An Analysis of Very Large-Scale PV (VLS-PV) Systems Using Amorphous Silicon Solar Cells in the Gobi Desert

Masakazu Ito[1], Kazuhiko Kato[2], Keiichi Komoto[3], Tetsuo Kichimi[4], Hiroyuki Sugihara[5], Kosuke Kurokawa[1]

[1] Tokyo University of Agriculture and Technology (TUAT), 2-24-16 Naka-cho, Koganei, Tokyo, 184-8588, Japan, Tel/Fax: +81-42-388-7445, E-mail: itomasa@cc.tuat.ac.jp
[2] National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba Central 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568, Japan
[3] Fuji Research Institute Corp. (FRIC), 2-3 Nishiki-cho, Kanda, Chiyoda-ku, Tokyo, Japan
[4] Resources Total System (RTS), Shinkawa, Chuo-ku, Tokyo, 104-0033, Japan
[5] Kandenko Co. Ltd., Chiyoda-machi, Niihari, Ibaraki, 315-0052, Japan

ABSTRACT

Thin-film silicon solar cells including amorphous silicon (a-Si) solar cells are expected to be environment-friendly due to their less energy requirement. Then a Very Large-Scale Power Generation (VLS-PV) system for the Gobi desert is designed in detail by assuming that the thin-film solar cells were used.
As a result, 19 cent/kWh generation cost, 2.6-year energy payback time (EPT), and 18 g-C/kWh CO2 emission rate were obtained based on present thin-film technology. They are a little higher than poly crystalline Si case. On the other hand, another case in which technological progress was supposed in near future indicated 6.5 cent/kWh generation cost, 1.6-year EPT, and 11 g-C/kWh CO2 emission rate.

KEYWORDS

VLS-PV, amorphous silicon, LCA, Energy Payback Time, CO2 emission rate, Desert

1. INTRODUCTION

1.1 Background
We are at the beginning of stage which we make. As you know there are many world problems such as energy problem, food crisis, reduction of biodiversity and forest, and so on. It depends on your choice; save world or not.

In this stage, we focused on energy problem and global worming. World energy demand has been rapidly expanding due to the world economic growth and population increase, especially in developing countries. According to an IEA report, total CO_2 emissions and total primary energy supply in 2030 in the world will be twice as much as in 2000, as shown in Figure 1. If world energy demands continue to increase, the primary energy may dry up in this century. In addition,

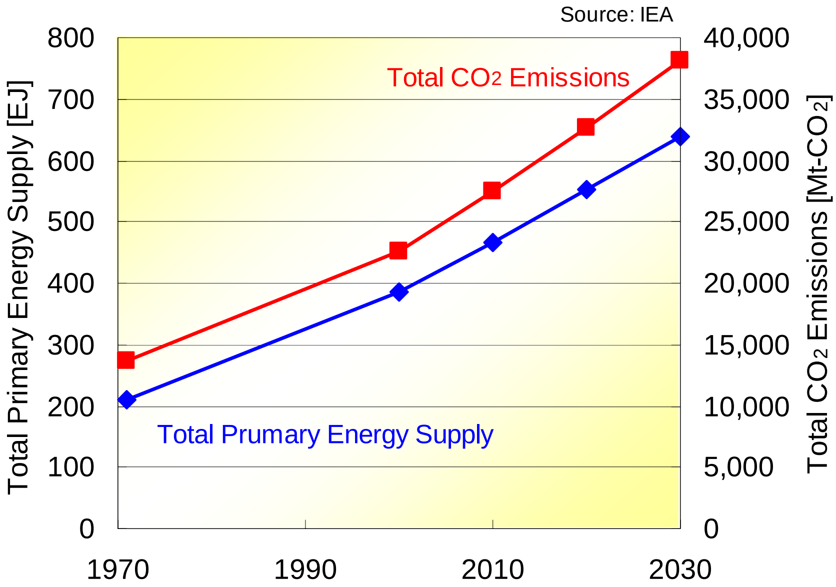

Fig. 1 Outlook of world primary energy supply and CO_2 emissions

too much energy consumption causes a variety of serious environmental problems such as global warming, acid rain and so on. But, renewable energies are expected to resolve both the energy problem and the environmental problems. Photovoltaic power generation system (PV system) is one of promising renewables. Because the PV system need no fuel, no emission and very low maintenance at the operation stage. However, the solar energy has a disadvantage, that is, its low energy density by nature. Therefore, to generate large power such as nuclear power plant, the PV system must be introduced at very large-scale.

1.2 DESERT POTENTIAL

High irradiation and very large unutilized land areas exist in world deserts. For example, even the Gobi desert that locates on high latitude has higher irradiation (4.7kWh/m^2/d) than Tokyo (3.5kWh/m^2/d). Furthermore, the Sahara desert has more irradiation, or 7.4kWh/m^2/d. Theoretically, PV systems installed in the Gobi desert with 50% space factor, has potential to generate energy as much as the recent world energy supply (384 EJ in 2000).

Table 1 Global irradiation in the world deserts [1]

Major deserts	Country	Global irradiation [kWh/m^2/year]
Sahara	Mauritania	7.36
Negev	Israel	5.31
Thar	India	5.96
Sonoran	Mexico	5.47
Great Sandy	Australia	8.92
Gobi	China	4.67
Tokyo (Reference)	Japan	3.47

2. OBJECTIVE

VLS-PV systems using poly crystalline Si solar cells were already designed and they showed that the system might produce much more energy with low life-cycle CO2 emissions than energy requirement for its life-cycle even if it is located at high latitude desert such as Gobi desert.[3][4] The purpose of this study is to obtain a possibility of VLS-PV system using thin-film Si solar cells including amorphous Si (a-Si) solar cells, because it requires lower energy to produce than poly crystalline Si solar cells. In addition, thin-film silicon solar module is advanced very rapidly and expected to be higher efficiency in near future. So, we assumed it would be twelve percent efficiency in near future. And VLS-PV system using this kind of module is evaluated from economic and environmental view points.

3. METHODOLOGY OF EVALUATION

3.1 Life-Cycle Assessment

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, energy payback time (EPT) and CO_2 emission rate of the VLS-PV system were calculated with this method. These indices are defined by following equations.

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

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

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

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

3.2 Case Studies

Case studies were assumed for three cases. The first case was using a commercial poly-crystalline silicon solar cell module. The second case was a commercial a-Si solar cell module. The last case was thin-film silicon solar cell module with twelve percent efficiency, which is being developed. For this calculation, material data is referred from a NEDO report [5]. The module specifications used in this study are shown in Table 2, 3.

Table 2 Case studies list

Module	Kyocera KC 120S (Reference)	Kaneka LSU	Near future case
Cell type	Poly Crystalline Si	Amorphous Si	Thin-film Si
Efficiency	12.8 %	6.9 %	12.0 %
Array type	Fixed flat plate system		
Evaluation type	Economic, environment		
Index	Cost, EPT, CO_2 emission rate		
Site	Gobi (China)		

Table 3 Kaneka LSU module specification

Nominal power	58 W
Efficiency of module	6.9 %
Height, Width	920 mm, 920 mm
Weight	12.5 kg
Voltage MPP	63.0 V
Current MPP	0.92A
Voltage open circuit	85.0 V
Current short circuit	1.12 A
Coefficient of voltage	-243.0 mV/°C
Coefficient of current	+0.80 mA/°C
Coefficient of power	-0.22 %/°C

Ref: Photon int'l magazine

4. SYSTEM PLANNING

All parts of a 100MW VLS-PV system were designed based on concept of LCA. The design assumptions are explained as follows.

4.1 Installation Area

Major desert, Gobi was chosen for installing VLS-PV system. A desert area is suitable for PV system in view of irradiation and land capacity.

Both irradiation and ambient temperature data referred from World Irradiation Data Book[1] were used for system designs, as shown in Table 4. When the installation sites have no direct and diffuse irradiation data, the direct and diffuse irradiation data were estimated from global irradiation data by using Liu-Jordan model. Finally in-plain irradiation data was obtained by using rb model, Hey model and isotropic model.

4.2 System Assumptions

VLS-PV systems were designed based on the following assumptions.

1) Total capacity is about 100MW, which consists of four sets of 25MW unit field. A 25MW unit consists of 50 sets of 500kW unit system.
2) South-faced fixed flat array structure, one axis E-W tracking array structure and foundation are designed. Wind pressure and earthquake are also taken into account.
3) System performance ratio, as shown in Table 4, is assumed considering operating temperature, degradation, load matching factor, efficiency factor, inverter officiating and so on.
4) The system lifetime is assumed to be 30 years.
5) Module price is fixed. Modules in practical use are assumed 4.0 USD/W. Thin-film module price in near future is supposed at 1.0 USD/W.
6) Inverter price and array tilt angle are given as valuable parameters. The four levels of inverter

Table 4 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

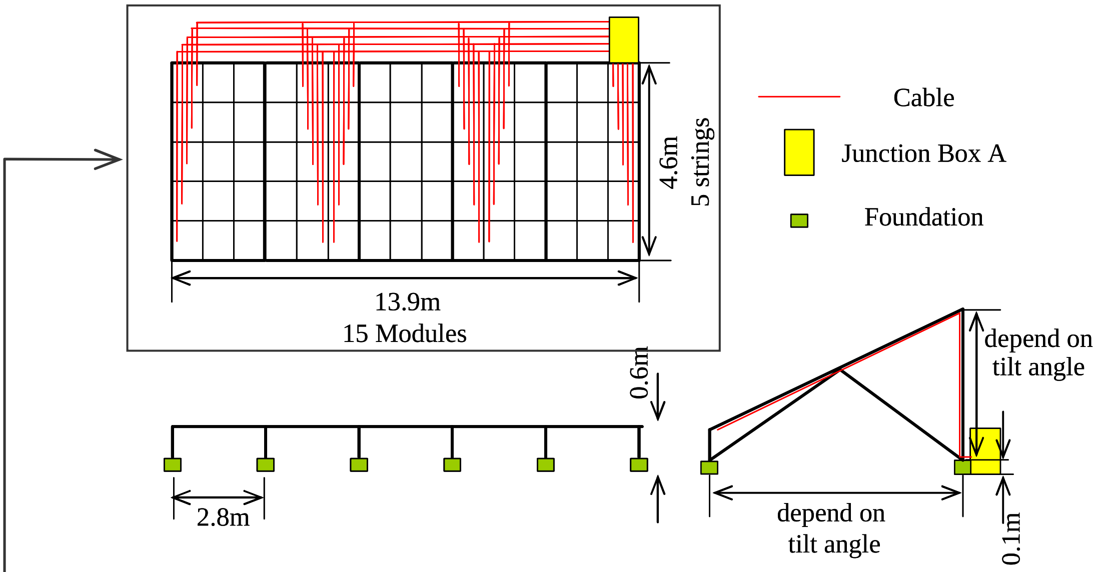

Fig.2 Array support design for amorphous Si cells

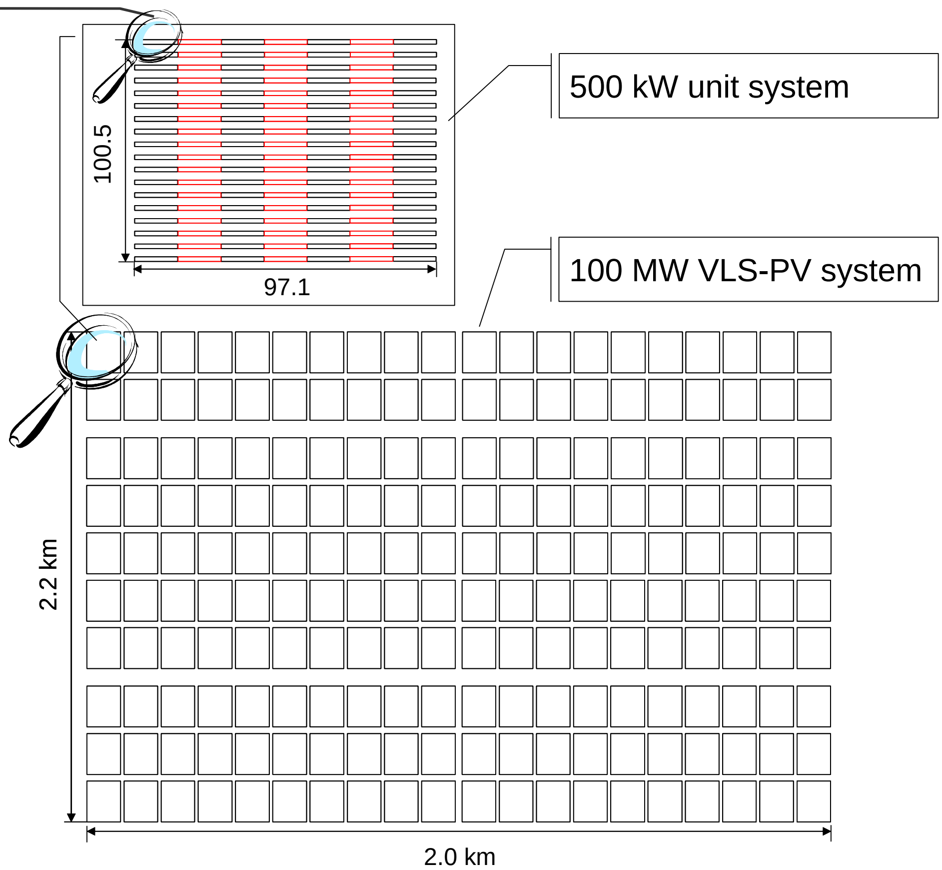

Fig.3 Unit layout for 100 MW system for amorphous Si solar cells

unit price of 500kW is also set to 0.136 [million USD] for module price 4.0 USD/W, 0.159 for 3.0, 0.181 for 2.0, 0.204 for 1.0. Interest rate is asssumed to be 3%/year. And

7) Land preparation is considered.

4.3 Transport

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 the installation site by marine and land transport.

Table 5 Example of required component for 100 MW VLS-PV system. (a-Si case)

Item		Unit	10º	20º	30º	40º
Material requirement						
PV module		piece	1,890,000	1,890,000	1,890,000	1,890,000
Array support structure		ton	17,757	18,432	19,063	22,366
Foundation		m^3	71,183	88,906	109,350	159,181
Cable	600 V CV 2 mm^2 (single core)	km	13,695	14,301	14,869	15,462
	600 V CV 8 mm^2 (double core)	km	526	526	526	526
	600 V CV 60 mm^2 (single core)	km	361	345	419	480
	6,6 kV CV-T 22 mm^2	km	37	38	38	39
	6,6 kV CV 200 mm^2 (single core)	km	33	33	33	33
	110 kV CV 150 mm^2 (single core)	km	14	16	19	23
Trough		m^3	73,085	77,035	80,511	83,408
Common apparatus						
Inverter (with transformer)		set	202	202	202	202
6,6 kV capacitor		set	202	202	202	202
6,6 KV GIS		set	4	4	4	4
110 kV/6.6kV transformer		set	5	5	5	5
110 kV GIS		set	4	4	4	4
2,4MVA capacitor		set	1	1	1	1
Common power board		set	1	1	1	1
Transportation						
Heavy oil consumption		ton	353	354	357	359
Diesel oil consumption		kl	11,129	12,602	14,225	17,853
Transmission						
Cable	110 kV TACSR 410 mm^2	km	1,202	1,202	1,202	1,202
	AC 70 mm^2	km	100	100	100	100
Pylon (steel)		ton	7,348	7,348	7,348	7,348
Foundation		ton	16,977	16,977	16,977	16,977
Construction						
Diesel oil consumption		kl	206	273	332	382
Labour requirement		Man-year	7,980	8,059	8,135	8,360

4.4 Operation and Maintenance

1) The method of operation and maintenance are calculated in view of experience of real PV system model, or PV-USA project [2].
2) Three shifts of three operator team work in 100MW PV station. One team works in maintenance, and the other teams operate for alternation.
3) 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 etc. Furthermore a supervisory charge is added to the cost for the installation of certain apparatus.
4) Decommission stage is not included in this study.

5. DESIGNING VLS-PV SYSTEMS

5.1 Array support structure and foundation

Fig.2 shows the basic structure of array support for 30 degree tilt angle. Top of foundation form ground is 0.1 m and the lowest position of module is 0.2 m from the ground. It is assumed that array support is made of zinc-plated stainless steel (SS 400), and thickness of several types of steel material are chosen according to stress analysis assuming that the wind velocity is 42m/s (based upon the Design standard of structure steel [10] by the Japanese Society of Architecture).

Cubicle foundations made of concrete are applied. Its rectangular solid is about 0.8 m each considering the design standard of support structure for power transmission by the Institute of Electrical Engineering in Japan. Material composition of the concrete is determined in order to obtain 240 kg/cm^2 of concrete strength; 347 kg/m^3, 603 kg/m3 sand, 11,180 kg/m3 gravel and 170 l/m^3 water. Fig.3 shows layout of array unit which is shown as Fig.2. It is based on “assumption 1)”.

5.2 Wiring

The shorter and simple wiring is designed in order to prevent miss wiring. The current capacity of cable is selected to make voltage drop less than 4 %. It is determined from Japan Industrial Standards-JIS.

5.3 Transmission

Table 6 Estimated annual power generation and system capacity

	Annual power generation [GJ]				System capacity [MW]
Tilt angle=	10	20	30	40	
Poly-Si	147	156	161	162	100.8
a-Si	158	168	173	174	109.6
Thin-film module in near future	154	163	168	169	106.6

Electric transmission system is assumed 100 km, 2 channels and 110 kV for connecting to existing transmission. It consists of steel towers, foundations, cables and grand wires. They are considered wind velocity 42 m/s. After calculations, 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. Table 5 is a summary of required materials for 100 MW VLS-PV system.

6. EVALUATION RESULTS

By using the results of the system design and operation and maintenance, a life-cycle of amorphous-Si and thin-film-Si 100MW VLS-PV systems in the world deserts were evaluated in terms of life-cycle cost, energy and CO2 emission. Summary of results are shown in Table 5. Table 6 shows annual power generation and system capacity of each system.

6.1 System Component

The 100MW VLS-PV systems using amorphous module in the Gobi deserts are designed on the basis of the above assumptions. Table 6 shows example of result. This system required 4.4 km^2 land area which is twice as much as poly crystalline case. Array support requirement is 19 thousand ton steel, and foundation needed 252 thousand ton concrete. Land requirement is considered due to spacing between PV arrays. If thin-film module efficiency reaches twelve percent, these items are reduced drastically. Land requirement is 2.5 km2, Array support is 11 thousand ton steel, and foundation is 140 kton.

Table 6 System components (30 degree case)

Module	Unit	KC120S (Kyocera)	LSU (Kaneka)	Thin-film module in near future
Assumed module price	USD/W	4.0	4.0	1.0
Module	10^3	840	1,890	1,050
Area	km^2	2.2	4.4	2.5
Array support	ton	9,658	19,063	10,590
Foundation	kton	136	252	140
Cost	U.S.Cent/kWh	17.7	18.8	6.5
EPT	year	1.8	2.6	1.6
CO2 emissions rate	g-C/kWh	12.8	17.8	10.5

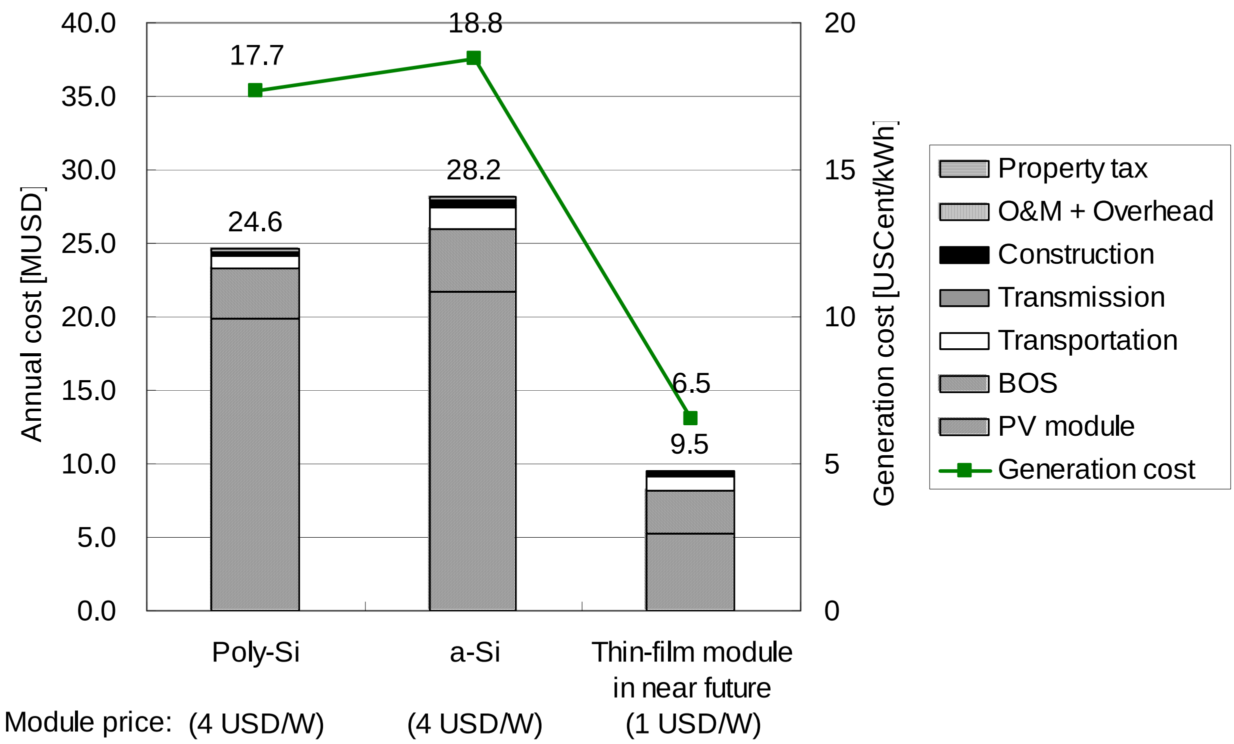

Fig .4 Annual cost for a-Si case (30 degree case)

6.2 Cost Estimation

In this study, both investment cost and O&M cost of 100MW PV system for each installation systems were estimated to obtain generation cost. Total investment cost includes labor cost for system construction as well as system component cost. Fig.4 shows annual cost for current a-Si module and developed a-Si module in near future. Majority of both annual cost is PV module, and second majority is BOS. In other words, if the module price reduces one USD/W, module cost is still majority. There are much differences of BOS and transportations between both systems. Because higher efficiency of developed module reduce requirement of modules, arrays, foundations and so on. Amorphous module system is a little higher than poly crystalline case, but its difference is very small. When thin-film modules are developed in near future, the generation cost of 1 USD/W module price reaches 6.5 cent/kWh.

6.3 Energy and CO2 Emission Analysis in Gobi desert

Fig.5 shows required energy and energy payback time of each system. Energy Payback Times

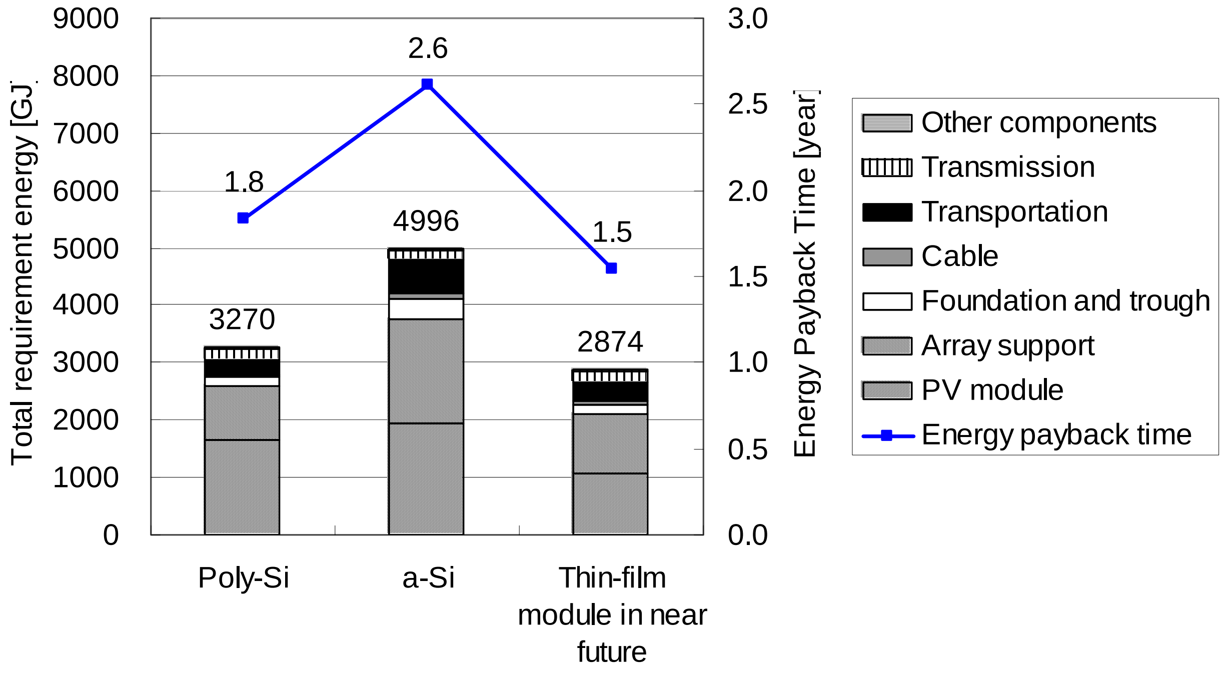

Fig.5 Total energy requirement and Energy payback time (30 degree case)

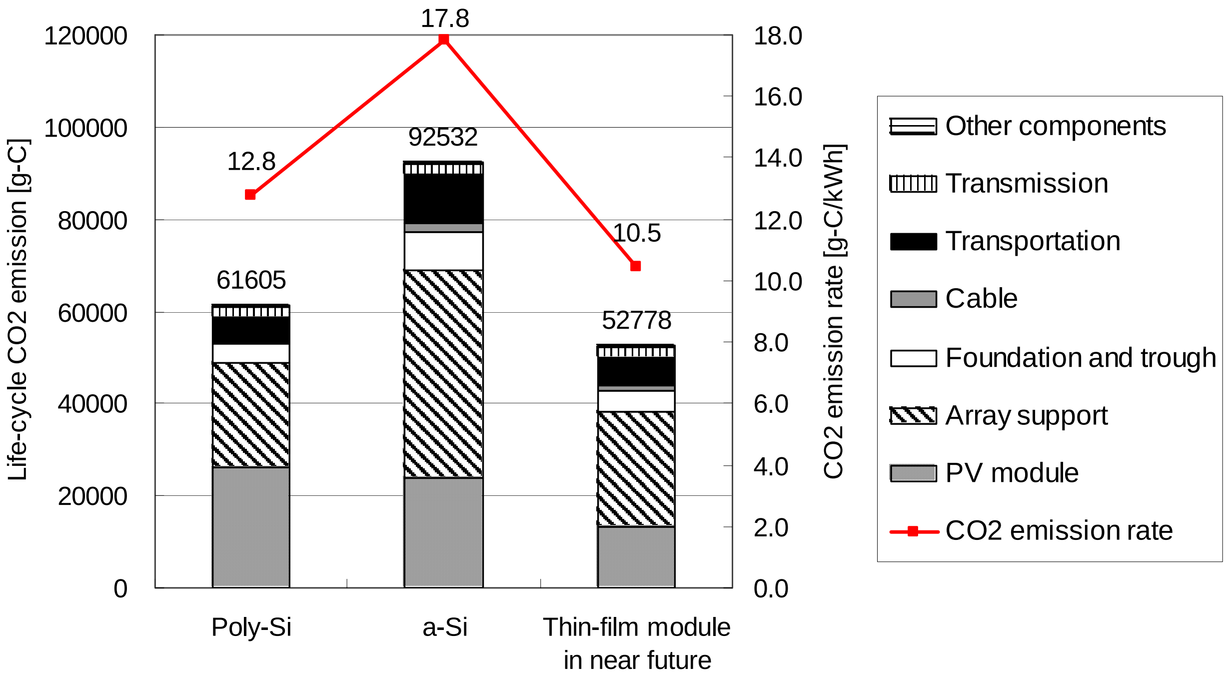

Fig.6 Life-cycle CO2 emission and CO2 emission rate (30 degree case)

(EPT) for each system were estimated by using LCA. In case of poly crystalline silicon solar module, EPT is 1.8 years, and 2.6 year of EPT is obtained for amorphous silicon solar modules. With developed thin-film silicon solar module, EPT should be obtained 1.6 years. These are difference between EPTs. However, if these EPTs 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. Majority is Array support in a-Si case and thin-film case, and second majority is PV module, because of its efficiency.

Three kinds of modules are assumed for 100 MW VLS-PV systems, and their CO2 emissions are estimated. It is 12.8 g-C/kWh for poly crystalline silicon case, 17.8 for amorphous silicon case, and 10.5 for new thin-film technology. Majority of all systems is array support. In case of a-Si, CO2 emissions of array support is very high if compare poly crystalline case. However, if thin-film-technology is developed more, total CO2 emission will be decrease drastically.

7 CONCLUSION

100MW Very Large-Scale power generation systems installed in the Gobi desert was designed and its potential was evaluated from economic and environmental viewpoints. Assuming 4.0 USD/W of amorphous PV module price and 3% of annual interest rate, generation cost was estimated 18.8 U.S.Cent/kWh in Gobi desert. From an environmental view point, Energy Payback Time was obtained 2.6 years, and CO2 emissions rate was also obtained 17.8 g-C/kWh. Amorphous silicon solar module requires lower energy than crystalline module to produce. But in case of VLS-PV systems for desert area, total energy requirement of amorphous silicon module was higher than poly 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. So we assumed thin-film silicon module with twelve percent efficiency, and evaluated it from the same method, LCA. 6.5 U.S.cent/kWh generation cost, 1.6-year EPT, and 10.5 g-C/kWh CO2 emissions rate were obtained.

These results suggest that the total energy requirement throughout the life-cycle of all VLS-PV systems 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 CO2 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.

Anyway, new thin-film technology is now developing drastically. Especially, Kaneka hybrid module is remarkable. Thin-film technology is expected for energy resource reduction and cost reduction. We hope expected thin-film module comes in very near future.

ACKNOWLEDGEMENT

This work is supported in part by Sumitomo Foundation. Authors thank them very much.

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