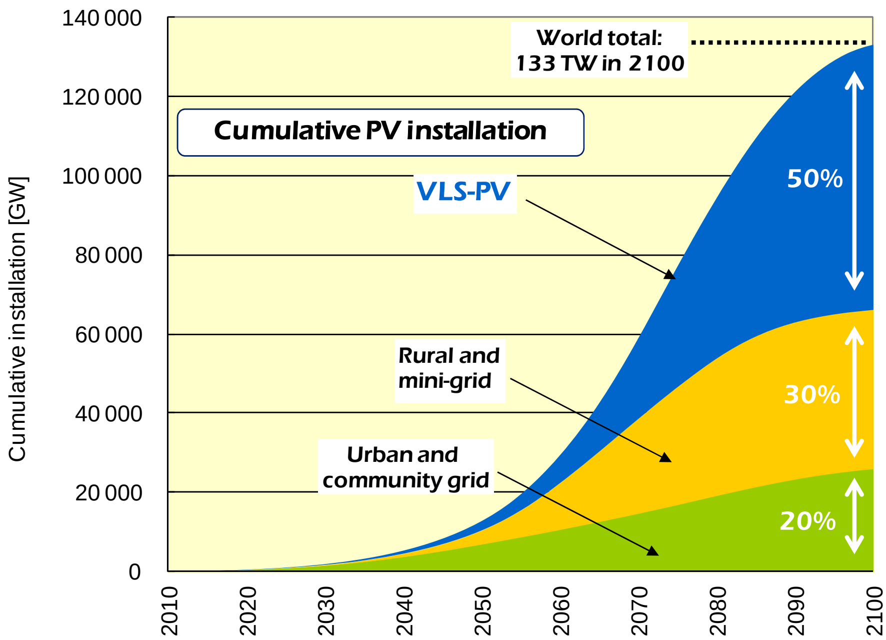

Fig. F.1-1 VLS-PV roadmap (updated)

F.2 Considerable option for 100% renewable energy supplying system

Global deployment of PV power plants will be accelerated by developing energy supplying system combined with other renewables and energy storage technologies. The integrated system will compensate their fluctuations each other and secure the electricity supply by the renewable energy technologies. The renewable energy can also be used to produce gaseous or liquid renewable energy-based fuels when the power supply surpasses the demand. One of the advantages of this technology is that the energy can be stored in a stable manner and the renewable energy fuels can be used for non-electricity energy demand such as heat or vehicle fuels. Fig. F.2-1 shows one of those systems. As shown in the figure, CO_2 captured and stored in the existing power plant or captured from ambient air is used to produce renewable energy fuels; hence, it has a multiple environmental effects.

Although there are technical and economic barriers to be solved for the renewable energy-based fuel production system, low carbon energy system with 100 % renewable energy is certainly possible with this integrated system.

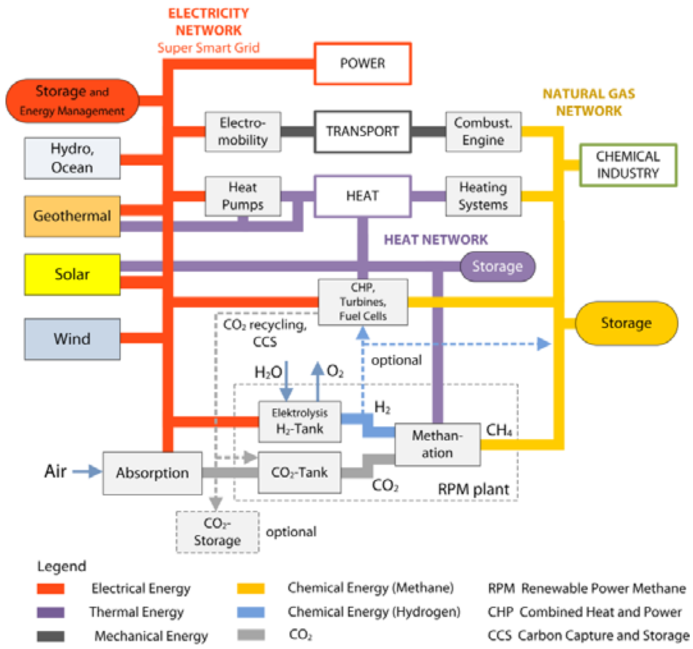

Fig. F.2-1 Hybrid PV-Wind-RPM plant as the integral centrepiece of a future sustainable energy supply system[21)]

F.3 VLS-PV supergrid in the Northeast Asia

The cross-border supply networks for electricity are the prerequisite for the mass deployment of PV power plants. There are global or regional network concepts proposed including ‘Desertec’ in the Mediterranean region with solar energy in the Sahara desert[27)] and ‘GOBITEC/Asian Super Grid’ in the Asian region with renewable energy in the Gobi desert[24)]. Task8 group also proposed a concept of a VLS-PV supergrid in the Northeast Asia[28)].

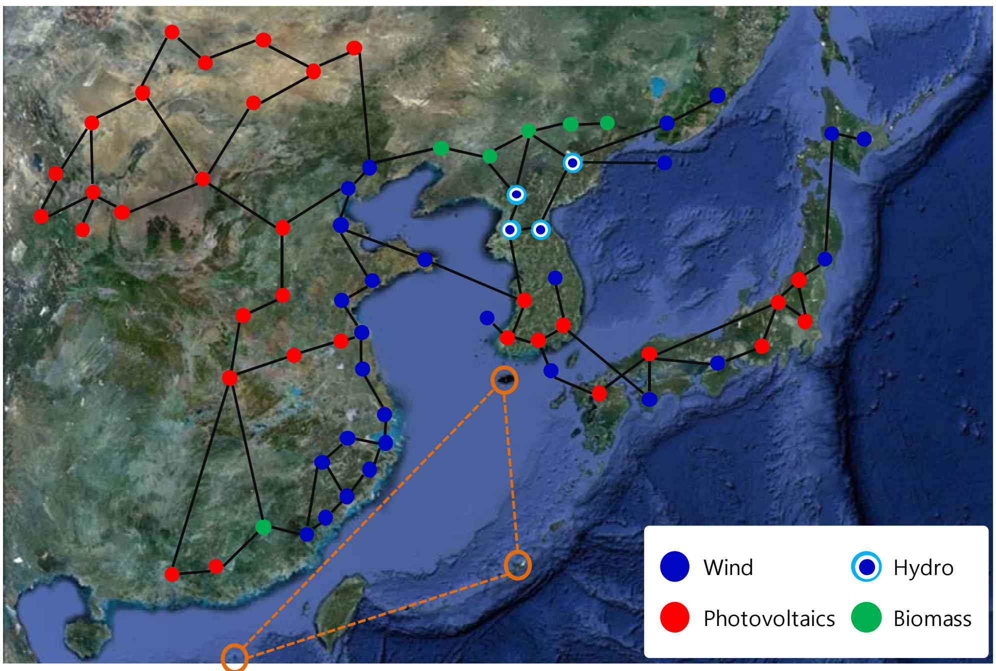

Fig. F.3-1 Example of supergrid design in the Northeast Asia[29)]

For Northeast Asia, it is proposed that the excellent solar and wind resources of the Gobi desert could be utilized for the load centers in China, Korea and Japan as a contribution to the energy transformation ahead. The area is composed by regions, which can be interconnected by a high voltage direct current (HVDC) transmission grid. Our precise analysis has shown that expected total system levelized cost of electricity (LCOE), including generation, curtailment, storage and HVDC transmission grid, will be 0,064 EUR/kWh and 0,081 EUR/kWh for centralized and decentralized approaches for 2030 assumptions. The importing regions are Japan, Korea, East China and South China, which receive their energy mainly from Northeast China, North China and Central China. The electricity generation shares of the cost optimized system design can reach up to 39 % for PV and 47 % for wind energy (decentralized, 2030) and additional hydro power utilization. The results for 100 % renewable resources-based energy systems are lower in LCOE by about 30-40 % than recent findings in Europe for the non-sustainable alternatives nuclear energy, natural gas and coal based carbon capture and storage technologies. These findings clearly indicate that a 100 % renewable resources-based energy system is the real policy option.

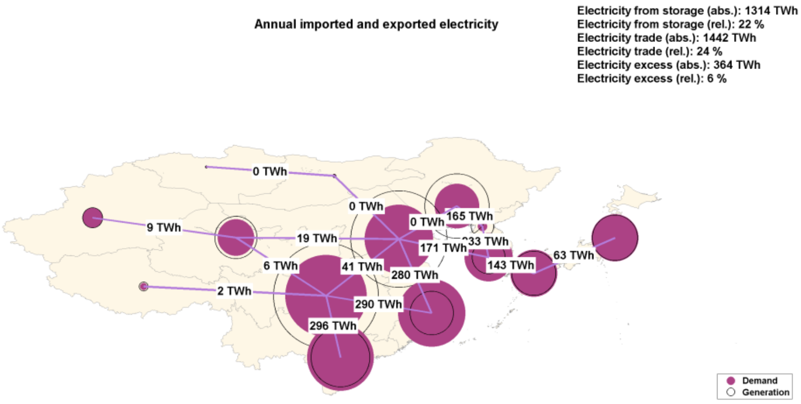

Fig. F.3-2 Annual generation and demand for area-wide open trade scenario for Northeast Asia and reference year 2030[30)]

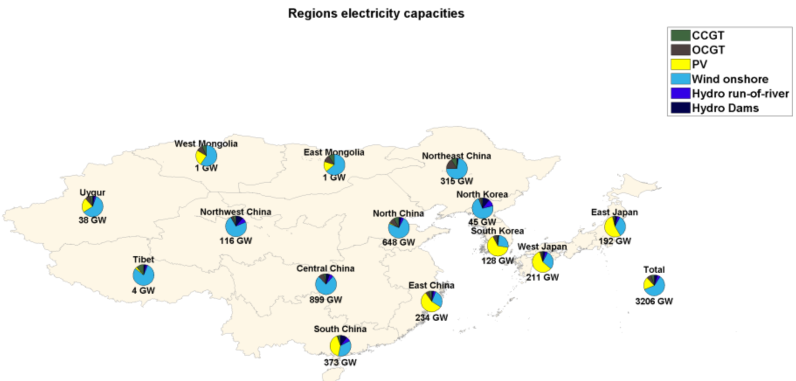

Fig. F.3-3 Installed capacities for area-wide open trade scenario for Northeast Asia and reference year 2030[30)]

Supposing to supply the incremental electricity demand in the Northeast Asia by the PV electricity, annual installed capacity required to fulfil the demand will be a few hundred GW per year. On the other hand, PV power plants installed in the Gobi desert with 1 000 GW (=1 TW) generation capacity have a potential to improve the ecological balance, from unsustainable to sustainable.

It will be difficult, of course, to immediately start a super grid project, including construction of hundreds of GW of PV power plants. However, socio-economic benefits as well as environmental value of a concept of a VLS-PV supergrid in Northeast Asia should be seriously taken into account from a long-term viewpoint. In order to achieve the goal, technical and institutional issues for international grid connection should be addressed and discussed in a more intensive manner.

G. Conclusions and recommendations: Directions for VLS-PV

< Why VLS-PV? >

- PV is one of the promising renewable energy technologeis to solve the energy and environmental issues in the world. In one of the scenarios (2DS hi-Ren) presented in the recent report by IEA, PV become the second largest energy source in 2050 and its contribution to the CO_2 reductions is the largest among all the power generation technologies.
- As solar energy is a low-density energy in nature, vast land areas with high solar irradiation are necessary to extensively utilise the solar energy as the major power source. From that viewpoint, large scale PV power plants should play an important role as well as distributed PV systems.
- One-third of land surface of the earth is covered by dry deserts, and the irradiation levels in those areas are generally high. Estimate shows that only 8 % of the desert area is enough to generate annual energy demand today.
- The detail study on site suitability assessment using remote sensing technology with satellite images show that PV power generation potential of world six deserts, namely Sahara, Gobi, Great Sandy, Thar, Sonora and Negev, is approximately 5 times of the world energy demand and 33 times of world electricity generation in 2012.
- It is obvious that the desert areas have abundant potential and promising areas for PV power plants.

< VLS-PV is already available! >

- PV market is rapidly growing, especially in a latter half of 2000s. Cumulative PV installation in the world achieved 100 GW in 2012 and 140 GW at the end of 2013. Major PV market shifted from Europe to USA, China, Japan and other regions. Especially, expansion of Chinese market is remarkable.
- Currently, the large scale PV power plants account for at least 10-15 % of cumulative PV installation in the world.
- The largest PV power plants record in the world has been broken every year. In 2011, 200 MW PV power plant started operation in China, and the capacity of this plant was expanded to 300 MW in 2013 and to 500 MW in late 2014. In 2012, 250MW PV power plant started operation in USA, and its capacity was expanded to 290 MW in 2013. In early 2013, 320 MW PV power plant started operation in China, and its capacity was expanded to 520 MW in 2014. Further, in USA, two 550 MW PV plants started operation in late 2014.
- As shown above, PV power plants with several hundred MW scales are already in the commercial stage and technically feasible. It may be reasonable to expect that GW-scale PV power plants will come on the market in near future.
- CPV is another promising technology option suitable in the desert environment.
- In order that PV power plants to be one of the major power sources in the future, technology development such as grid integration with energy storage and long-distance electricity transmission including HVDC (High Voltage Direct Current) will be essential.
- PV power plants in the desert have to endure the severe environmental conditions, such as soiling, temperature cycle. As one of countermeasures for soiling, cleaning option of the PV plants can be justified if the cost for cleaning is lower than the income generated by the solutions. In general, a cost for cleaning is heavily depending upon the local cost of labour and water.
- There are a number of countermeasures available as well as simulation tools for soiling issue.
- Besides soiling, sand storm and particles, high temperature and large temperature difference between day and night, exposure to intense ultraviolet irradiation, etc. are significant and special issues for PV power plants in the deserts environment. Evaluation methods for those issues are not standardised internationally yet, and further discussions are needed.

< VLS-PV can provide low-cost electricity! >

- Initial cost for PV installation has been decreasing. In some regions, LCOE of PV technology is already reached to the level of residential electricity tariff.
- When it comes to the PV power plant in the desert environment, the LCOE is already low even with the current module price level (0,10 USD/kWh). In the near future, PV power plants will become more competitive against conventional power plants.

< VLS-PV is a key for sustainable environment! >

- The PV system is an alternative energy technology and one of the promising technologies for climate change mitigation.
- The EPBT (Energy Pay-Back Time) of large scale PV power plants are within ranges of 1 to 3 years. Assuming 30 years lifetime, PV can produce 10 to 30 times more energy than the total energy consumed throughout its life-cycle.
- CO_2 emission rates of large scale PV power plants are between 30 to 70 g-CO_2/kWh. The rate is very small and it is one-tenth or one-twentieth of average CO_2 emission rate in China or Africa, coal-based country.
- The Ecological Footprint (EF) is expressed by the capability of ecosystem required to purify, absorb and mitigate the impact of human activities. The EF is compared with the Biocapacity (BC) which means a capability of ecosystem. The EF and BC in the Northeast Asian region can be balanced by installing the 1 TW VLS-PV plants in the Gobi desert covering China and Mongolia. The environmental effect can be further exploited if the development is coupled with afforestation and agricultural development in the surrounding area.
- PV technologies consume water at the production stage to some extent, but little during their operation. Clearly, PV power plants will contribute to saving ground water use by substituting conventional power plants inland.

< VLS-PV can contribute to sustainable social development! >

- GW-scale PV power plant will create substantial and stable demand for PV system components as well as employment for construction, operation and maintenance if such works are managed in an appropriate manner. In our study, GW-scale PV power plant with sustainable social development scenario is proposed.
- At the initial stage, 25 MW of PV power plant, and PV module factory with 25 MW/year capacity are constructed nearby. The modules produced are supplied for the plant construction purpose exclusively. The capacity of the factory is expanded every 25 MW/year every 10 years and reached 100 MW/year after 30 years. Then, a capacity of PV power plant will achieve 1 GW in 24 years and 1,5 GW in 31 years.
- Under the scenario, approximately 9 thousand jobs are created during the projected period, and approximately 400 stable jobs are created annually. If it is coupled with indirect employments, the impacts of VLS-PV on sustainable job creation can be doubled.
- It is ideal to transfer technology as much as possible to the local labours employed to operate by themselves at certain stage. This will contribute to an intrinsic regional development with PV industry.
- If the components of the PV power plant other than PV modules, such as inverters, cables, support structures, foundation, etc. are manufactured locally or if recycling factories of end-of-life components introduced nearby, sustainable ‘Scrap and Build’ concept of PV power plant can be realised.
- In addition to creating PV industry in local based on technology transfer as discussed above, various values can be created through the sustainable desert community development concept. Electricity generated from PV power plant can be used for water supply in the regions through ground water pump, desalination technologies, or irrigation system, and will contribute to mitigating land degradation in the area of question. Adequate quantity of the power and water supply can also be used for recovering vegetation as well as agricultural productions in the regions.

- In some areas including the Middle-East, North Africa, and the South Asia, the water consumptions have exceeded the renewable water resources within regions, and the large-scale desalination plants are expected to secure sustainable water supply. In general terms, those areas have abundant solar energy and have desert or dry land close to coastal regions. A combination of PV power plant and desalination plant can provide attractive options to the regions in questions.

< How VLS-PV can contribute as a major power source? >

- To deploy large scale PV power plants as a major power source, integration with other energy sources must be discussed from global energy supply point of view.
- Task8 group has proposed a VLS-PV roadmap towards 2100. The roadmap aims to provide one-third of the primary energy by PV in the world, and the expected cumulative PV capacity in 2100 will be 133 TW, in which VLS-PV is account for 50 % of the total electricity from PV.
- The cross-border supply networks for electricity are the prerequisite for the mass deployment of PV power plants. Global deployment of PV power plants will be accelerated by developing energy supplying system combined with other renewables and energy storage technologies.
- The Gobi desert covering China and Mongolia has an abundant solar energy potential and one of the best candidate sites for large scale PV power plants in the desert environment. Task8 group also proposed a concept of a VLS-PV supergrid in the Northeast Asia.
- Our precise study shows that the expected LCOE, including generation, curtailment, storage and HVDC transmission grid, will be 0,064 EUR/kWh and 0,081 EUR/kWh for 2030 assumptions. This reveals that 100% renewable energy system in Northeast Asia will be reachable, although there are technical and institutional barriers to be solved.
- The renewable energy can also be used to produce gaseous or liquid fuel when the power supply surpasses the demand. One of the advantages of this technology is that the energy can be stored in a stable manner and the renewable energy fuels can be used for non-electricity energy demand such as heat or vehicle fuels. The low carbon energy system with 100 % renewable energy is certainly possible in the future.

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