Comparison of thin film versus crystalline PV modules for utility-scale electric power production in Pakistan

Ijaz Husnain[a,b,*], Warda Mushtaq[a], Zuhair S Khan[a]

[a]US-Pakistan Centre for Advanced studies in Energy (US-PCASE), NUST H-12, Islamabad 44000, Pak

[b]School of Electrical, Computer and Energy Engineering, Arizona State University (ASU),Tempe AZ 85287, USA

* Corresponding author: ihusnain@asu.edu

Abstract

Today energy has become an important global concern. The development and economic growth of a country is directly connected with the progress in the energy sector and energy availability. Combustion of fossil fuels is not only leading towards the depletion of their resources, but also causing hazardous environmental impacts. That's why the world is searching for cleaner and sustainable resources which can replace fossils. Recent surveys show that renewables have maximum consumption growth by source in the past few years. Among the renewable resources, Solar PV offers huge potential as well as is relatively easy to deploy.

In this study, we first assess the feasibility of different sites in Pakistan for installation of solar photovoltaic (PV) technology to produce utility-scale electric power. Energy performance of solar PV in ten different cities of Pakistan is extensively studied. Furthermore, nowadays consumers are attracted towards deployment of thin film solar PV modules instead of crystalline silicon solar cells due to low manufacturing costs. Here, we also determine the economic viability of thin film PV and crystalline Si (c-Si) PV modules, for a 20MW power plant in Bahawalpur, Pakistan uses NREL system advisor model (SAM). The weather data for this model is obtained from National Solar Radiation Data Base (NSRDB). Upon detailed investigations and analyses, it is revealed that thin film PV is more suitable than crystalline Si due to availability of the large barren area in Pakistan. Capacity Factor (CF) for thin film and c-Si PV is 18.86% and 18.54% respectively. Performance Ratio (PR) is calculated to be 0.76 and 0.75 respectively. Also, simulation results show that total annual energy produced by thin film versus c-Si is 33,041 MWh and 32,469 MWh respectively. Finally, analysis of the CF and PR for different cities of Pakistan demonstrates significant annual energy production for utility-scale electric power production as compared to other European countries.

Keywords: : *Solar energy;Photovoltaic system;Utility scale;System advisor model; performance ratio;*

1. INTRODUCTION

The increment in consuming energy on our planet is threatening. The world energy consumption was about 1.17×10^{15} in 2005. [1] This trend estimates the energy consumption will increase 53% from 2008 to 2035 [2]. Energy consumption for the OECD (organization for economic co-operation) countries i.e. U.S.A, Canada, Germany etc. increase only 0.6% per year while for non- OECD countries like Pakistan, China, India increase up to averagely 2.3% per year. This immense amount of increment in energy demand in non-OCED countries invoke to produce low cost and environment friendly production of electricity.

On average the Sun irradiance on Earth surface is ~ 5 $kWhm^{-2}day^{-1}$. With this solar irradiance it's easy to fulfil the increasing energy demands. The natural resources of energy on earth rapidly depleting and also the fossil fuels had bad impact on environment make the renewable as a perfect alternative. While wind and hydro energies have been used for many years, the solar market has been expanding rapidly as more efficient and cost effective solar devices begin to be developed.

Among solar devices, silicon cells first come to mind. Efficiencies upwards of 15-20% have been achieved for crystalline silicon devices [3]. However, the cost of purifying crystalline silicon is very high and energy intensive. Due to this high cost, focus has shifted to thin film solar cells, which have greatly reduced cost of production. Currently the most popular thin film device uses CdTe and $CuIn_xGa_{(1-x)}Se_2$ (CIGS) as the light-absorbing layer and thus far cell efficiencies of up to 20.4% have been recorded [4].

Pakistan is struggling since last decade to fulfil its energy demand. Pakistan is huge potential of solar PV. For the last decade or so, Pakistan has been facing a severe energy crisis. With installed generation capacity of about 23,600 MW,

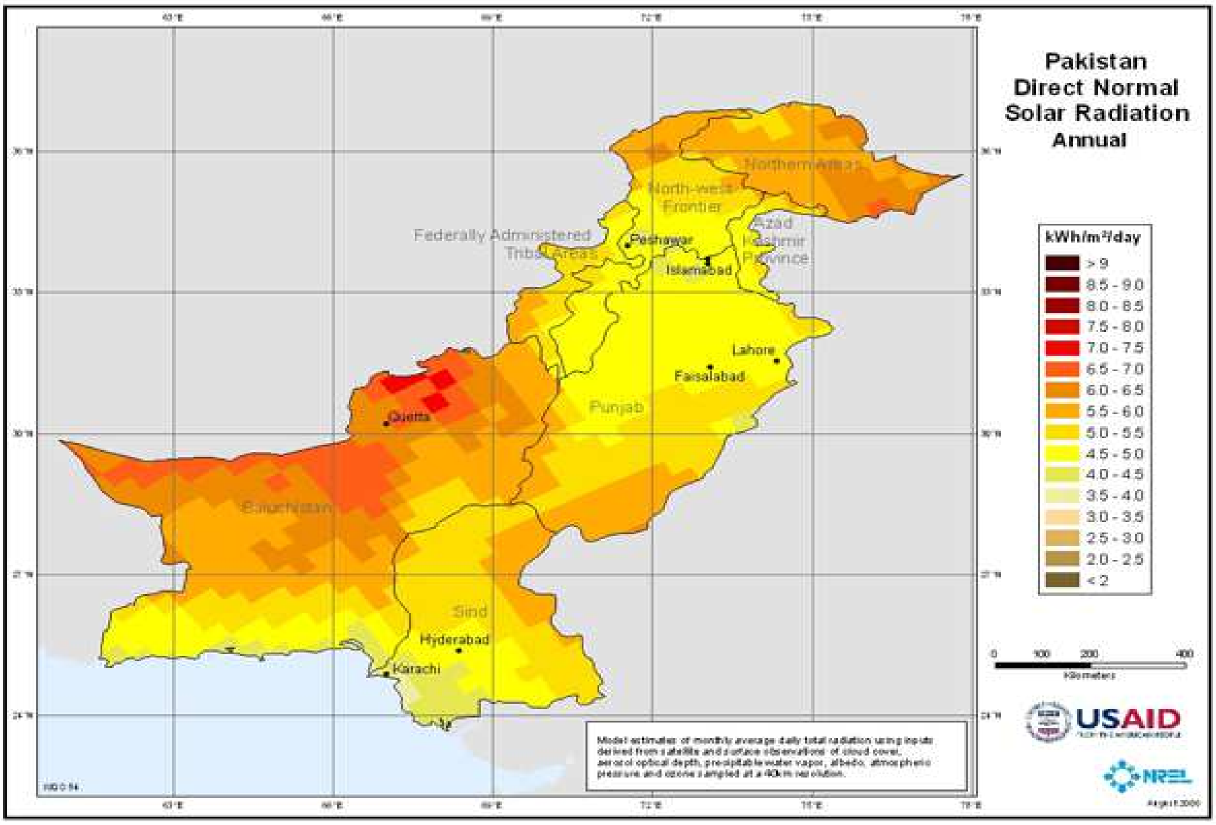

Fig. 1. Pakistan solar radiation Map

the country is facing a power shortage of approximately 3,000 MW to 6,000 MW during peak hours. The crisis worsens during summer months, leading to prolonged load shedding of 8 to 18 hours that varies significantly between urban and rural areas. 37% of Pakistan's fuel mix is based on fuel oil which means the cost of generation is expensive and highly dependent on oil price changes leading to cost vulnerability. Renewables (other than large hydro), which could lessen this cost vulnerability, contribute less than 1% of the current renewable energy mix.

Pakistan has tremendous potential to meet its power demand needs from renewable energy sources and, in particular, solar.

In Pakistan the solar irradiance in the areas like southwest have potential relative with the world producing energy from the solar PV. The global horizontal irradiance (GHI) of the southwest area is over than 1500 kWh/m² which is 90% of the area. The preliminary analysis of The World Bank of GHI for Pakistan is 2071 kWh/m². It shows that Pakistan has vast potential of solar PV for the energy production.

a. Crystalline Si

Crystalline silicon is promising technology and well established in world. More than 80% of PV market share by crystalline Si. The first generation solar cells are made of crystalline silicon, which is also known as traditional or conventional solar cell ware developed in 1950s which is still used widely across the world. Crystalline solar cells are made of silicon wafers about 160 to 200 µm, which is also called wafer-based solar cell.

b. Thin film (CdTe)

A second generation solar cell is thin film solar cell which is made of depositing one or more thin layers of photovoltaic material on substrate, substrate is made-up by metal, plastic or glass. There are several solar cell such as copper indium gallium diselenide (CIGS), cadmium telluride (CdTe) and amorphous silicon (a-Si) where thin film technology is used. [5]. Among the thin film solar cells, CdTe mostly used as commercial solar cell. It's a lower cost as compared to conventional crystalline silicon for megawatt system. Its energy payback is less than a year as compared to silicon which is 2.3 year [6-8]In the world the largest photovoltaic power plant CdTe solar cells are used in Topaz Solar Farm (550 MW) and Desert Sunlight Solar Form (550 MW) in California. It contributes 5.1% of the worldwide, more than half of the thin film market is all about in 2013[9] . The company, First Solar which is situated at Tempe, Arizona is the prominent manufacturer for the CdTe.

Table 1. Comparison of Mono-Si Vs CdTe module

Parameter	Mono-Si	CdTe
Cell efficiency	16.5%	15.6%
Derate cell to module efficiency	8.5%	13.9%
Module efficiency	15.1%	13.4%
Wafer thickness / layer thickness	190 µm	4.0 µm
Kerf loss	190 µm	–
Silver per cell	9.6 g/m2	–
Glass thickness	4.0 mm	3.5 mm
Operational lifetime	30 years	30 years

Source: IEA-PVPS, Life Cycle Assessment, March 2015 [10]

2. MODELLING & METHODOLOGY

The computational software used in this project was SAM (System Advisor Model) which facilitates the researcher involved in renewable energy industry to enhance the performance and assist with financial problems. System advisor model use to predict the energy performance, grid connectivity installation and operating cost for specific designed parameters and inputs.
Weather data file used of national solar radiation data base. The most recent version of NSRDB was established by physical solar model. Data available in this version is from 1998 to 2014.meteorological data for NRSDB is comprised of 30-minutes solar. Data available along the area by latitude 60° N on north and -20° S on south, and longitude 175° W on the west and 25° E on the east.
In our work modeling is based on location, type of module used and assess the energy performance of utility scale PV solar plant at ten different locations in Pakistan.

a. Capacity factor calculation

The capacity factor is defined as the ratio between the system's predicted electrical output in the first year of operation to the nameplate output, which is equally defined as the amount of energy generated in a year operated at nameplate capacity.

$$CF = \frac{\textbf{Net Annual Energy (kWhac/yr)}}{\textbf{System Capacity (kWdc or kWac)}} \times \frac{1}{\textbf{8760 (h/yr)}} \qquad (1)$$

The Nameplate capacity of the system depends on the modelled technology. One of the feature using same is it to convert the units to an appropriated value such as (MW, kW, or W) before using in their calculations. A DC power rating is used for photovoltaic model and for other AC power rating is used.
Capacity is to be defined as the optimal power generation of the power plant usually measured in kW, MW or GW rating. Which is also rated the efficiency of that plant is actually the capacity factor.

b. Performance ratio calculation

Industrialist uses a different method for the calculation of performance ratio. SAM method proposed by NREL of USA [5]. Performance ratio calculated by SAM as follows

$$P.R = \frac{\text{Annual Energy (kWh)}}{(\text{Input Radiation (kWh)} \times \text{Module Efficiency (\%)})} \quad (2)$$

Annual energy is the system total net AC electrical o/p per year, whereas the i/p radiation is the total solar energy incident on the array after seeding and soiling for the year. Module Efficiency is the module nameplate conversion efficiency.

3. DATA COLLECTION

3.1 Viability of 20 MW solar PV plants in Pakistan

Pakistan country has huge potential of solar PV. As the cost of solar PV decreasing worldwide. Now there is chance for thirds world countries to take benefit from it and enhance the quality of life. Here below is energy assessment of PV of different cities of Pakistan Using system advisor model.

Table 2. 20MW solar PV system in different cities of Pakistan

City	Solar Radiation (kWh/m2/Day)	Annual Energy (GWh)	Capacity factor (%)	Performance Ratio	E yield (kWh/kW)
Swat	5.18	33	18.8	0.79	1651
Peshawar	5.16	31	17.7	0.75	1547
Islamabad	4.02	30.7	17.5	0.76	1534
Lahore	4.68	29.5	16.8	0.74	1475
Faisalabad	5.03	30	17.1	0.74	1501
Bahawalpur	5.13	32.3	18.4	0.75	1614
Jacobabad	5.17	32.9	18.8	0.74	1648
Gilgit	4.57	33.8	19.3	0.84	1694
Karachi	5.34	35.5	20.3	0.76	1777
Quetta	5.46	38.2	21.8	0.78	1912
Sibi	5.23	34.6	19.8	0.75	1731

3.2 20 MW PV plant at Bahawalpur

20 megawatt AC solar PV system analysed by system advisor model located at Bahawalpur, Punjab Pakistan. System is analysed for crystalline Si and CdTe thin film solar cells. Parameter of analysis are annual energy production, capacity factor and performance ratio.

3.2.1 Energy production by c-Si

For analysis mono-c-Si (Sun Power SPR-E1910-COM) module is used. Capacity of each module is 310.1 DC Watts. Total energy produced by c-Si in year is 32,459,000 kWh.

3.2.2 Energy production by thin film

For thin film CdTe solar cell were used. Capacity of each module is 117 dcW. Total energy produced per year is 33,041,000 kWh.

Modules	
SunPower SPR-E19-310-COM	
Cell material	Mono-c-Si
Module area	1.6 m²
Module capacity	310.1 DC Watts
Quantity	64,476
Total capacity	20 DC MW
Total area	105,160 m²
Inverters	
SMA America: SC750CP-US 342V	
Unit capacity	770 AC kW
Input voltage	545 - 820 VDC DC V
Quantity	24
Total capacity	18.5 AC MW
DC to AC Capacity Ratio	1.08
AC losses (%)	1.0
Array	
Strings	5,373
Modules per string	12
String voltage (DC V)	656.4
Tilt (deg from horizontal)	30.0
Azimuth (deg E of N)	180
Tracking	no
Backtracking	-
Self shading	no
Rotation limit (deg)	-
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.4
Performance Adjustments	
Availability/Curtailment	none
Degradation	0.5 %/yr
Hourly or custom losses	none
Annual Results (in Year 1)	
GHI kW/m²/day	5.4
POA kW/m²/day	5.0
Net to inverter	33,387,000 DC kWh
Net to grid	32,469,000 AC kWh
Capacity factor	18.54
Performance ratio	0.75

Fig. 2. Performance of 20MW solar PV base on c-Si

Modules	
First Solar FS-4117A-2	
Cell material	CdTe
Module area	0.7 m²
Module capacity	117.5 DC Watts
Quantity	170,235
Total capacity	20 DC MW
Total area	122,569 m²
Inverters	
SMA America: SC750CP-US 342V	
Unit capacity	770 AC kW
Input voltage	545 - 820 VDC DC V
Quantity	24
Total capacity	18.5 AC MW
DC to AC Capacity Ratio	1.08
AC losses (%)	1.0
Array	
Strings	18,915
Modules per string	9
String voltage (DC V)	640.8
Tilt (deg from horizontal)	30.0
Azimuth (deg E of N)	180
Tracking	no
Backtracking	-
Self shading	no
Rotation limit (deg)	-
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.4
Performance Adjustments	
Availability/Curtailment	none
Degradation	0.5 %/yr
Hourly or custom losses	none
Annual Results (in Year 1)	
GHI kW/m²/day	5.4
POA kW/m²/day	5.0
Net to inverter	33,975,000 DC kWh
Net to grid	33,041,000 AC kWh
Capacity factor	18.86
Performance ratio	0.76

Fig. 3. Performance of 20MW solar PV base on CdTe

4. DISCUSSION

System advisor model to used analysed the performance of utility scale PV system for the different location in Pakistan. Assessment is on the base of solar radiation data used for different location. In Table.2 performance of solar power in different cities of Pakistan. In most cities, energy yield is greater than 1500 kWh per kW of nameplate capacity. Performance ratio is greater than 0.75 and capacity factor is also good above 18%.At the base of above two parameters, solar PV is suitable in most cities. But the problem of land for utility-scale production. So in Table.2 on the base of C.F, P.R, and cheap & vast land availability south-west area of Pakistan like Quetta, Sibi, Jacobabad and Bahawalpur are much suitable for the utility-scale production of electricity..

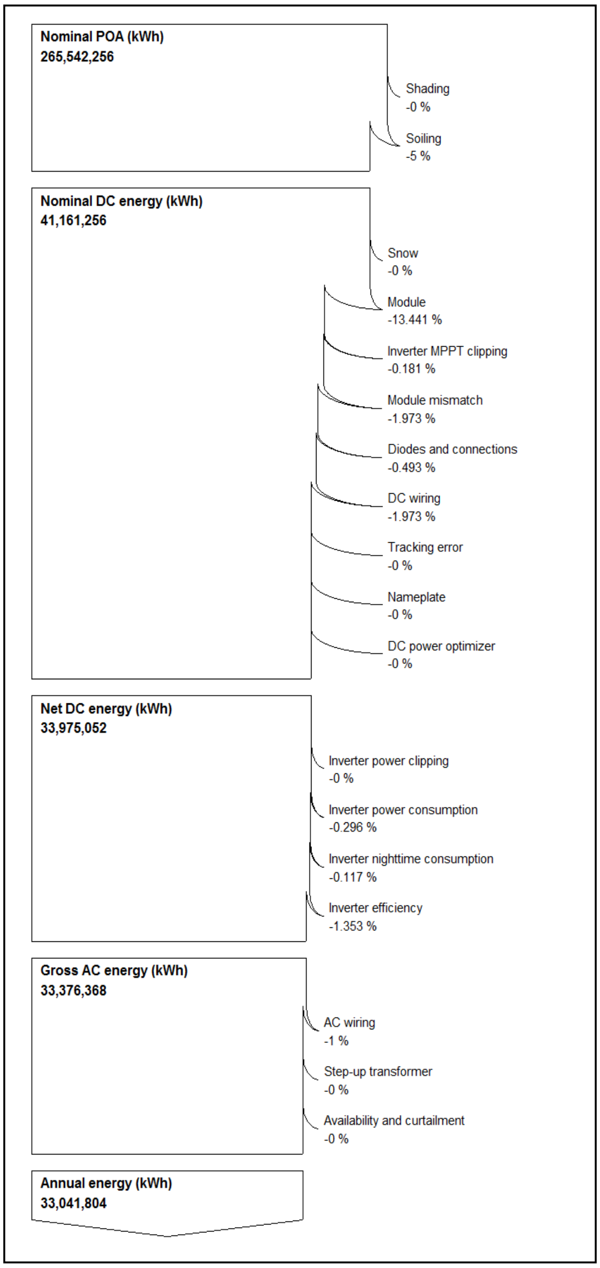

Fig. 2. Loss diagram of CdTe system

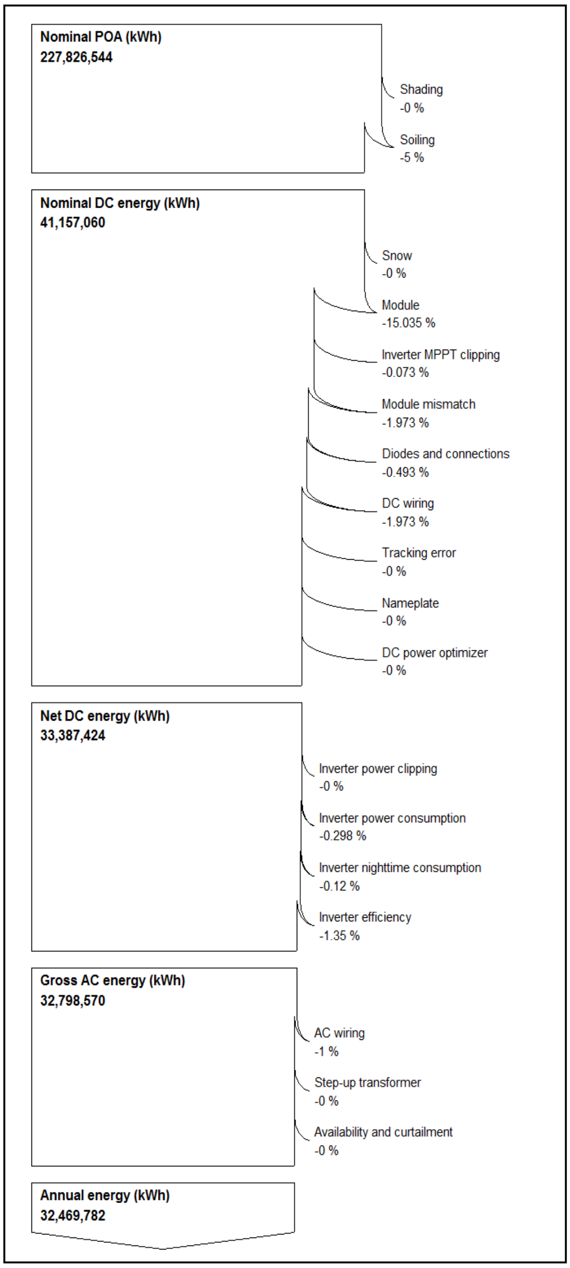

Fig. 3. Loss diagram of c-Si system

In the comparison of mono-crystalline silicon solar cell and Cadmium telluride, the thin film is based on their energy out. It already is proven that efficiency of the thin film is less than crystalline technology but the cost of production make thin film competitive with crystalline technology. Due to different properties of material both technologies have different output power. Fig.2 and Fig.3 show that total energy produced by Mono-c-Si system which fed to the grid is 32,469,000 kWhac and the CdTe system is 33,041,000 kWhac. A CdTe system producing more energy as they both have same input radiation and nameplate capacity is due CdTe is more resistant against high temperature. It produces 10% more power as the temperature of module rising up to 60oC or above.

Loss diagrams Fig.4 and Fig.5 tells the story of losses in both solar PV technologies. In both PV systems are same except the module loss in mono-c-Si is 15% and 13.4% for CdTe base PV system. This module loss makes difference in the final energy output of the both system Losses

5. CONCLUSION

Utility-scale Solar PV system analyzed for ten different cities of Pakistan with various locations and different climate using the NREL System Advisor Model (SAM) software. Performance comparison of crystalline silicon with the thin film solar cell for utility scale power production in Bahawalpur area also done by using the SAM. Results show that Quetta is the most suitable city for utility-scale PV power production with capacity factor 21.8% and performance ratio is 0.78. Simulation result also suggests another city like Bahawalpur, Jacobabad, and Sibi also the good and exploitable potential for utility-scale PV system.
In the comparison of crystalline silicon with Cadmium telluride (CdTe), thin film result shows that annual energy produced by the thin film is greater than energy produced by crystalline silicon (Mo-c-Si). Annual energy produced by CdTe thin film is 33,04,000 kWh and by Mo-c-Si is 32,469,000 kWh. Capacity factor and performance ratio of CdTe and Mo-c-Si are 18.86% & 18.54% and .76 &.75 respectively.
The result also reveals that Pakistan is a tremendous amount of solar PV potential for Megawatt installation. Thin film solar PV is more feasible as compared to costly crystalline silicon technology..

References

[1] Lewis, Nathan S., and George Crabtree. "Basic research needs for solar energy utilization: report of the basic energy sciences workshop on solar energy utilization, April 18-21, 2005." (2005).

[2] Doman, L. E. A., Vipin. Metelitsa, Alexander. Leahy, Michael. ; *International Energy Outlook 2011*, Administration, U. S. E. I., Ed.; Government Prinitng Office: Washington, 2011

[3] Bagnall, Darren M., and Matt Boreland. "Photovoltaic technologies." *Energy Policy* 36, no. 12 (2008): 4390-4396.

[4] Xu, Jun, Chun-Yan Luan, Yong-Bing Tang, Xue Chen, Juan Antnio Zapien, Wen-Jun Zhang, Hoi-Lun Kwong, Xiang-Min Meng, Shuit-Tong Lee, and Chun-Sing Lee. "Low-temperature synthesis of CuInSe2 nanotube array on conducting glass substrates for solar cell application." *ACS nano* 4, no. 10 (2010): 6064-6070

[5] Bagher, Askari Mohammad, Mirzaei Mahmoud Abadi Vahid, and Mirhabibi Mohsen. "Types of Solar Cells and Application." *American Journal of Optics and Photonics* 3, no. 5 (2015): 94-113.

[6] Peng, Jinqing, Lin Lu, and Hongxing Yang. "Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems." *Renewable and Sustainable Energy Reviews* 19 (2013): 255-274.

[7] de Wild-Scholten, MJ Mariska. "Energy payback time and carbon footprint of commercial photovoltaic systems." *Solar Energy Materials and Solar Cells*119 (2013): 296-305.

[8] Fthenakis, Vasilis, and Hyung Chul Kim. "Life-cycle uses of water in US electricity generation." *Renewable and Sustainable Energy Reviews* 14, no. 7 (2010): 2039-2048.

[9] Green, Martin A., Keith Emery, Yoshihiro Hishikawa, Wilhelm Warta, and Ewan D. Dunlop. "Solar cell efficiency tables (Version 45)." *Progress in photovoltaics: research and applications* 23, no. 1 (2015): 1-9.

[10] Peng, Jinqing, Lin Lu, and Hongxing Yang. "Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems." *Renewable and Sustainable Energy Reviews* 19 (2013): 255-274.