COMPARATIVE STUDY OF M-SI, A-SI AND CDTE SYSTEM OF VERY LARGE-SCALE PV (VLS-PV) SYSTEMS IN DESERT

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ABSTRACT: Thin film technologies require lower energy to produce than crystalline PV module, but unfortunately, efficiency is lower than crystalline PV module. The authors focus attention on the point, and research possibilities to install Very Large-Scale PV system using multi crystalline silicon module, amorphous silicon module or CdTe PV module. If the module price reduces 1 USD/W, the generation cost reduces to 6-8 US cent/kWh. From an environmental point of view, Energy Payback Time was obtained 2-3 years, and CO_2 emissions rate was also obtained 17-23 g-C/kWh. In case of VLS-PV systems in desert area, total energy requirement of thin-film module was higher than crystalline silicon module because of its efficiency. Total energy requirement throughout the life-cycle of the PV system can be recovered in a short period much less than its lifetime. Therefore VLS-PV system is useful for energy resource saving. The much lower CO_2 emission rate of VLS-PV than that of existing coal-fired power plants means that it is a very effective energy technology for preventing global warming.
Keywords: Large Grid-connected PV system, Economic Analysis, Environmental Effect

1 INTRODUCTION

A desert has big potential, high irradiation and huge land area. And desert area is not only sand desert, but many types of lands exist. For example, rock desert, desert step, mountains and gravel desert, which is consist of small rocks and hard soil. Authors are focused on its potentials and simulate a 100 MW Very Large-Scale PV system installed in a desert area to obtain a possibility.

There are many kinds of Photovoltaic modules, for example, mono crystalline, multi crystalline silicon, a-Si, CdTe, hybrid, ribbon, EFG, HIT, CIS and so on. When we discuss their characters, we talk about power, efficiency, voltage, current, etc. However, we look toward environmental character, there are also kinds of characters. PV module require energy to produce. The amount of energy is different between PV modules. The authors focused on this point, and investigate the PV modules which installed in desert area in large scale.

Basically, thin film technologies require lower energy to produce than crystalline PV module, but unfortunately, efficiency is lower than crystalline PV module. The authors focus attention on the point, and research possibilities to install Very Large-Scale PV system using multi crystalline silicon module, amorphous silicon module or CdTe PV module.

Table 1 Geographic information for Gobi desert

Location		Hohhot (40°N 111°E)
Performance ratio (PR)		0.78
Ambient temperature [°C]		5.8
In-plane irradiation	Tilt angle=10°	1,854
	Tilt angle=20°	1,964
	Tilt angle=30°	2,026
	Tilt angle=40°	2,037

In this study, we are focusing comparative study between PV modules, which are m-Si, a-Si and CdTe PV module. These studies are obtained cost and environmental discussion which are generation cost, Energy Payback Time and CO_2 emission rate. For detail comparison, we focused on only Gobi desert in China. Geographical information is shown in Table 1.

2 METHODOLOGY

2.1 Basic methodology

A methodology of “Life-Cycle Assessment (LCA)” is a appropriate measure to evaluate the potential of VLS-PV systems in detail, because a purpose of this methodology is to evaluate its input and output from cradle to grave. In this study, generation cost of the VLS-PV system was calculated with the method. These indices are defined by following equation.

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

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

$$\text{Generation Cost [cent/kWh]} = \frac{\text{Annual expense of the PV system [cent/year]}}{\text{Annual power generation [kWh/year]}}$$

EPT means years to recover primary energy consumption throughout its life-cycle by its own energy production. In this study, EPT is calculated as China electricity. CO_2 emission rate is a useful index to know how much the PV system is effective for the global warming.

2.2 Design scheme

Based on concept of LCA, VLS-PV system followed these steps. Detailed schemes are shown in Chapter 4.

1) Basic assumptions such as capacity, component, transport etc. are planed.
2) Irradiations for static system in Gobi deserts is calculated.
3) Module layout, array structures, foundations, transmissions and wires are designed.
4) All materials' price, maintenance, tax, wages etc. are considered, and generation costs are calculated.

3 SYSTEM DESIGN

3.1 Basic assumptions

These assumptions are applied for three case studies.

(1) The VLS-PV system is assumed to be 100 MW.

(2) Fixed flat plate system is faced south.

(3) PV module is assumed m-Si, a-Si and CdTe [1] (see Table 2). Energy and CO_2 emission data of PV modules were referred from NEDO report [2].

(4) Life-time is 30 years.

(5) 500 kW DC-AC inverters are installed, and 6 kV/110 kV transformers pressurize voltage.

(6) Capacity of basic unit is 500 kW, 25 MW unit is consisted of 50 sets of 500 kW unit. Four 25 MW unit make 100 MW VLS-PV.

(7) PV module, cable and common apparatuses are imported from Japan. Array structures, foundations, troughs and transmission towers are produced by their country. In this study, marine and land transport is considered.

(8)Land preparation is considered.

Table 2 PV module specifications

Module type	m- Si	a-Si	CdTe
Nominal power	120 W	58 W	65 W
Efficiency of module	12.8 %	6.9 %	9.03 %
Length, Width	966 mm, 971 mm	920 mm, 920 mm	1200 mm, 600 mm
Weight	11.9 kg	12.5 kg	11.4 kg
Voltage MPP	16.9 V	63.0 V	67.0 V
Current MPP	7.1 A	0.92A	1.0 A
Voltage open circuit	21.4 V	85.0 V	91 V
Current short circuit	7.45 A	1.12 A	1.15 A
Coefficient of voltage	-82 mV/ºC	-243.0 mV/ºC	-0.29 %/ºC
Coefficient of current	+6.0 mA/ºC	+0.80 mA/ºC	+0.04 %/ºC
Coefficient of power	-0.5 %/ºC	-0.22 %/ºC	-0.25 %/ºC

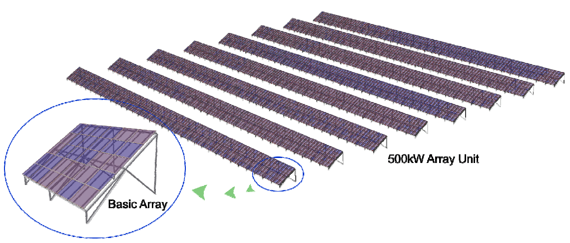

Figure 2 Image of basic array and 500 kW array unit

3.2 Irradiations

Both irradiation and ambient temperature data were referred from World Irradiation Data Book used for system designs, as shown in Table 1. In-plain irradiation data is calculated by using rb model, Hey model and isotropic model.

3.3 Module layout

PV arrays are with enough space between them. It was assumed that PV array don't shade others when 10° solar elevation in midwinter. Considering open circuit voltage and layout, 15 modules per one string for a-Si system, 20 for CdTe and 21 modules per one string for m-Si system. Basic arrays were placed as shown in Figure 2 and 3. It is considered for simple wiring and enough spacing.

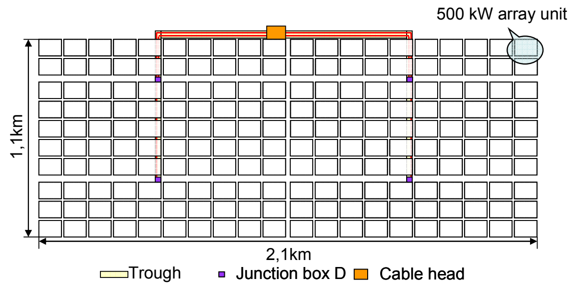

Figure 3 500 kW unit layout for m-Si PV module case

3.4 Array structures and foundations design

Array structure and foundations were designed based on 42 m/s wind velocity and 0.2 G earthquake. A zinc-plated stainless steel (SS 400) for array and concrete for foundation were designed by using Design standard of structure steel.

3.5 Transmissions

Electric transmissions are assumed 100 km, 2 channels and 110 kV for connecting to existing power transmission. It consists of steel towers, foundations, cables and grand wires. Cables and ground wires are decided TACSR 410 sq and AC 70 sq, 22.0 ton steel towers and 22.1 m^3 foundations are required 334 towers with foundations for 100 km transmission. Transmission loss is considered for 100 km. It has been studied previous paper [4].

3.6 Operation and maintenance

The method of operation and maintenance are calculated in view of experience of real PV system model, PV-USA project [5]. Three shifts of three operator team work in 100MW PV station. One team works in maintenance, and the other teams operate for alternation. Concerning labor cost, different labor requirement for system construction was estimated by considering local conditions of each country, and unit labor cost was referred from ILO statistics [6] etc. Furthermore a supervisory charge is added to the cost for the installation of certain apparatus. Decommission stage is not included in this study stage now.

4 EVALUATION RESULT

4.1 System Component

The 100MW VLS-PV systems using m-Si, a-Si and CdTe PV module in the Gobi deserts are designed on the basis of the above assumptions. Table 18 shows details and Table 28 shows summary of required materials of 100 MW scale PV system. A 100 MW VLS-PV systems with a-Si PV module require 4.4 km^2 land area which is twice as m-Si case. Character of CdTe module system is moderate model which is between m-Si case and a-Si case. In a-Si case, array support requirement is 19 thousand ton steel, and foundation needed 110 thousand ton concrete. Land requirement is considered due to spacing between PV arrays.

Table 3 Requirement of 100 MW PV system components

PV module	m-Si	a-Si	CdTe
piece (thousand)	849	1,909	1,616
Capacity (MW)	100.8	109.62	104
Land requirement (km_2)			
Tilt=10º	1.43	2.72	2.05
Tilt=20º	1.91	3.62	2.76
Tilt=30º	2.33	4.40	3.38
Tilt=40º	2.69	5.06	3.91
Array support structure (ton)			
Tilt=10º	8,375	17,936	16,302
Tilt=20º	8,693	18,618	17,667
Tilt=30º	9,755	19,255	18,690
Tilt=40º	10,871	22,591	19,755
Foundation (m^3)			
Tilt=10º	39,913	71,902	45,733
Tilt=20º	39,913	89,804	45,733
Tilt=30º	59,578	110,455	68,267
Tilt=40º	84,829	160,789	97,200
Cable (30º)			
600 V CV 2 sq (km)	1,434	16521	10284
600 V CV 8 sq double core (km)	173	584	487
600 V CV 60 sq (km)	109	497	203
6,6 kV CV-T 22 sq (km)	33	44	33
6,6 kV CV 200 sq (km)	38	36	36
110 kV CV 150 sq (km)	29	43	35
Trough (30º) (m^3)	34,052	80,511	50,457
Common apparatus			
Inverter with transformer (set)		202	
6,6 kV circuit breaker (set)		208	
110 kV/6.6kV transformer (set)		5	
110 kV disconnecting SW (set)		18	
110 kV GIS (set)		10	
SVC (set)		2	
Common power board (set)		1	
Power transmission corresponding to 100 MW PV system			
Transmission line			
110 kV TACSR 410 sq (km)		401	
AC 70 sq (km)		33	
Pylon (steel) (km)*		2,229	
Foundation (km)*		5,150	

*Three transmission equipments are assumed for 1 GW. Therefore 333 MW capacity is calculated for 100 MW system

4.2 Cost Estimation

In this study, both investment cost and operation and maintenance cost of 100 MW PV systems for each installation systems are estimated to obtain generation cost. Total investment cost includes labor cost for system construction as well as system component cost. Majority of both initial and annual cost is PV module, and second majority is BOS. Even if the module price reduces one USD/W, module cost is still majority. There are differences of BOS and transportations between the systems. Because higher efficiency of PV module reduces required arrays, foundations and so on. Amorphous module system is a little higher than multi crystalline case, but its difference is very small.

4.3 Generation cost

Figure 4 shows the result of generation cost of the 100 MW VLS-PV system using CdTe PV module in Gobi desert in China. It is obtained by dividing annual cost by power generation. Power generation at 40º tilt angle is the highest, but wind pressure is also the highest. It causes thick steel for array and large foundation. Therefore, minimum generation cost is obtained at 30 degree array tilt angle in each PV module systems. Generation cost is around 20 US cent/kWh at 4 USD/W PV module price. If the module price reduces 2 USD/W or 1 USD/W, generation cost reaches 11 or 7 US cent/kWh.

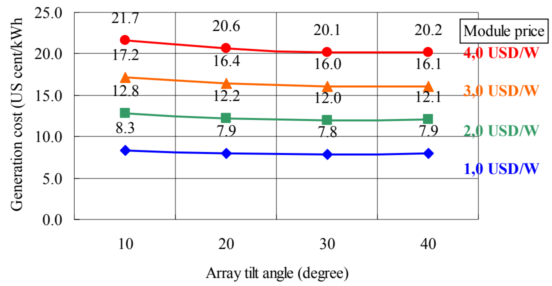

Figure 4 Generation cost of CdTe PV module case

Table 4 Generation cost of 100 MW VLS-PV systems at optimal tilt angle (30º)

PV module type	m-Si	a-Si	CdTe
1 USD/W	6.7	8.1	7.8
2 USD/W	10.5	11.5	12.0
3 USD/W	14.3	15.4	16.0
4 USD/W	18.2	19.3	20.1

4.4 Energy and CO_2 Emission Analysis in Gobi desert

Figure 5 and Table 5 show required energy and energy payback time of each system. Energy Payback Time (EPT) for each system is estimated by using LCA. In case of multi crystalline silicon solar module, EPT is 2.1 years, and 3.0 year of EPT is obtained for amorphous silicon solar modules, 2.3 year of EPT for CdTe PV modules. These are difference between EPT of systems. However, if these EPT are compared from its life-time, their values are very small. These systems must be said they can produce much energy than its required energy in its life-cycle.

Three kinds of PV modules are assumed for 100 MW VLS-PV systems, and their CO_2 emissions are estimated 13.3 g-C/kWh for multi crystalline silicon case, 19.7 for amorphous silicon case, and 16.7 for CdTe module technology. Majority of all systems is array support. In case of a-Si PV module, CO_2 emission of array support is large if compared with multi crystalline case.

Figure 7 is a summary of energy payback time and CO_2 emission rate. It can be said high module efficiency can reduce energy payback time and CO_2 emissions rate. Because it can reduce array support structures and foundations, that require much energy to produce. If the PV module installed in roof top or slope, it is not big required energy differences, because array support structure can be installed in small size.

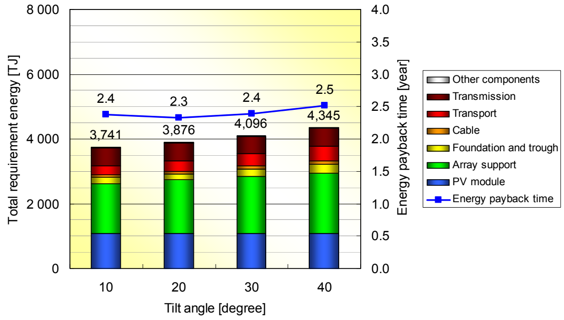

Figure 5 Total energy requirement and energy payback time of a 100 MW VLS-PV system by using CdTe PV module

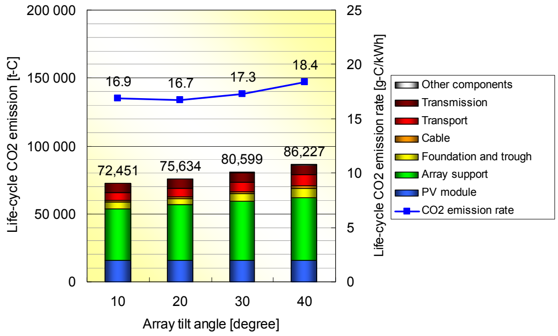

Figure 6 Life-cycle CO_2 emissions and life-cycle CO_2 emission rate of a 100 MW PV system for CdTe PV module

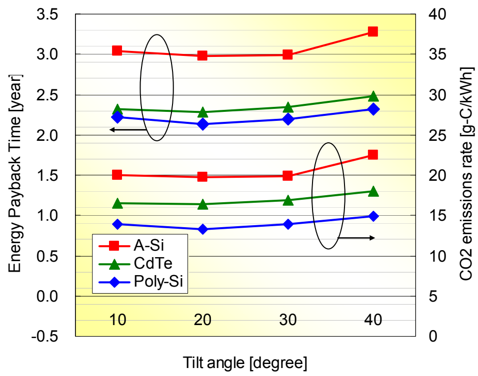

Figure 7 Comparison of VLS-PV systems of m-Si, a-Si and CdTe module

Table 5 Energy Payback Time and CO_2 emissions rate of three type modules in function of array tilt angle

		10	20	30	40
EPT [year]	m-Si	2.2	2.1	2.2	2.3
	a-Si	3.0	3.0	3.0	3.3
	CdTe	2.3	2.3	2.3	2.5
CO_2 emissions rate [g-C/kWh]	m-Si	13.9	13.3	13.9	14.9
	a-Si	20.0	19.7	20.0	22.4
	CdTe	16.5	16.4	17.0	18.0

5. CONCLUSION

100MW Very Large-Scale power generation systems installed in Gobi desert were designed and their potentials were evaluated from economic and environmental viewpoints. This comparative study was considered all equipments, transport, operation and maintenance and transmission loss. Assuming 4.0 USD/W of m-Si PV module price and 3% of annual interest rate, generation cost was estimated 19.1 U.S.Cent/kWh and 19.3 US cent/kWh with land transport in Huhhot in Gobi desert. If the module price reduces 1 USD/W, the generation cost reduces to 6-8 US cent/kWh. From an environmental point of view, Energy Payback Time was obtained 2-3 years, and CO_2 emissions rate was also obtained 17-23 g-C/kWh. Amorphous silicon solar module and CdTe module requires lower energy than crystalline module to produce. But in case of VLS-PV systems for desert area, total energy requirement of thin-film module was higher than crystalline silicon module because of its efficiency. However, thin-film silicon module is now being developing very much, and it will be more developed in near future.

This study suggests that the total energy requirement throughout the life-cycle of the PV system considering production and transportation of system components, system construction, operation and maintenance can be recovered in a short period much less than its lifetime. Therefore VLS-PV system is useful for energy resource saving. The much lower CO_2 emission rate of VLS-PV than that of existing coal-fired power plants means that it is a very effective energy technology for preventing global warming.

REFERENCES

[1] Photon international, Feb 2005.
[2] Development of Technology Commercializing Photovoltaic Power Generation System, Research and Development of Photovoltaic Power Generation Application System and Peripheral Technologies, Research and Development on the Evaluation Technology of Photovoltaic Power Generation system (2000), NEDO 27-38 pp
[3] Japan Weather Association, World Irradiation Data Book, FY1991 NEDO Contract Report
[4] M. Ito et al, Analysis of transmission losses of Very Large-Scale Photovoltaic power generation systems (VLS-PV) in world desert, Proceedings of 31st IEEE PVSC (2005), 1706-1709 pp
[5] C.Jennings, A.B.Reyes & K.P.O', Brien PVUSA utility-scale system capital and maintenance costs, *WCPEC-1, Dec, 5-9, 1994, Hawaii.*
[6] ILO, Year Book of Labour Statistics 1999