Green and Emission Free Manufacturing: Application of Grid Connected Solar Photovoltaic Technologies in Food Manufacturing Plant

Joy Dassgupta, Zeinab Hajiabolhasani, and Romeo Marian
University of South Australia, Adelaide, Australia
Email: {dasjy002.author, Zeinab.Hajiabolhasani, Romeo.Marian}@unisa.edu.edu

***Abstract*—In Singapore, food manufacturing plants currently receive electricity from the national grid supply where the power generation is mainly based on fossil fuels. Singapore lacks land mass, and thus there are limited possible sources of renewable energy for the generation of electricity. Solar energy therefore, might be a buoyant source for the fulfilment of the country's energy requirements in the manufacturing sector. Moreover, solar energy technologies are environmentally friendly. This paper describes a feasibility study for the application of grid connected solar photovoltaic technologies in a food manufacturing plant. The study may help to discover opportunities for using solar energy to fulfil the electrical energy needs in food manufacturing facilities while contributing to an emission free environment.**

***Index Terms*—solar photovoltaic (SPV) technology, solar irradiation, solar energy, food manufacturing facilities**

I. Introduction

Singapore is a country that is highly dependent on imported oil and gas to meet the nation's energy need. For the past two decades, the increasing concern about global warming due to emissions of greenhouse gases from combustion of fossil fuels has been putting pressure on many governments across the globe to alter energy politics and strategies. In order to adapt a more self-sufficient energy mix with renewable energy resources and a more sustainable energy system, Singapore is investing in research on different methods to generate sustainable energy solutions. However, the potential for using possible renewable energy options are limited; since Singapore is a small physical size (715.8km^2), and resource-constrained country, with high population density (~5.47 million).

Currently, the main source of electricity generation in Singapore is fossil fuels where the electricity is supplied to customers through the grid. Also, food manufacturing facilities -an industrial sector that is growing everyday- receive electricity from the grid. Since the number of food manufacturing industries in Singapore is growing, the demand of electricity is increasing accordingly. To meet the increased demand, it is essential to generate more electrical power. In the absence of a change in operations, this would ultimately increase fossil fuel usage. Greater consumption of fossil fuels has negative impacts on economic feasibility and environment sustainability.

A number of approaches have already been introduced to tackle this increased electricity demand without affecting the environment [1]-[3]. Among them, renewable energy exploitation (e.g. solar energy, geothermal energy, and tidal energy) is one of the most economical and environmentally friendly approaches for generating electricity.

Due to lack of major river systems in Singapore, hydroelectric power cannot be harnessed. Wind speeds, on the other hand, are too low owing to insufficient land footprints. Moreover, geothermal energy prospects are meagre. Hence, calm seas with limited tidal ranges are not suitable for commercial tidal power generation. To this end, another irregular resource of energy that is significantly better adapted in tropical weather conditions and therefore could become widely used in Singapore is solar energy.

Yet, there are some obstacles that prevent using solar energy in Singapore e.g. insufficient availability of lands for the large scale deployment of solar panels or the presence of high cloud cover across Singapore and urban shading which causes intermittency. However, solar energy is still one of the green alternatives that can be utilized, and implemented under such circumstances.

Geographically, Singapore is well sited for solar radiations throughout the year. Photovoltaic technologies can be utilized to convert the solar radiations into electricity [4], [5]. Therefore, it is very important to understand the technical, economical, and environmental impacts for the application of solar photovoltaic technologies in the manufacturing sector.

II. Photovoltaic Technology

Photovoltaics, in short "PV", is a method through which solar energy transformed into direct electrical currency using devices called solar panels. Each panel composed of smaller units namely solar cells to supply widely distributed renewable energy source – the sun (Fig. 1).

Sunlight can be considered as a flux of particles called photons, whereas an electric current is a flux of electrons.

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In fact, solar cells convert the energy of a photon flux into electric energy, whereby each incoming photon with adequate energy leads to an energetically excited electron that can deliver energy to an external load. A solar PV system is powered by many crystalline or thin film PV modules. Individual PV cells are interconnected to form a PV module. PV cells are made of light-sensitive semiconductor materials that use photons to dislodge electrons to drive an electric current. To this end, more detailed specification of PV system will be discussed in the following section.

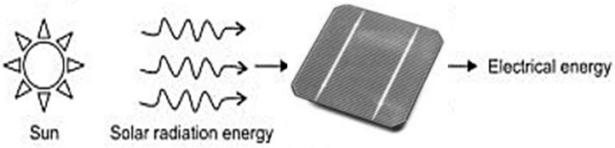

Figure 1. A schematic fundamental block diagram of a PV system [6]

In this paper, it is aimed to provide a feasibility analysis of the application of SPV technologies in industrial sectors. Our goal is to explore the effectiveness of possible cost saving alternatives, as well as to build up emission free environment using renewable energy resource – the solar energy. Finally, it will implicate to make sustainable development of the Singapore's urban environment by the numerable reduction of carbon emission.

III. Methodology

The feasibility study was carried out in a food manufacturing plant, including five sub-plants$_{i=1:5}$ located in *Jurong*, Singapore. Based on the acquired information from these plants, a methodology with two main sections, *data collection*, and *implementation* respectively, is developed. Firstly, in the data collection phase, the amount of energy required in the manufacturing plant is determined. Secondly, the technical feasibility analysis, economical feasibility assessment, and environmental impact of using SPV technologies are done in the implementation phase. Finally, the results and findings are summarized

A. Data Collection

In a food manufacturing plant, electrical energy is utilized to power the function of a variety of electrical devices such as lights, air conditioning, air handling units, heating and cooling equipment, food processing machines, other office equipment etc. In this plant, the yearly average usage of electrical energy in sub plants$_{1:5}$, from office accessories, canteen and others is measured around %30 of the total consumption which is 470,288.97 kilowatt-hour (kWh). Hence, the daily usage of electricity is about 1288.46kWh that is currently supplied by *Tuas Power Supply Pte. Ltd*. Fig. 2. displays the average distribution of total electrical energy consumption at each sub-plant. In suplant$_1$ For instance, 52% of electricity is consumed in machineries section at maximum level, whereas approximately 4% of electricity usage is associated with office accessories and other activities.

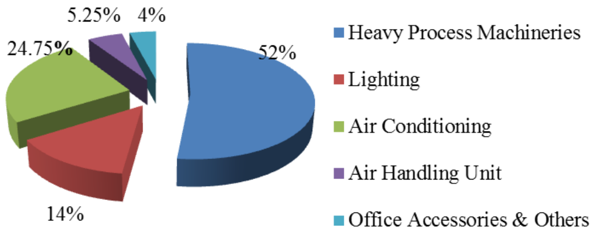

Figure 2. Electrical consumption distribution matrix for sup-plant$_1$

B. Implementation

This section provides the detailed calculation for solar photovoltaic systems design; combined with feasibility assessment and detailed environmental impact.

Singapore is located at 1.3 degrees north of the equator, thus a horizontal mounting system is the best suited for the solar PV panel installation [6]. The amount of electricity generated depends on the intensity and the duration for which sunlight is available at a given location and the conversion efficiency of the solar PV system. The intensity of incident sunlight, i.e. solar irradiation, is expressed in terms of kW per unit area (kW/m^2). Irradiation fluctuates throughout the day and exhibits seasonal trends. This is referred to as solar insolation, which is expressed in kWh/m^2. Insolation may be more conveniently expressed as peak sun hours. This refers to the number of hours that the sun shines at its maximum intensity at a particular location. Located near the equator, Singapore is regarded as a favorable site for solar installations.

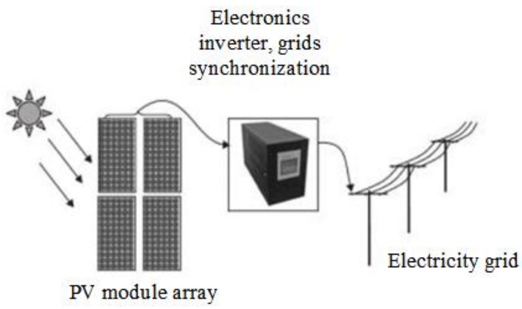

Figure 3. PV system connected with electricity grid [6]

Also, in Singapore, supplying electricity from the grid is reliable. So, the grid connected PV system is the best selection which further reduces the necessities of using large battery bank. Grid-connected PV systems are designed to function in parallel and interconnected with the electric utility grid [7]. A schematic block diagram of a PV system is shown in Fig. 3. As it can be seen, the primary element in grid-connected PV systems is the inverter, or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand.

In order to analyse a grid connected solar PV system, it is required to know some basic information. These are but not limited to plant's yearly electricity consumption (U_y), annual average of solar irradiation (SI_{ave}), and power rating of PV panel (P_{pv}). The customised information regarding to this case study is summarized in Table I.

TABLE I. GRID CONNECTED SOLAR PV SYSTEM SPECIFICATIONS

U_y [kWp]	SI_{ave} [kWh/m^2]	P_{pv} [kWp]
470,288.97	4.56 peak sun hours/day	0.3

Design of a grid connected solar PV system can be achieved through the following six steps. For simplicity, all notations used in this study are illustrated in Table II.

TABLE II. NOTATION

Total load connected to solar PV system	L_{pv}
Number of inverter	N_I
Each Solar panel actual output Wh	O_s
Available inverter (*Solectria*)	P_I
Power rating of PV panel	P_{pv}
System rating	S_r
Annual average of solar irradiation	SI_{ave}
Solar panel watts	SP_w
Total number of solar panels	T_s
Total electrical energy consumption per day	U_d
Electricity usage per year in the plant	U_y

1) Load calculation

Through conducting a simple calculation, given yearly electricity consumption in Table III, and considering the cost per kWh energy of 0.29 (SGD), the total amount of consumed energy in the manufacturing plant, and its corresponding cost is computed. Therefore, the total electrical load per day (U_d), is derived 1288.460 [kWh/day].

TABLE III. YEARLY ENERGY CONSUMPTION IN MANUFACTURING PLANT

Month	Energy Consumption (kWh)	Cost (SGD)
Jan	124352	36062.05
Feb	126766	36762.27
Mar	123352	35771.96
Apr	139366	40416.17
May	129477	37548.35
Jun	133149	38613.19
Jul	141867	41141.44
Aug	139763	40531.38
Sep	129504	37556.02
Oct	134189	38914.67
Nov	117462	34064.02
Dec	128383	37231.13
Total	**1567630**	**454612.7**

2) Solar PV panel watts based on irradiation calculation

Each solar panel watts under ideal condition is computed through (1) that is summarized in Table IV.

$$SP_w = P_{pv} \times SI_{ave} \tag{1}$$

TABLE IV. TOTAL SOLAR PV PANEL WATT [KWH]

P_{pv} [kWp]	SI_{ave} [kWh/m^2]	SP_w [kWh]
0.3	4.560	1.368

3) Inefficiency compensation

Like in any system components, there might be some inefficiency in each part of solar power system. To overcome this potential problem and determine the actual output from the PV module, an operating factor α is used. This factor differs between 60%-90% depending upon temperature, dust on panel etc. Assuming the total system inefficiency (α) is about 30%, the system efficiency including energy losses due to panel temperature is 0.7 (70%) [8], [9]. Thus, the energy that each panel will actually deliver on an average (O_s) is estimated 0.9576kWh (1.368×0.7).

4) Number of solar PV panels

One of the most critical decisions in constructing a solar panel array is which panel to choose. This can be decided through credential list associated with each solar panel. It includes several important factors such as energy production, cost-per-watt, and panel size. Herein, investigation on these three parameters is undertaken. As it is shown in Table V, the total number of solar panels (T_S) is calculated through equation (2). Consequently, system rating (S_r) is obtained 4kWp (1346×0.3).

$$T_S = \frac{U_d}{O_s} \tag{2}$$

TABLE V. TOTAL NUMBER OF SOLAR PANELS

U_d [kWh]	O_s [kWh]	T_s
1288.460	0.9576	1346

5) Inverter size calculation

Having U_y, then total load connected to the solar PV system would be 53.69kW. To this end, the total number of inverters is 27 which can be computed through (3).

$$N_I = \frac{S_r}{P_I} \tag{3}$$

where P_I is the available inverter (*Solectria*) with the rating of 15kw.

It should be noted that, the main advantage of using smaller inverters is to match the power output of the PV array more precisely. Moreover, having smaller inverters is beneficial to split the array system into several smaller, independent parts. This method avoids a total shutdown of the array system in case of a single inverter failing.

6) Required area for installation

The roof area of *manufacturing* plant is 2983m^2. It is mostly a flat area consisting of three inclined flat sections that would potentially be used for the solar panel array. All the way these are clear of obstructions and free of any shading. The slight inclination (about 30°) of the roof is orientated to north, ideal for the installation of a PV system. Also, there is internal access to the main portion of the roof, which makes inspections, repairs and mist removal easier. This would also facilitate in monitoring the solar panels.

The total area needed for installing these panels can be calculated by multiplying the dimension of each panel with the total number of panels (Table VI). Since the available roof area in this plant is 2983m^2; hence, PV system installation is technically feasible. In fact, with the available roof area 93 extra PV cell can be installed. Even though, it will slightly increase the fixed costs but it worth it because over the time it will be paid off.

TABLE VI. THE TOTAL REQUIRED AREA

T_s	Panels Dimension [L × W] m^2	Total Area m^2
1346	1.955 × 0.991	2607.76

7) Economic context

An accurate economic model depends not only on accurate formulas, but on various parameters that can be estimated with high level certainty, backed by historical figures or measurements. The costs estimation and payback period calculations are shown in Table VII. It should be noted that *depreciation period* particularly has been excluded from calculation. As it is demonstrated, the first three sections, *System Size and Cost*, *Installation and Other Fees*, and *System Life and Maintenance* are required to determine the solar panels cost/watt, inverters and other equipment costs, installation fees, and maintenance cost. The initial system cost is the total cost of each of the components such as solar panels, inverters, installation, and maintenance.

TABLE VII. COST AND PAYBACK PERIOD

Section 1: System Size and Cost		
Desired system size	403.8	kW
Cost per watt	1.400	SGD
Solar components cost	565320.00	SGD
Inverters	233820.00	SGD
Other equipment	126500.00	SGD
Section 2: Installation and Other fees		
Installation cost per watt	0.68	SGD
Total installation and fees	250850.00	SGD
Other Fees	85000.00	SGD
Section 3: System Life and Maintenance		
System life expectancy	25	years
Yearly maintenance cost	-	SGD
Inverter warranty extension cost	4%	
Maintenance cost adjustor	2%	
Total initial system cost	1261490.00	SGD
Section 4: Energy Usage		
Yearly energy consumption	470288.97	kWh
Cost of electricity	0.29	SGD/kWh
Yearly electrical energy cost	136383.8	SGD
Section 5: Payback Period		
Payback period = Total initial investment / Annual savings	9.25~10	years

The typical warranty on solar panels is twenty-five years. Since there is no moving part in a solar panel, maintenance costs are found to be extremely minimal. Due to the fact that the lifetime warranties of solar panels are generally twenty years or more, it is unlikely that any maintenance costs will be realized within this time period. The standard lifetime of a *Solectria* inverter is usually five years. However, optional warranty extensions are possible to ten, fifteen or twenty years for inverters based on overall system life. Therefore, both the inverter warranty extension and necessary replacement costs are estimated to be less than 4% and to only occur after a long period of time and throughout the whole system life. The maintenance costs of an array will generally reside in labor, not replacement parts. Thus, maintenance costs for solar systems are estimated at costing approximately 2% of the initial system cost.

The current electricity cost based on recent electricity rates in Singapore is 0.29 *SGD*/kWh which is calculated in section four. Finally, the possible *Payback Period* over the initial investment and its annual savings is described in Section 5. Accordingly, electricity generation is from renewable energy source (solar) so that the total energy cost is calculated as yearly savings, which help to attain a ten years (approximately) payback period.

IV. FEASIBILITY ASSESSMENT

Payback period calculations are significant when conducting economic feasibility studies, because return on investment takes place over time. From the previous section's payback calculation, it was estimated that the payback period is approximately ten years whereas life cycle of the system is twenty-five years. Therefore, it is possible that the initial investment returns within the first ten years. Consequently, the remaining fifteen years are expected to return a profit over its warranty period in terms of electricity cost. Based on the payback period calculation, a graphical representation of the total cash flow versus years is depicted in Fig. 4. From this analysis, it is clearly concluded that the project with this investment will be economically feasible.

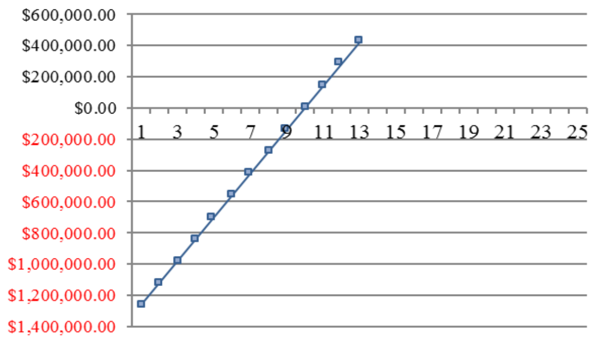

Figure 4. Cash flow

V. ENVIRONMENTAL IMPACT

The significance of solar panel systems goes far beyond financial factors. A carbon trail is a measurement of the impact that a person or a building has on the environment. It is usually represented as the number of tons of carbon dioxide released into the atmosphere. Examples include but are not limited to power plants, cars, and burning heating oil. Finding solutions to the increased emissions problem is critical to environmental sustainability. However, offsetting the world's carbon emissions by planting trees isn't an efficient way out to the problem of increased emissions. A better solution is reducing the emissions themselves.

Reduction of emissions requires cutting back the use of fossil fuels. This means driving less, using cars that are more efficient, and meeting high standards for emissions testing. It also means using less electricity, and when possible looking for 'green' alternatives. As a result, the solar PV system is one of the green alternatives which can positively impact on the environment to reduce emission. Singapore's Grid Emission Factors (GEF) based on the 'Simple Operating Margin' (OM) method, stood at 0.5146kg CO_2/kWh in 2011 [10], [11]. This factor measures the amount of CO_2 produced for the same net generated electricity. 1kWh electricity generation, for instance, produces 0.5146kg of CO_2 which results in 470.289kWh electricity generation per year. Therefore, 242,010.7kg CO_2 will be produced accordingly. Thus, the CO_2 emission reduces per year by 242,010.7kg. Hence, it is possible to reduce the emission of CO_2 yearly while burning fossil fuels for generating electricity. Moreover, it was highlighted how this solar PV system is environmentally friendly.

VI. Results and Conclusion

The results of this feasibility study that summarized in Table VIII, shows that this grid connected PV system for this manufacturing plant is technically, economically and environmentally feasible. This feasibility study for the application of grid connected solar PV technologies in a food manufacturing plant has shown a wide impact in only nine years and three months payback period (approximately). It provides a plan for saving a large proportion of energy costs whilst offering the prosperity of an emission free environment for the future.

TABLE VIII. Result Summary

Type	Result
Technical Feasibility	Feasible
Economical Feasibility	Feasible
Environmental Benefit	Beneficial
End Result	Suggested

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Joy Dassgupta is currently a postgraduate student of School of Engineering at University of South Australia (UniSA). He completed his GradCertEng (TM) from UniSA in 2014. Before this, he received his B.E. (EEE) from IUBAT, Bangladesh in 2010. Along with the academic credentials, he also worked as an Electrical Engineering professional for multiple industries in different countries for around 5 years. His research interests are Solar PV Technology, Smart Grid, Energy Efficiency and Optimization.

Zeinab Hajiabolhasani was born in Tehran, Iran, in 1984. She received the B.E. degree in Software engineering in 2008 and M.Sc. in Mechatronics engineering ranked 1st, from Azad University, Tehran, Iran in 2010. She has joined the University of South Australia (UniSA) in Jan 2011 contributing in some research projects and teaching at school of ITMS and School of Engineering. As a lecturer, Zeinab delivered *Manufacturing Systems Strategies* for Master of Engineering program in Engineering & Technology Management in Kaplan College, Singapore, 2014.

Mrs. Hajiabolhasani is currently undertaking a PhD research project in *Simulation-Optimization of Supply Chain* which is funded by Australian government and UniSA (*Postgraduate Award and Postgraduate Research Award*); School of Engineering. She has published several journals and high prestige conference papers. Her main fields of interests includes in: machine vision systems, optimization and simulation modelling, AI in manufacturing and industrial engineering.

Romeo Marian is Senior Lecturer and Discipline Leader – Mechanical in the School of Engineering, University of South Australia. He has extensive research and development experience in research organizations, industry and academia in areas ranging from MEMS to heavy engineering, from mechanical, thermal (heat exchange and combustion), electrical (high potential electric fields) systems, fluid mechanics, hydraulic drives, to welding. Recent preoccupations and teaching include artificial intelligence, computational mechanics, logistics and quality management and optimization. Dr. Marian has a number of book chapters, patents, journals, and high prestige refereed conference papers.