A Life-cycle Analysis of Very Large-scale PV (VLS-PV) System in the Gobi desert

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Abstract

A very large-scale photovoltaic power generation (VLS-PV) system is designed 100MW PV system assuming that the system is installed on the Gobi desert, which is one of major deserts in the world. Array arrangement, array support, foundation, wiring, and so on are designed in detail. Then energy payback time (EPT), life-cycle CO_2 emission rate and generation cost of the system are estimated based on the methodology of life-cycle analysis (LCA). As a result of the estimation, 1.7 year of EPT and 12 g-C/kWh of CO_2 emission rate are obtained. These show that VLS-PV on the Gobi desert would be very promising for the global energy and environmental issues. The generation cost is calculated at 13 Yen/kWh assuming that PV module price is 100 Yen/W and system lifetime is 30 years.

Introduction

Recently, world energy demand has been rapidly expanding due to the world economic growth and population increase, especially in developing countries. Though more energy will be required to meet the increasing energy demand, there will be serious problems such as world energy supply problem and the global environmental issue. The need for nuclear power will enlarge as one of major options, however difficulties in its siting are more and more notable at the same time. Renewable energy is expected to have large potential as an alternative energy resource without constraint on energy supply or greenhouse gas emissions such as CO_2. One of promising renewable energy is solar energy. Although the solar energy is low density by nature, it has a large potential assuming that world deserts can be available. Therefore we focused on introducing photovoltaic power generation (VLS-PV) system on desert on a very large scale. Even the Gobi desert that locates on high latitude has more irradiation (4.59 $kWh/m_2/d$) than Seoul (3.33 $kWh/m_2/d$) and Tokyo (3.34 $kWh/m_2/d$). Theoretically, PV systems installed on a half of Gobi desert, has potential to generate as mach energy as recent world primary energy supply (361EJ in 1997). However, PV system needs a great deal of energy as well as money throughout its life cycle such as production,

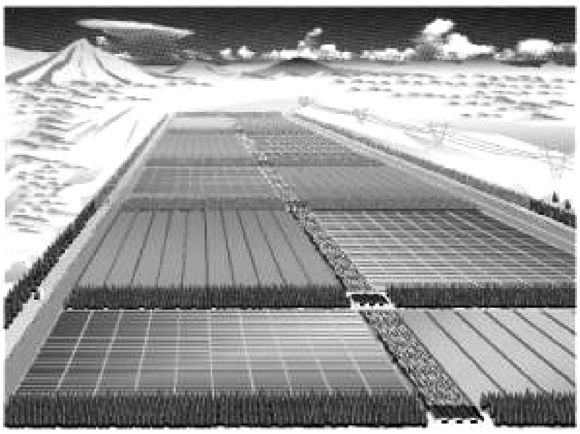


Figure 1: Image of VLS-PV system on desert

transportation and construction. The purpose of this study is to design very large-scale PV (VLS-PV) System on the Gobi desert and evaluate its potential from economic and environmental viewpoints.

Methodology of evaluation

A methodology of "Life-Cycle Analysis (LCA)" is employed in this study to evaluate the potential of VLS-PV system. The LCA is a major tool to evaluate environmental impact of product throughout their life-cycle. We estimate requirement of energy and material for life-cycle of VLS-PV that we designed, that is, manufacture and transportation of system components, system construction, and operation. Then we calculated three indices, Energy Payback Time (EPT), life-cycle CO_2 emission rate and generation cost. They are defined by following equations.

$$\text{Generation Cost (Yen/kWh)} = \frac{\text{Annual expence of the PV system [Yen/year]}}{\text{Annual power generation [kWh/year]}}$$

$$\text{EPT (Year)} = \frac{\text{Total primary energy requirement of the PV system throughout its life - cycle [kWh]}}{\text{Annual power generation [kWh/year]}}$$

EPT means years to recover primary energy consumption throughout its life-cycle by its own energy production.

$$CO_2 \text{ Emission rate (g - C/kWh)} = \frac{\text{Total } CO_2 \text{ emission on life - cycle (g - C)}}{\text{Annual power generation [kWh/year]} \times \text{Lifetime [year]}}$$

CO_2 emission rate is a useful index to know how much the PV system is effective to the global warming.

Major assumptions

As described above, in this study it is assumed that a 100MW VLS-PV system is installed on the Gobi desert, which is one of large deserts in Asia. The VLS-PV system is designed based on the following assumptions:

(1) Irradiation and ambient temperature data used for system design are those for Huh-hot (40°49' N, 89°12' E), inner-Mongolia, China, as shown in Table 1;
(2) Total capacity is about 100MW, which consist of numbers of 500kW unit systems;
(3) South-faced fixed flat array structure is employed;
(4) Polycrystalline silicon PV module with 12.8% efficiency is employed;
(5) System performance ratio is assumed at 78% considering operation temperature, cell temperature factor, load matching factor, efficiency deviation factor, inverter mismatch factor and so on, and lifetime is 30 years;
(6) Module and inverter price, and array tilt angle are given valuable parameters (module price and inverter price are respectively 100 yen/W-16.3 million yen/unit, 200-19.0, 300-21.8, 400-24.5, 500-24.5, tilt angle 10º-40º);
(7) Array support and foundation are produced in China, and other system components such as modules, cables and inverters are manufactured in Japan. All the components are transported to some installation site on the Gobi desert by marine and land transport. Land preparation is also considered.
(8) The method of operation and maintenance are calculated in view of experience of real PV

system model, PVUSA project [1].

(9) Three teams of three operators each work in 100MW PV system. One team works in maintenance, and the other teams operate for alternation.

(10) Total annual cost is defined by following equations: (1) Total annual cost consist of annual depreciation cost, annual operation and maintenance cost, annual land rent and annual overhead expense; (2) Annual depreciation cost consist of annual investment cost, annual land cost and annual property tax. (3) Annual expense rate times capital investment cost make annual investment cost. This study is assumed that annual land rent is no charge.

(11) Decommission stage is not included in this stage.

Table 1: Annual average data for Huh-hot

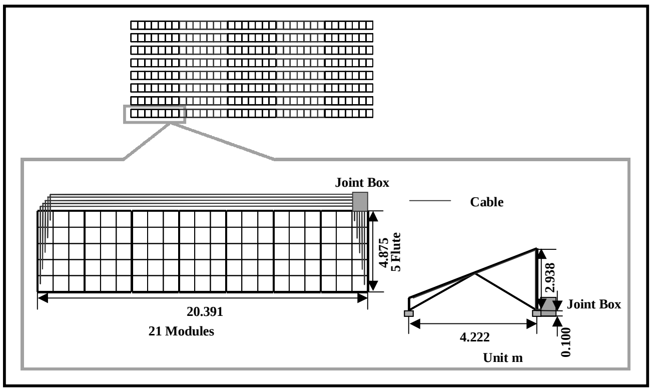
Ambient temperature	5.8 C°
In-plane irradiation	
Tilt angle=10°	1,854 kWh/m^2/yr.
Tilt angle=20°	1,964 kWh/m^2/yr.
Tilt angle=30°	2,026 kWh/m^2/yr.
Tilt angle=40°	2,037 kWh/m^2/yr.

Table 2: Major requirement data for evaluation

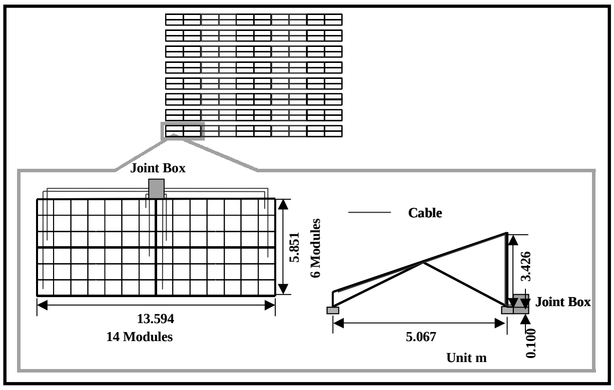
item	unit	data	unit	data
Fuel consumption for generating (Japan)	Mcal/kWh	2.48	g-C/kWh	114
Fuel consumption for generating (China Generating end)	Mcal/kWh	2.639		
Generating efficiency(China Generating end)	%	33		
Fuel consumption for generating (China Receiving end)	Mcal/kWh	2.87		
Generating efficiency (China Receiving end)	%	30		
Calory of standard charcoal (China)	Mcal/SCE-t	7000		
Standard charcoal	Mcal/t	6126	g-C/Mcal	103.6
Petroleum	Mcal/t	10750	g-C/Mcal	80.2
Heavy oil	Mcal/*l*	9.7	g-C/Mcal	81.1
PV module (Japan)	Mcal/piece	468	g-C/piece	30,791
Steel (China)	Mcal/t	11277	kg-C/t	1,168
Silicon steel（Japan）	Mcal/t	3,211	kg-C/t	321
Galvanized steel (China)	Mcal/t	22554	kg-C/t	2,336
aluminum（Japan）	Mcal/t	54,400	kg-C/t	2,130
Cement (China)	Mcal/t	1214.9	kg-C/t	126
Copper (Japan)	Mcal/t	11116	kg-C/t	771
High density polyethylene（Japan）	Mcal/t	3,779	kg-C/t	264
Polyvinyl chloride（Japan）	Mcal/t	7,025	kg-C/t	373
Epoxy resin（Japan）	Mcal/t	9,683	kg-C/t	754
Distance of land transport	km	600	Mcal/(t･km)	0.442
Distance of marine transport	km	1,000	kg-oil/(kt･mile)	7.99
Total working days in year	day/year	240		
Ratio of general expenses to deposits		0.85		

Design procedure of VLS-PV system

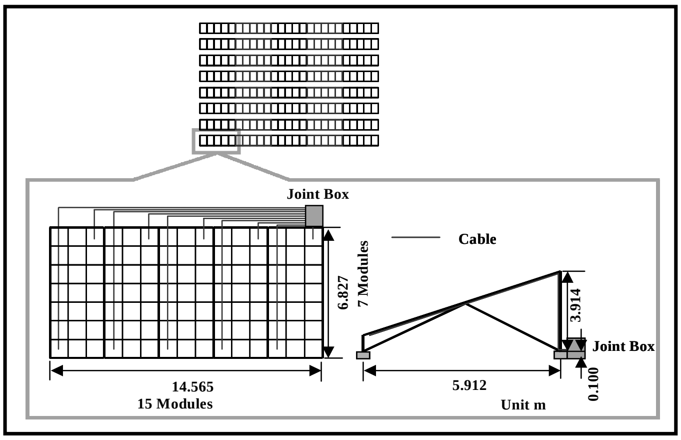
Based on the assumptions described above, the VLS-PV system on the Gobi desert is designed in detail. The procedure of its designs divided into some steps; PV module arrangement, array support design, foundation design, and wiring. Three kind of the PV module arrangement are prepared: (1) wide model, (2) moderate model, (3) tall model. Three design options and their wiring configuration are shown in Figure 2.



Design option 1 (wide model)



Design option 2 (moderate model)



Design option 3 (tall model)

Figure 2: Design options

Based on the design standard on structures for transmissions [5] rectangular foundation is designed.

The shorter and simple wiring is designed in order to prevent miss wiring. Capacity of cable is selected by the current and keep voltage drop less than 4%. It is determined from Japanese Industrial Standards.

Table 3: Lifecycle stages of VLS-PV taken into account in this study

Component	PV module	Cable	Inverter	Common apparatus	Array support	Foundation
Manufacture	Japan	Japan	Japan	Japan	China	China
Transport						
Marine	O	O	O			
Land	O	O	O	O	O	O
Construction						
Land preparation						
System installation	O	O	O	O	O	O

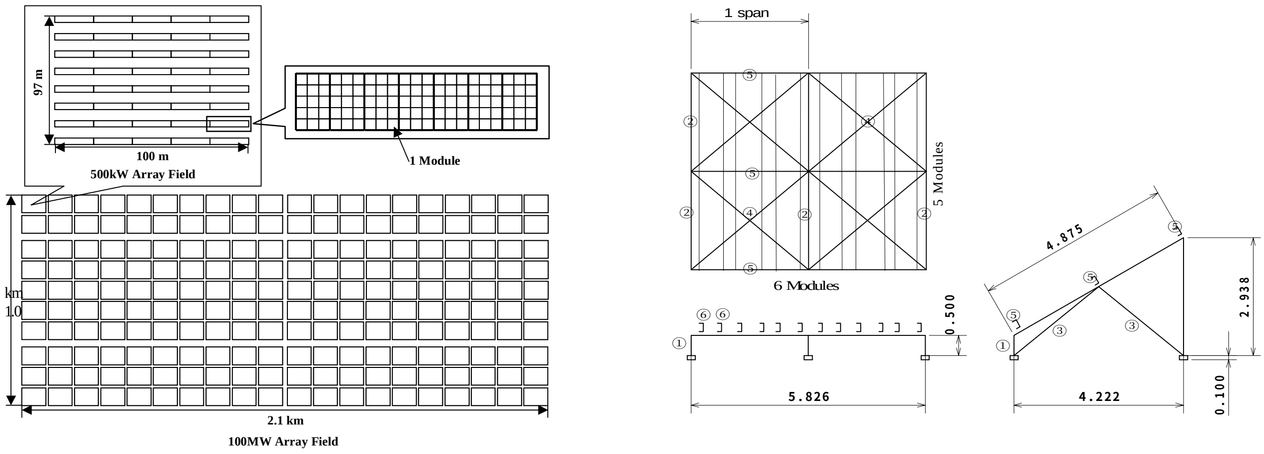


Figure 3: Array design (30º, Wide model)

Table 4: Requirement of components for 100MW VLS-PV system on the Gobi desert (Wide model)

Item		Unit	Tilt angle [º]			
			10	20	30	40
Land requirement		km^2	1.4	1.8	2.3	2.6
PV module		piece	840000			
Array support		ton	8291	8606	9658	10763
Foundation		ton	90881	90881	135660	193156
Trough		ton	10368	10691	10975	11212
Inverter with transformer		set	200			
Circuit breaker	6.6kV	set	200			
600V XLPE cable	$2.0mm^2$-single core	km	1060	1228	1291	1349
	$8.0mm^2$-two core	km	156			
	$60\text{-}100mm^2$-single core	km	60	79	96	110
6.6kV XLPE cable	$22mm^2$-three core	km	19	24	29	34
6.6kV XLPE cable	$200mm^2$-single core	km	34			
110kV XLPE cable	$150mm^2$-single core	km	10	12	13	14
Common apparatus	6.6kV vacuum circuit breaker	set	4			
	6.6/110kV transformer	set	5			
	110kV GIS	set	5			
	Capacitor	set	1			
	Filter	set	1			
	Power board	set	1			
	Control panel	set	1			

Evaluation results

Based on the assumptions described above, the 100MW VLS-PV system on the Gobi desert is designed. Table 4 shows result of components required for the 100MW VLS-PV system. Amount of array support and foundation increase in proportion to the tilt angle because of wind pressure. Land requirement also increase in proportion to the tilt angles due to spacing between PV arrays in front and behind. The increase in land requirement result in the increase in cable length.

Estimation results of capital investment cost for three design options show that the wide model (Design option 1) have the least capital investment cost. Figure 4 shows that generation cost of the 100MW VLS-PV system for different tilt angles and different PV module price, assuming 30 years lifetime and 6% of annual interest rate. Annual power generation is also given in the Figure 4. Regardless of PV module price, the least generation cost is obtained at 30º-tilt angle, which is different from that for the most annual power generation. Though the generation cost with 500 yen/W module price, i.e., 30 yen/kWh, it reduced to about 10 yen/W with 100 yen/W module price. It is higher than generation cost in China (4.3 yen/kWh). In case of 3% of annual interest rate, module cost which is 7.4 yen/kWh is still high. If module efficiency will be developed more, module price will be decrease.

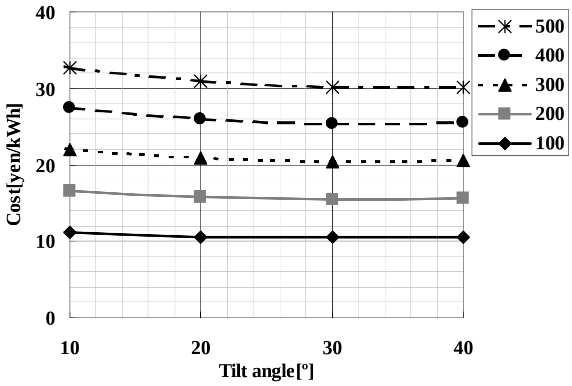


Figure 4: Result of generation cost
(Wide model)

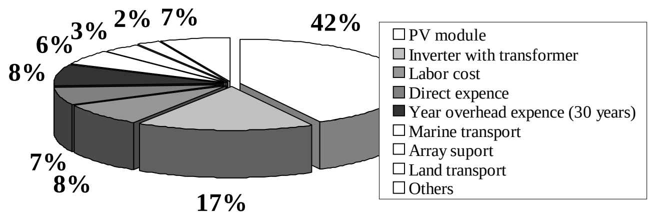


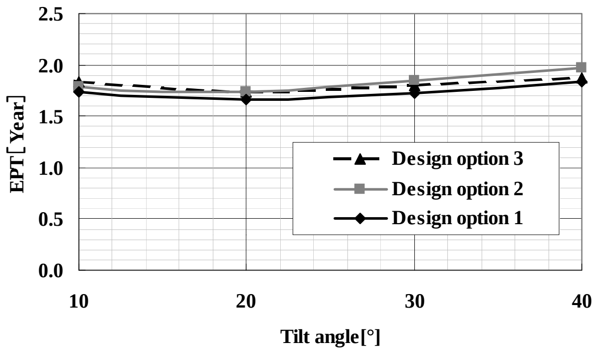
Figure 5: Breakdown of the generation cost
(tilt angle: 30º, PV module price: 100 yen/W)

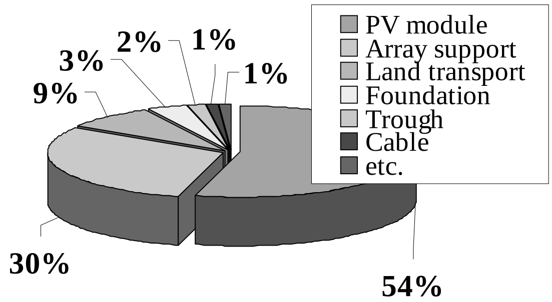
Figure 5 represents breakdown of the generation cost for 100 yen/W PV module price and 30º-tilt angle by cost component. Even though 100 yen/W PV module is assumed, its fraction is 42% of the total. Inverter cost accounted for 17% of all. Accordingly, half of the generation cost is due to PV module and inverter cost.

EPT for each the design options are given in Figure 6, which suggests that employing 20º-tilt angle system of the Wide model gives better EPT. It is less than 2 years, that is, the VLS-PV system can produce net power after 2-year operation.

Life-cycle CO_2 emission rate of three design options shown in Figure 7. It suggests that the best system configuration is 20º-tilt angle and Wide model. CO_2 emission rate is 12g-C/kWh, which is much less than average CO_2 emission rate of utility in China (=260g-C/kWh).

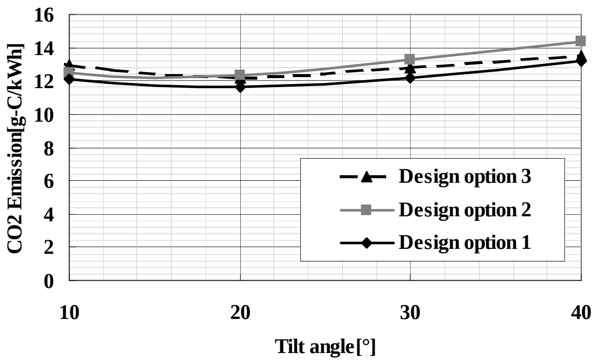
When tilt angle is 20º, EPT and CO_2 emission have the minimum values. That is because the increase of tilt angle requires thick array support and big foundation. These need large energy in making steel or concrete, which make the total energy and the total CO_2 output increase. On 10º-tilt angle, EPT and CO_2 emission is larger than other tilt angle systems because of low system output energy.

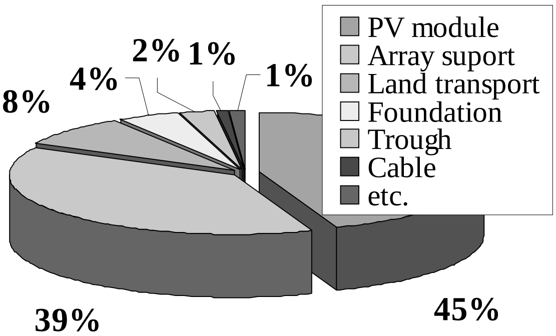




Result of EPT Breakdown of energy

Figure 6: Result of EPT (Wide model, 30º)





Result of CO_2 emission Breakdown of CO_2 output

Figure 7: Result of CO_2 emission (Wide model, 30º)

Conclusion

A 100MW VLS-PV system install on the Gobi desert is designed in detail and evaluated potential from economic and environmental viewpoints. Both EPT and life-cycle CO_2 emission rate suggest that large-scale introduction of PV technology on the Gobi desert is very much promising for energy resource saving and the global environmental issue. On the other hand, assuming 100 yen/W of PV module price and 3% of annual interest rate, generation cost of the VLS-PV is higher than China. In order to reduce the generation cost, simpler system design, module efficiency and system performance ratio has to be developed.

Now we are planning to design and evaluate the VLS-PV system installed with other modules such as CdS and Amorphous by applying the same approach used in this study. Furthermore, applications, power transmission systems and thin film modules appropriate for the system on the desert should be discussed. One of possible options may be irrigation system. A reason of desertification may be human activities as well as natural phenomenon.

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