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Environmental Impact Analysis of Solar Power Generation Process Using Multicrystalline and Amorphous Silicon Solar Cells in Thailand

Wasin Khaenson*, Somchai Maneewan*[1] and Chantana Punlek*

Abstract – *This paper presents the results of the environmental impact assessment into two different technologies for the production of solar power in Thailand. It considers mass and energy flows over the whole power generation process and compares two types of silicon solar cell; multicrystalline and amorphous. The process operations that make up the system are the solar cell array, inverter stations, transformer stations, a control center and substations. This study also examines the economic feasibility of such power stations, by analyzing their investment costs and the internal rate of return (IRR). After analyzing the results, 1 kWh of solar power generation was found to have an impact upon both human health and ecosystem quality, whilst resource depletion was unaffected. When the overall impact was compared against the non-renewable power generating technologies of natural gas, combined cycle and coal-fired power stations, solar energy was found to have an appreciably lower environmental impact, with the multicrystalline plant having the lowest impact of all. However, the economic analysis revealed that, despite their low environmental cost, under the present market conditions both solar power technologies are not financially viable.*

Keywords – Amorphous silicon, life cycle assessment, multicrystalline silicon, solar cell power plant.

1. INTRODUCTION

Solar energy is the conversion of sunlight into electricity. It is also among the cleanest and most abundant energy sources available. The process uses photovoltaic cells (PV) to convert light into an electric current using the photovoltaic effect [1]. A solar cell, or photovoltaic cell (PV), is a device constructed from materials which exhibit the photovoltaic effect - a unique property where electrons are released at the atomic level when exposed to photons of light. These newly freed electrons can be collected by creating a positive/negative imbalance within the cell, resulting in an electric current and thus electricity. When a number of these cells are connected together, they form a photovoltaic module which can produce electricity at a certain direct current voltage. Since the current generated is directly dependent upon the amount of light hitting the module, they are generally wired together in giant arrays in order to maximize the electricity produced [2]. There are various different designs of solar cells, differing in the type of materials used to construct the semi-conductor (the part of the cell which undergoes the photovoltaic effect). Crystalline silicon (c-Si) is by far the most common choice, and is used in almost 90% of photovoltaic cells today [3], [4]. However, a growing market is that of thin film solar cells, which includes amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS) [5].

Thailand's solar energy can potentially be generated in significant quantities because of the country's tropical location. In the first quarter of 2017 (January to March), the final renewable energy consumption was 2,895 ktoe, an increase of 4.4% on the same time the previous year. Heat energy consumption accounted for the greatest share, 1,798 ktoe of the total final renewable energy consumption, followed by electricity, and biofuels (ethanol and biodiesels) which measured 661 ktoe, and 436 ktoe, respectively. Of this final renewable energy, solar energy accounted for 98 ktoe or 686.33 MW of the power generated, an increase of 18.07% from the previous year. This has resulted in both a decrease in energy imports (amounting to 1,257.34 million baht), and also a decrease in CO_2 emission (amounting to 0.3 million tons) [6]. Although all forms of solar energy can potentially decrease CO_2 emission, the other environmental impacts can vary depending on the technology used to construct the photovoltaic module.

The task of this paper is to carry out a comparative study of the main environmental impacts of power generated from solar energy, at each stage of the process. The environmental impact is measured using life cycle assessment (LCA). This is a technique that evaluates the environmental impact of each stage of a product's life, from cradle to grave, thus enabling a quantitative estimation of its environmental impact at every stage of its life cycle [7]. The LCA provides a comprehensive view of the various environmental aspects of the product or process, thus creating a more accurate picture of the environmental trade-offs in product and process selection, and ensuring a more accurate decision making process [8], [9]. The four stages of the LCA are: (1) Goal and scope definition, (2) Life cycle inventory (LCI), (3) Life cycle impact assessment (LCIA), and (4) Interpretation [10]-[12]. Finally, in addition to the environmental aspects, economic analysis has been undertaken to ascertain the financial viability of constructing and operated solar power plants under current market conditions.

*Department of Physics, Faculty of Science, Naresuan University, Phitsanulok, 65000, Thailand.

[1]Corresponding author;
Tel: +665 596 3552.
E-mail: somchaim@nu.ac.th.

2. EXPERIMENTAL SET UP

2.1 Goal and Scope Definition

This study assessed the environmental impact and economic viability of the solar power generating process resultant from the two leading types of solar cell module in Thailand, using the life cycle assessment. Two solar cell power plants were studied as shown in Figure 1; one plant in northern Thailand using multicrystalline silicon solar cells, generating 90 MW, and one in central Thailand using thin film amorphous silicon cells, generating 55 MW. Both plants were the largest in their respective regions. The most important specifications are given in Table 1. The electricity generated was sold to the Electricity Generating Authority of Thailand (EGAT) and Provincial Electricity Authority (PEA).

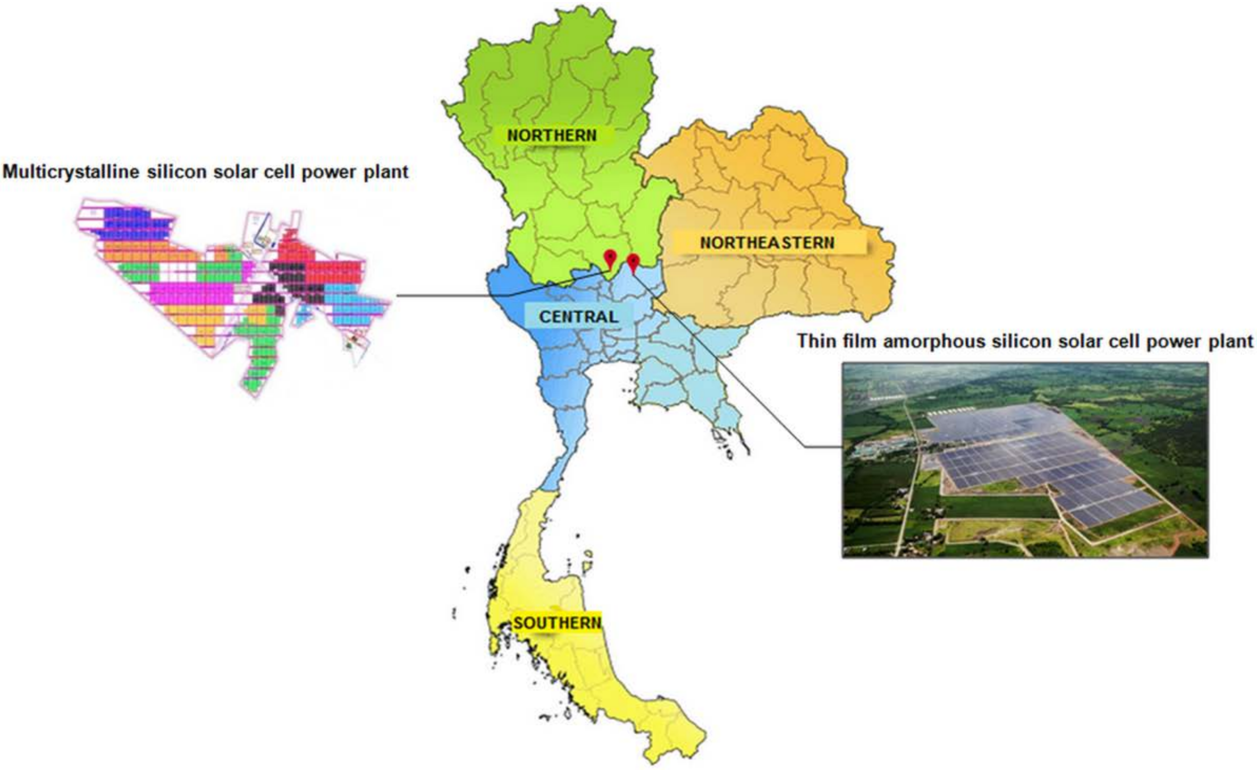

Fig. 1. Site of solar cell power plants studied.

2.2 Functional Unit

The functional unit used for this study was 1 kWh of power generated by the solar cell power plant. The environmental impact results were calculated in terms of Pt per functional unit of 1 kWh.

2.3 Allocation

This study focused solely on the solar power generation process. Other stages, such as the manufacture or recycling of the solar cell modules were not taken into account.

2.4 System Boundaries

The process of solar power generation was subdivided into five system boundaries; the solar cell array, inverter stations, transformer stations, a control center and substations [13]-[15]. The process studied is shown in Figures 2 and 3. Details of the five subsystems are provided as follows:

- Solar cell array: This process consisted of solar cell modules which were wired together to form an array. Erecting the arrays required significant amounts of land. They converted the solar energy directly into electricity utilizing the photovoltaic effect.
- Inverter stations: Inverters changed the direct current (DC) from the solar cell array process into alternating current (AC).
- Transformer stations: Transformers were used to increase or decrease the voltages of alternating current to the appropriate level.
- Control center: The control center monitored and controlled all processes for generating electricity, from the solar cell array through to the substations.
- Substations: Substations connected and switched the electricity lines, and changed the voltage using transformers.

Table 1. Specifications of solar cell power plants studied.

Description	Northern solar cell power plant					Central solar cell power plant		
General								
The average annual power generated	139,446 MWh					109,054 MWh		
Total power consumption	762 MWh					565 MWh		
Total water consumption	20,043 m^3					5,729 m^3		
Power plant area	296 hectares					192 hectares		
The average annual solar radiation	5.18 $kWh/m^2/day$					5.55 $kWh/m^2/day$		
Solar module								
Cell type	multi-Si	multi-Si	multi-Si	multi-Si		a-Si	a-Si	
Maximum power (Pmax)	245 W	250 W	245 W	250 W		128 W	135 W	
Open-circuit voltage (Voc)	37.1 V	37.2 V	37.3 V	37.4 V		59.8 V	61.3 V	
Short-circuit current (Isc)	8.63 A	8.69 A	8.73 A	8.83 A		3.45 A	3.41 A	
Maximum power voltage (Vmp)	37.1 V	30.3 V	29.9 V	30.1 V		45.4 V	47 V	
Maximum power current (Imp)	8.63 A	8.27 A	8.19 A	8.31 A		2.82 A	2.88 A	
Expected lifetime	25 years	25 years	25 years	25 years		25 years	25 years	
Installed number	157,300	98,098	57,200	196,196		456,750	108,864	
Inverter								
Rated output power	500 kW					250 kW		
Rated output voltage	340 Vac					440 Vac		
Rated output current	860 Arms					328 Arms		
Rated input voltage (DC)	586 Vdc					600 Vdc		
Efficiency	≥98%					≥95%		
Installed number	180					220		
Transformer								
Rated voltage (kV)	22	22	22	22	22	22	22	115
Rated power (kVA)	50	100	160	250	1,250	1,250	2,500	50,000
Rated frequency (Hz)	50	50	50	50	50	50	50	50
Installed number	3	6	1	1	90	1	27	2

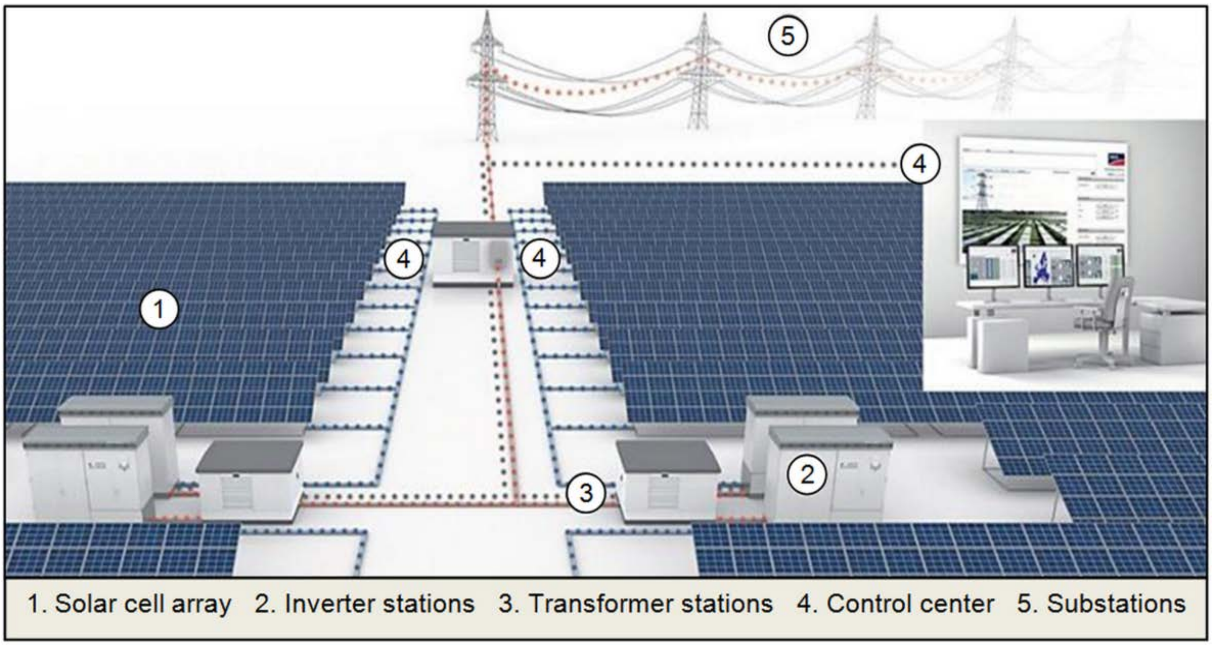

Fig. 2. The system boundary of power generation from solar energy.

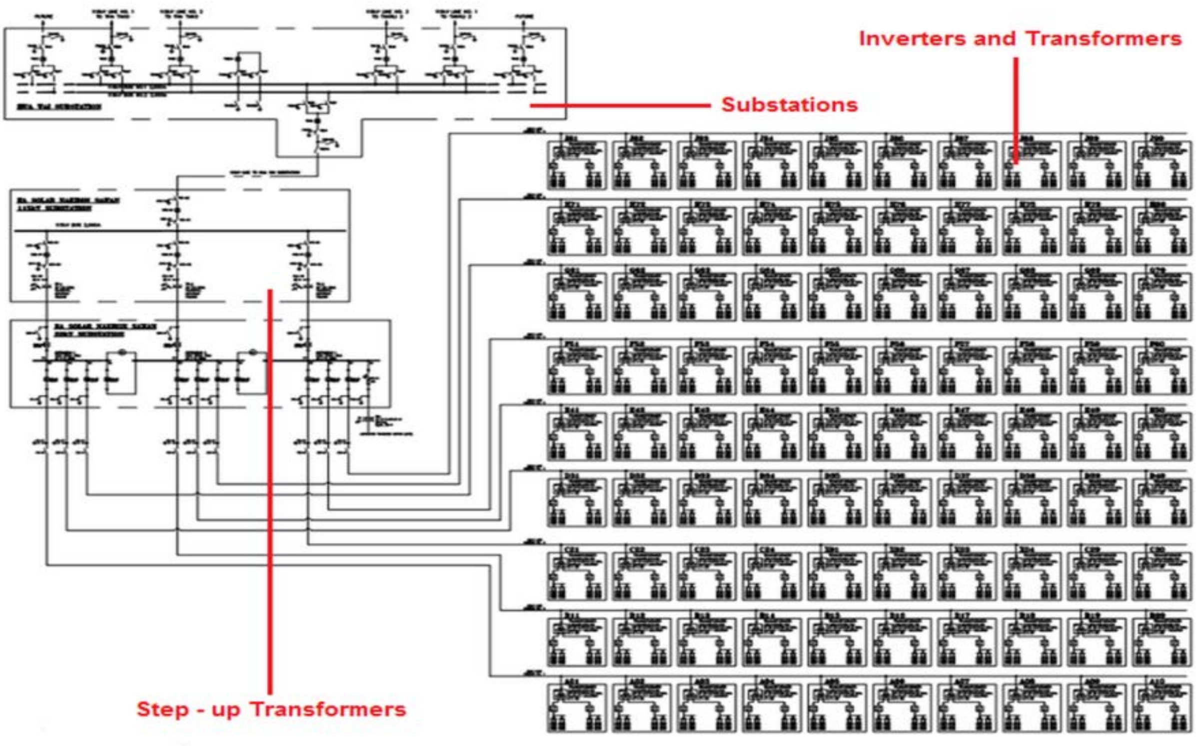

Fig. 3. Electrical single line diagram.

2.5 Life Cycle Impact Assessment (LCIA)

The Eco-indicator 99 (H, A) end-of-point impact assessment method was also used in the analysis. The impact categories examined were human health, ecosystem quality and resource depletion [16], [17].

Human health comprised of studies on the carcinogenic impact, the respiration of both organic and inorganic substances, radiation, climate change and ozone depletion. The impact on human health was measured in disability adjusted life years (DALYs) [18]. The study of ecosystem quality comprised of acidification and eutrophication, ecotoxicity and land use. The damage to ecosystem quality was measured in terms of PDF*m^2*yr. Lastly, resource depletion measured the depletion of mineral and fossil fuels. Damage was measured in terms of MJ surplus energy, and represented the surplus energy needed for future extractions of mineral and fossil fuels [19].

The three damage categories had different units so they were made to use a set of dimensionless weighting factors. The final result was measured in terms of eco-points (Pt) [20].

3. RESULT AND DISCUSSION

3.1 Life Cycle Inventory (LCI)

Life cycle inventory was used to analyze the data input and output from the various processes. At each stage of the power generation process, input and output data was obtained from solar cell power plant surveys (system studies, material measurement and accounting). Tables 2 and 3 list the data used in the analysis of 1 kWh of power generated from solar energy. It should be noted that at the solar cell array stage, the two power plants had notably different results. This is because the multicrystalline plant required an electrical input, and this resulted in the emission of nitrogen, oxygen, water vapor, nitric oxide, nitrogen dioxide and NO_x. None of these gases were produced in the amorphous silicon plant because amorphous cells require no such electrical input. In both power plants, water consumption was used for cleaning the solar cell array and utilities in the control center. The power plant sites were flat areas which would otherwise have been used for growing field sugar cane, rice and eucalyptus.

3.2 Environmental Impact Assessment of the Life Cycle Steps

The characterized results for 1 kWh of power generation was found to have a negative impact upon: the respiration of organic and inorganic substances, climate change, acidification and eutrophication, and land use (see Table 4).

Each impact category was measured by different units so all data had to be calculated into a single environmental impact function - the eco-point (Pt). After aggregation, land use was found to be the main impact category, due to the vast amount of arable land used to construct the power plant and erect the arrays. The land use of the multicrystalline plant measured 1.48E-02 m^2 to generate 1 kWh of power, whilst the thin film amorphous plant used 1.67E-02 m^2. This was followed, to a much lesser extent, by climate change, the respiration of inorganic substances, acidification and eutrophication, and the respiration of organic substances, respectively (see Figure 4). Of the various processes the solar cell array had by far the largest impact on land use (see Figure 5).

Of the impact categories studied, the power generation processes impacted upon human health and ecosystem quality, while no processes were found to be detrimental to resource depletion. Ecosystem quality was by far the most significant impact category, being about forty five times greater than that of human health. In the multicrystalline plant, ecosystem quality measured 9.77E-04 Pt, of which 9.76E-04 Pt was land use. Conversely, human health was calculated at only 1.60E-05 Pt. In the amorphous solar cell plant, ecosystem quality measured 1.10E-03 Pt, of which 1.09E-03 Pt can be accounted for by land use. Human health was only 4.00E-05 Pt (see Figure 6).

In terms of the overall environmental impact of the power generating process, the use of thin film amorphous silicon solar cells had a higher impact than that of multicrystalline silicon solar cells, which measured 1.14E-03 Pt and 9.93E-04 Pt, respectively. This was ostensibly due to the differing types of solar cell used and the lower conversion efficiency of the thin film amorphous cells [21]. Individual thin film amorphous cells can not generate a significant amount of electricity [22]. Most of them operate at around 7-13% efficiency, meaning that they require up to four times the amount of space that multicyrstalline solar cells would require. They also degrade faster than multicrystalline based cells and thus have a shorter life expectancy. Hence, multicrystalline silicon solar cells are by far the most common choice, and are used in almost 90% of solar cell power plants today [3], [4]. It should be noted however, that thin film amorphous cells are a growing market and technology is advancing at a significant pace [5]. It is possible that in the upcoming decades, amorphous cells may be able to compete with their multicrystalline counterparts in terms of both efficiency and longevity.

Table 2. Input and output associated per kWh power generated from multicrystalline silicon solar cell power plant.

Description	Unit	Solar cell array	Inverter stations	Transformer stations	Control center	Substations
Input						
Solar energy	kWh	4.87E+00	0	0	0	0
Electricity	kWh	2.00E-04	10.7E-04	7.10E-04	9.50E-04	9.20E-04
Water	cm^3	7.31E+01	0	0	2.79E+01	0
Arable land	m^2	1.48E-02	1.61E-05	8.06E-06	4.03E-05	4.84E-05
Output						
Carbon Dioxide	kg	1.66E-04	7.74E-04	5.17E-04	6.96E-04	6.66E-04
Methane	kg	0.68E-05	3.10E-05	2.07E-05	2.79E-05	2.66E-05
Nitrogen	kg	0.17E-02	0.89E-02	0.60E-02	0.80E-02	0.77E-02
Oxygen	kg	0.30E-03	1.61E-03	1.07E-03	1.43E-03	1.38E-03
Water Vapor	kg	0.11E-03	0.61E-03	0.41E-03	0.54E-03	0.53E-03
Nitric Oxide	kg	0.20E-07	1.08E-07	0.72E-07	0.96E-07	0.93E-07
Nitrogen Dioxide	kg	0.16E-08	0.87E-08	0.58E-08	0.77E-08	0.75E-08
NO_x	kg	0.33E-07	1.74E-07	1.16E-07	1.55E-07	1.50E-07

Table 3. Input and output associated per kWh electricity generated from amorphous silicon solar cell power plant.

Description	Unit	Solar cell array	Inverter stations	Transformer stations	Control center	Substations
Input						
Solar energy	kWh	9.46E+00	0	0	0	0
Electricity	kWh	0	1.67E-03	1.14E-03	0.83E-03	1.32E-03
Water	cm^3	4.74E+01	0	0	2.88E+00	0
Arable land	m^2	1.67E-02	2.81E-05	1.41E-05	4.21E-05	5.61E-05
Output						
Carbon Dioxide	kg	0.16E-04	12.1E-04	8.29E-04	6.06E-04	9.56E-04
Methane	kg	0.06E-05	4.84E-05	3.31E-05	2.43E-05	3.82E-05
Nitrogen	kg	0	1.40E-02	0.96E-02	0.70E-02	1.10E-02
Oxygen	kg	0	2.52E-03	1.72E-03	1.26E-03	1.99E-03
Water Vapor	kg	0	0.96E-03	0.65E-03	0.48E-03	0.75E-03
Nitric Oxide	kg	0	1.69E-07	1.16E-07	0.84E-07	1.33E-07
Nitrogen Dioxide	kg	0	0.14E-07	0.09E-07	0.07E-07	0.11E-07
NO_x	kg	0	2.72E-07	1.86E-07	1.36E-07	2.15E-07

Table 4. Characterised results for 1 kWh of power generation from solar energy.

Category Impact	Unit	Total	Solar cell array	Inverter Stations	Transformer Stations	Control Center	Substations
Multicrystalline silicon solar cell power plant							
Carcinogenic	DALYs	0	0	0	0	0	0
Resp. of organic substances	DALYs	1.46E-12	9.00E-14	4.00E-13	2.70E-13	3.60E-13	3.40E-13
Resp. of inorganic substances	DALYs	1.12E-10	5.81E-12	3.10E-11	2.07E-11	2.76E-11	2.67E-11
Radiation	DALYs	0	0	0	0	0	0
Climate change	DALYs	1.09E-09	6.48E-11	2.99E-10	2.00E-10	2.69E-10	2.57E-10
Ozone depletion	DALYs	0	0	0	0	0	0
Acidification / Eutrophication	PDF*m^2*yr	7.19E-06	3.73E-07	1.99E-06	1.33E-06	1.77E-06	1.72E-06
Ecotoxicity	PDF*m^2*yr	0	0	0	0	0	0
Land use	PDF*m^2*yr	1.25E-02	1.24E-02	1.35E-05	6.77E-06	3.39E-05	4.07E-05
Mineral	MJ surplus	0	0	0	0	0	0
Fossil fuel	MJ surplus	0	0	0	0	0	0
Amorphous silicon solar cell power plant							
Carcinogenic	DALYs	0	0	0	0	0	0
Resp. of organic substances	DALYs	1.85E-12	1.00E-14	6.20E-13	4.20E-13	3.10E-13	4.90E-13
Resp. of inorganic substances	DALYs	1.44E-10	0	4.85E-11	3.32E-11	2.42E-11	3.83E-11
Radiation	DALYs	0	0	0	0	0	0
Climate change	DALYs	1.40E-09	6.00E-12	4.67E-10	3.20E-10	2.34E-10	3.69E-10
Ozone depletion	DALYs	0	0	0	0	0	0
Acidification / Eutrophication	PDF*m^2*yr	9.27E-06	0	3.12E-06	2.13E-06	1.56E-06	2.46E-06
Ecotoxicity	PDF*m^2*yr	0	0	0	0	0	0
Land use	PDF*m^2*yr	1.41E-02	1.40E-02	2.36E-05	1.18E-05	3.54E-05	4.71E-05
Mineral	MJ surplus	0	0	0	0	0	0
Fossil fuel	MJ surplus	0	0	0	0	0	0

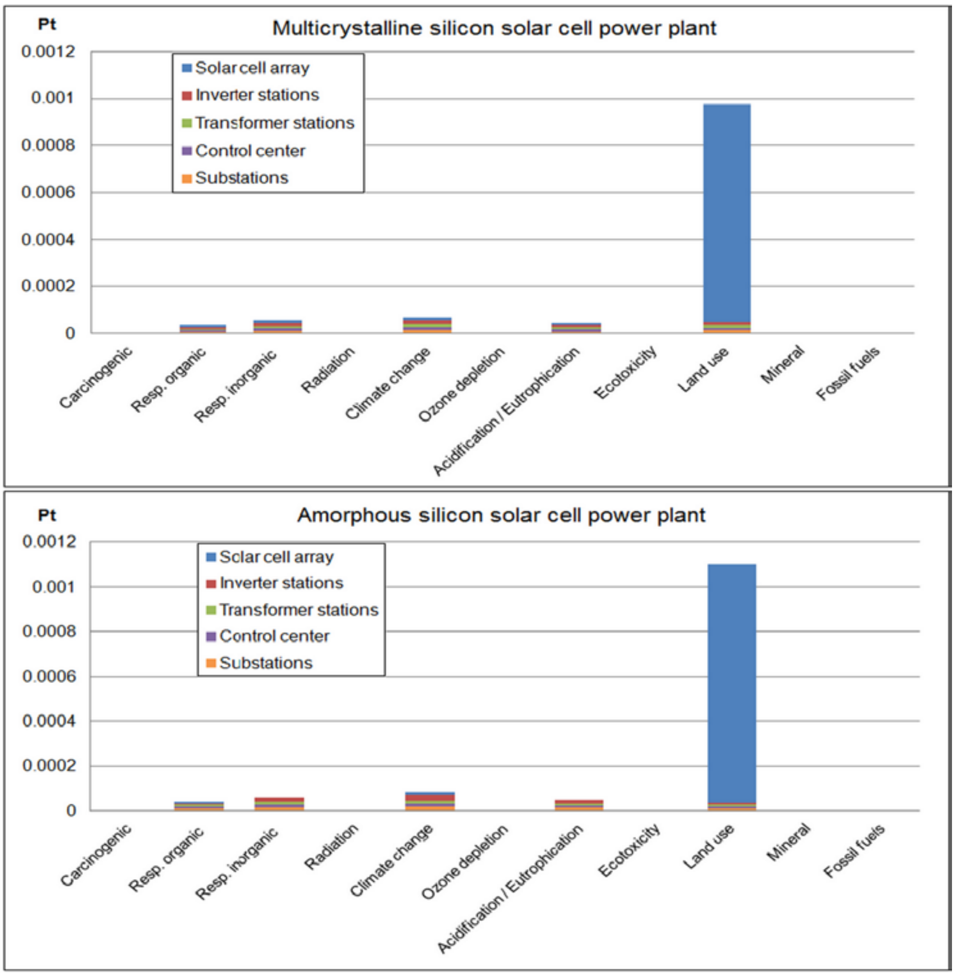

Fig. 4. Weighted environmental impacts of solar cell power plant.

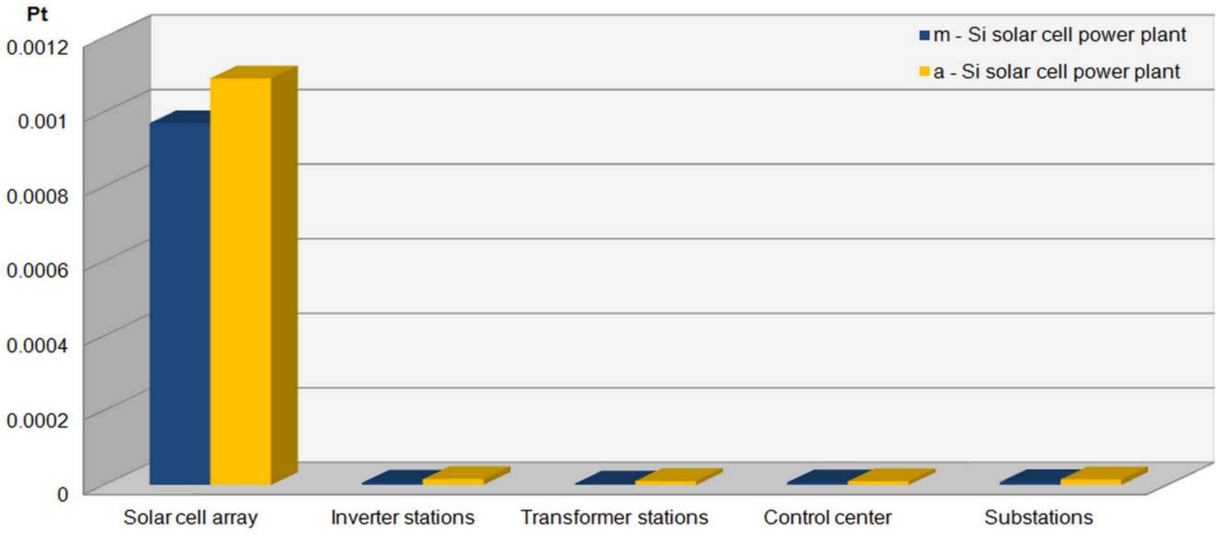

Fig. 5. Environmental impact of solar power generation processes.

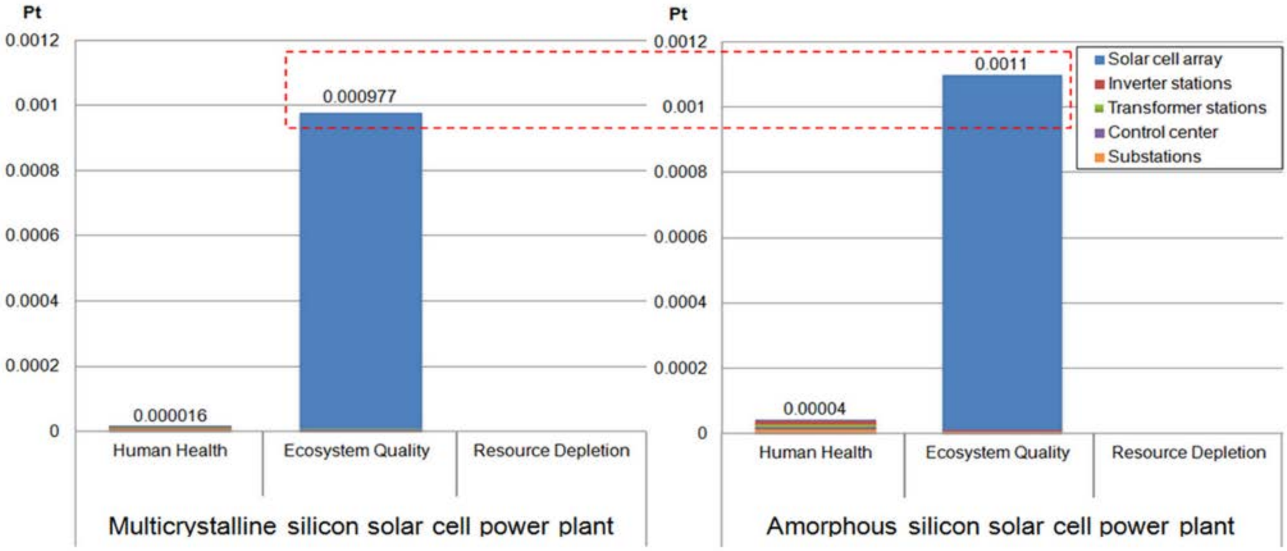

Fig. 6. End-of-point impact categories of solar power generation processes.

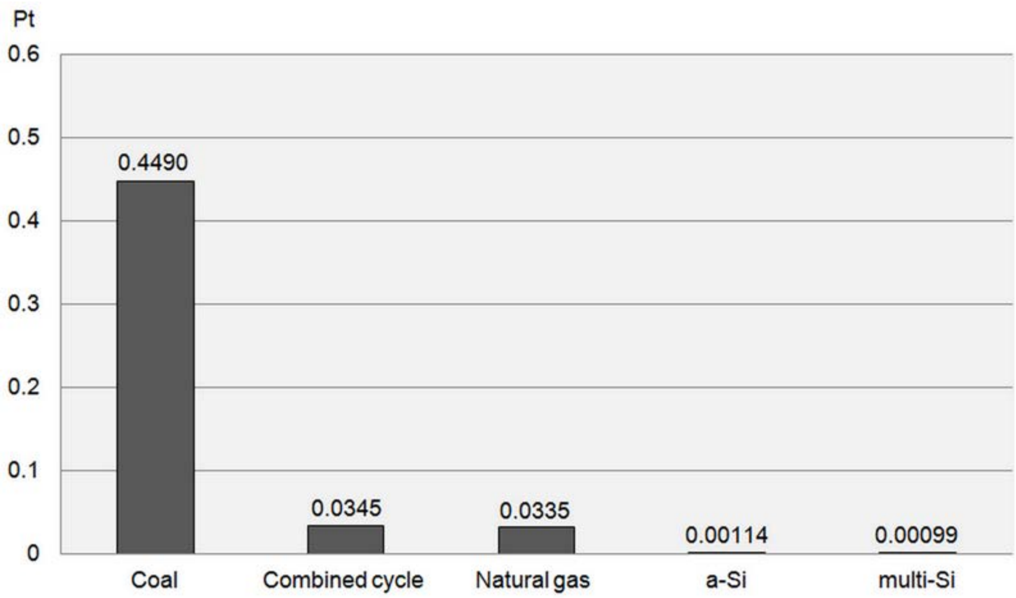

Fig. 7. Total environmental impact comparison of the various power plants in Thailand.

3.3 Total Environmental Impact Comparison with Various Technologies in Thailand

In order to get a true picture of the environmental impact of solar power, it must be compared with rival technologies and their environmental impact under identical conditions. Currently Thailand generates 65% of its total electricity from natural gas, whilst a further 19% comes from coal. Thus, the same set of characterisation factors were used to assess the impact of natural gas, coal-fired and combined cycle power plants for the generation of 1 kWh of electricity. All power plants were owned and operated by the Electrical Generating Authority of Thailand (EGAT).

The natural gas power plant studied was the largest and most modern of its kind in Thailand. Its total electricity generation capacity was 3,680 MW, serving 25 % of the country's electricity demand, and emitted CO2 and NOx [23]. The combined cycle power plant studied generated 2,100 MW, using both natural gas and fuel oil, the fuel oil contributing about 30% of the total energy. The power generating process resulted in emissions of CO, CO2, SO2, NOx, N2O and CH4 [24]. Finally, the coal-fired power plant was a 2,400 MW generating lignite fueled plant, the largest coal-fired plant in the country. The coal combustion process resulted in 'fly ash', fine particles containing very high concentrations of the most toxic elements, and the major cause of the environmental impact [25], [26].

As can be seen from Figure 7, the total environmental impact of both solar plants was significantly lower than that of the fossil fuel burning plants. The latter's reliance on fuel combustion had a very high impact upon resource depletion, in particular the extraction of fossil fuels. This lead to it being the main end-point impact category for both natural gas and combined cycle plants. However, in the case of coal, the impact was greatly exacerbated by carcinogenic heavy metal emissions, which dramatically increased the overall impact, with the main impact category being human health.

3.4 Economic Analysis

In addition to assessing the environmental impact, economic analysis was undertaken in order to ascertain whether investment in solar power generation represented a worthwhile use of resources in the current market. The economic analysis was based on parameters that are standard in the market, and considered the specific characteristics of the solar power plant type. The objective was to compare the economic or financial attractiveness of both power plants. The indicators used for economic analysis come under two categories: investment analysis, and benchmark analysis. The investment analysis included the unit cost of electricity generation in Bath/MW, the levelized cost of electricity (LCOE) in Bath/kWh, the payback period and, lastly, the benefit cost ratio. Benchmark analysis calculated the internal rate of return (IRR) of the plants, and compared them against an industry standardized benchmark to determine their financial viability when compared with alternatives in the current market.

3.4.1 Investment Analysis

The unit cost of electricity generation is the average total cost of producing one unit of output. The unit cost was calculated by dividing the total investment cost by the total installed capacity. The result is the cost per unit of output in baht/MW. The acceptable applied value range of the unit cost was calculated to be between 80-120 million baht/MW [27]. The total investment cost of the multicrystalline plant (including land and land preparation costs, substation cost, operation and maintenance costs, and agreement costs for technical advisors) was 9.491 billion baht, while the total installed capacity was 90 MW. This meant that the unit cost of electricity generation was approximately 105.46 million baht/MW, which was within the applied value range. Whilst investment costs around a third lower for the thin film amorphous plant (6.738 billion baht), lower efficiency meant that its total capacity was, at 55 MW, almost half and resulted in a higher unit cost of electricity generation of approximately 122.50 million baht/MW, which was higher than the applied value range.

The levelized cost of electricity (LCOE), typically expressed on a baht/kWh basis, is the estimated amount of money that it takes for a particular electricity generating plant to produce a kWh of electricity over its expected lifetime. LCOE offers several advantages as a cost metric, such as its ability to normalize costs into a consistent format across decades and technology types. The appropriate range of LCOE for solar energy is 1.63-3.87 baht/kWh [28]. LCOE in the multicrystalline plant was 2.73 baht/kWh over the course of its expected 25 year lifetime, whilst LCOE in the amorphous plant was 2.46 baht/kWh. Therefore, the LCOE's of both power plants were deemed to be within the appropriate range.

The payback period is the length of time required to recover the cost of an investment. The payback period is an important determinant as to whether the investment is undertaken, since the longer the payback period becomes, typically the less attractive the investment. The payback period is calculated by dividing the total investment cost by annual revenue. The payback period was 7 years for the multicrystalline plant, slightly longer than that of the amorphous power plant, at 6.5 years. Given that both plants had an estimated lifespan of 25 years, this represented an attractive investment opportunity.

The benefit cost ratio (BCR) is an indicator that attempts to summarize the overall value for money of a project or proposal. It is the ratio of the benefits cost of a project relative to its investment cost, the general rule being that if the benefit is higher than the investment cost, the project is a good investment. The BCR of the multicrystalline and amorphous plants were calculated at 3.56 and 3.80, respectively, which means for both plants the benefit cost was higher than that of the investment cost, and hence, they represented a good investment.

To summarize, investment analysis shows that, according to all indicators, the investment cost of the multicrystalline and the thin film amorphous solar cell power plants can be considered a sound investment, although the unit cost of the amorphous plant was found to be higher than the range. The investment cost of the multicrystalline plant was more attractive than that of the amorphous plant due to the relative inefficiency of the thin film solar cells and their lower energy output when compared to multicrystalline solar cells. It should be noted however, that the amorphous power plant in this study is the first of its kind to be built in Thailand and no other plant exists of a similar scale as described above. It is therefore a relatively new technology, and as with most new technologies, is likely to experience significant improvements in efficiency throughout the upcoming years.

3.4.2 Benchmark Analysis

Whilst investment analysis can determine whether a project represents a sound investment or not, it is only one factor in determining whether funds will be invested. Given a finite amount of capital with which to invest, investors must be concerned not only with whether their investment will be recouped, but with the rate of returns on said investment. That is to say, with a fixed amount of capital investors are unlikely to invest in solar power if it merely recoups their investment when other sections of the industry, for example natural gas, might double or triple it. Thus the financial attractiveness of solar power must be calculated and compared to the industry as a whole.

One way of doing this is by calculating the internal rate of return (IRR), which is a rate of return used in capital budgeting to measure and compare the profitability of investments [29]. It is the percentage rate earned on each baht invested for each period that it is invested (for example, one year). This is then compared against a benchmark figure for the industry as a whole, in order to ascertain whether the investment represents a profitable rate of return when compared to other investment opportunities. The benchmark is calculated using the weighted average cost of capital (WACC), this being the average of the minimum rate of return a company must earn (after tax) in order to satisfy its shareholders and creditors [30]. The benchmark is based on parameters that are standard in the market, such as the typical debt/equity finance structure in the Thai energy sector. If the default value of 50% debt and 50% equity financing is used, then the WACC is found to be around 13.05%. This was adopted as the benchmark [31]-[33].

The internal rate of return of the multicrystalline and thin film amorphous silicon power plants when calculated were both found to be lower than that of the benchmark, at 10.26% and 9.28%, respectively. Therefore it can be concluded that, although sound in terms of investment costs, investment in solar power plants do not represent a financially attractive option when compared to other sections of the industry in Thailand, in the current market.

4. CONCLUSIONS

This study has determined that the process of generating power from solar energy, calculated using the functional unit of 1 kWh, had an environmental impact on human health and ecosystem quality, while no stage of the process was found to affect resource depletion.

The main end-of-point impact category was that of ecosystem quality, due to the large area needed upon which to construct the solar cell array. This was most significant in the case of the central plant, where the lower conversion efficiency of the thin film amorphous solar cells required a greater area of land to be covered.

Therefore it can be concluded that, overall, the process of generating solar power from thin film amorphous solar cells was found to have a higher, and therefore more detrimental impact upon the environment when compared to that of multicrystalline silicon solar cells (for 1 kWh of power generation).

When compared to other sections of the industry, in terms of environmental impact, solar cell technology had the lowest impact when compared to natural gas, combined cycle and coal-fired power generation. All non-renewable technologies were found to significantly impact resource depletion, due to the extraction of fossil fuels, causing it to be the main end-of-point impact category for natural gas and combined cycle power. In the case of coal, the environmental impact was exacerbated by the carcinogenic effects of heavy metal emissions, causing human health to be the main impact category.

However, whilst solar power proved the superior technology in terms of the environment, it was unable to compete financially. Economic analysis revealed that, despite representing a sound investment opportunity, solar power plants failed to provide enough of a financial return to make them economically viable when compared to other forms of power generation in the industry. In the current market, despite representing one of the cleanest forms of electrical power generation, solar power of all types is unlikely to receive investment from private investors who will continue to favor the traditional and more environmentally damaging alternatives unless something is done to improve solar's financial viability.

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