Department of Mechanical and Aerospace Engineering

Optimisation of a Roof PV System with the Integration of an Energy Storage System: Case Study for a Factory in Malaysia

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A thesis submitted in partial fulfilment for the requirement of degree in

Master of Science in Renewable Energy Systems and The Environment

2023

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Abstract

Malaysia just like the rest of the world is trying to move towards a much greener world. A nice research gap was the opportunity to turn a commercial industrial buildings to utilise renewable energy and the scale of impact onto the national level was looked into.

A case study of a factory was selected, and its potential for roof PV systems was looked into and optimised. Optimising parameters such as pitch, PV module and inverter, GCR, tilt angle, etc enabled the energy generation of the system to increase. However, more optimisation to the entire system was required. Heat pumps, extra rooftop generation and piezoelectric tiles were able to then offset the demand load of the factory.

Due to limited generation hours, an energy storage was introduced. With the CAES system introduced additional energy consumption by the energy storage system components. But there was more than enough energy generated to offset this additional energy consumption values leaving with an approximate value of 30,000MWh/year of energy surplus to power other machines not discussed in this paper but preferably sold back to the grid as this would bring in profit to the company.

In order to ease the calculations for the CAES system, isothermal equations were used which are 'ideal' equations as they cannot be achieved realistically since machines and technologies all have efficiencies and other external factors affecting their performance from being at a perfect 100%.

From there, a simple NPV against project life assessment was made to see the economic feasibility of this proposed plan. Using isothermal ideal gas law equations and the NPV graph, it was safe to say that this proposed plan was feasible in terms of energy self-sufficiency and economically.

Acknowledgements

Throughout my experience in the University of Strathclyde, I could not have asked for anyone better than the group of lecturers and supervisors that were present and constantly guiding me all the way through this Masters engineering degree. I received plenty of support and useful feedback from all of them to achieve the best of my abilities. The knowledge and experience gained throughout this entire academic year will be cherished forever.

I would like to personally thank my supervisor, Dr William Dempster, for his continuous support and feedback. His willingness to share his knowledge and guide me whenever possible allowed me to complete this dissertation. With his guidance, I have furthered my knowledge in the topics covered leading to the completion of this dissertation. I appreciate all the time and effort he has put into helping and guiding me throughout this whole project.

I would also like to thank Jabil for sharing the information needed for this dissertation to be complete. I really appreciate all the help I received from them.

Lastly, I would like to dedicate this work to the most important people in my life, my family. I would like to thank my parents and uncle for their unwavering support throughout this whole year. There were ups and downs throughout this journey and without their love and support, I do not know if I would have been able to complete this paper. They continued to believe in me even when I may have doubted my work. I would like to also like to say thank you to my girlfriend, Ananya, who supported me and been so patient with me throughout this entire year. Thank you all so much. I could not have asked for a better family to dedicate this work to.

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Nomenclature

Symbol	Description	Units
CO_2	Carbon Dioxide	NA
GNI	Gross Net Income	$
MBIPV	Malaysia Building Integrated Photovoltaic	NA
IEA-PVPS	International Energy Agency Photovoltaics Power Systems	NA
OECD	Organisation for Economic Cooperation and Development	NA
PV	Solar Photovoltaics	NA
GC	Grid Connected	NA
DSSC	Dye-Sensitised Organic Solar Cells	NA
OPVD	Organic Photovoltaic Devices	NA
QDSSC	Quantum Dot-Sensitised Solar Cell	NA
MPPT	Maximum Power Point Tracking	NA
V_{OC}	Open-Circuit Voltage	V
I_{SC}	Short-Circuit Current	A
FF	Fill Factor	W
AC	Alternating Current	A
DC	Direct Current	A
GCR	Ground Coverage Ratio	%
AC unit	Air Conditioning Unit	NA
ASHP	Air Source Heat Pump	NA

WSHP	Water Source Heat Pump	NA
GSHP	Ground Source Heat Pump	NA
SEF	Sustainable Energy Floor	NA
HEF	Hybrid Energy Floor	NA
PHS	Pumped Hydro Storage	NA
CAES	Compressed Air Energy Storage	NA
FES	Flywheel Energy Storage	NA
SHS	Sensible Heat Storage	NA
LHS	Latent Heat Storage	NA
CHS	Chemical Heat Storage	NA
SCS	Supercapacitor Energy Storage	NA
A-CAES	Adiabatic Compressed Air Energy Storage	NA
I-CAES	Isothermal Compressed Air Energy Storage	NA
D-CAES	Diabatic Compressed Air Energy Storage	NA
RTE	Round Trip Efficiency	%
EG	Expander Generator	NA
STC	Standard Test Conditions	%

1.0 Introduction

Electricity has become one of the most important necessities of today's modern economy. With the increase in the population, more electricity had to be generated to match the new level of demand. Every year the consumption of fossil fuels has increased by 1.4 million barrels of oil [1]. Following this, most of the fossil fuels besides coal are predicted to be depleted by the year 2060 [2]. The terrible effects of using fossil fuels onto the environment as well as the depletion of fossil fuel reserves has shifted the global focus onto using cleaner renewable sources of energy.

Many countries have come together in reaching a common goal of net zero goals such as signing under the Paris Agreement. The Paris Agreement was a global effort to helping the environment with climate change. Under the agreement, all the 195 countries involved signed and pledged to making changes to their policies and economic strategies in order to achieve the common goal [3]. Under the long list of countries is Malaysia, another country striving towards the net zero goals [4].

Malaysia is currently an upper middle income country with its GNI between $4000 - $13000 in 2020 [5]. It is a developing nation which still is heavily reliant on fossil fuels. Strides have been made in the direction of renewable energy mostly in hydropower and biomass but still pale in comparison to the amount of fossil fuels used for power generation. A study done by R. Ali et al., (2012) showed that Malaysia stood at less than 1% of renewable energy mix in its total generation that year and planned to achieve a 5.5% mix by 2015 and subsequently a 11% mix by 2020 [6]. Another study done by Wan Abdullah. Wan Syakira et al., (2019) mentioned that by the year 2019, Malaysia had only managed to achieve a 2% mix from renewables mainly from solar energy [7]. From these studies it is apparent that Malaysia has made some progress into implementing renewable sources for power generation with the addition of solar PVs, but they were still not enough.

Solar and wind energy have been the main renewable sources of energy generation in many countries. Malaysia is a nation made up of 2 regions called the Peninsular Malaysia and East Malaysia which is separated by the South China sea. The Eastern part of Malaysia hosts 2 states called Sabah and Sarawak while the capital, Kuala Lumpur, is located in the Peninsular region of Malaysia. The country as a whole is located in the Southeast part of Asia lying slightly north of the equator line [8], [9]. This gave Malaysia its warm, humid, and tropical weather. Due to its geographical location, Malaysia has a better solar resource rather than wind.

Malaysia approximately has a yearly average of 1643 kWh/m^2 and a daily average of 4.5 kWh/m^2 of solar radiation. According to S.C. Chua et al., (2012), a study was done by the Malaysia Building Integrated Photovoltaic (MBIPV) which showed that Malaysia has the most electricity generation potential globally in terms of PV systems. The study also mentioned that Malaysia had joined the International Energy Agency Photovoltaics Power Systems (IEA-PVPS) in October 2008 and further participated in their Programme Tasks 1, 2, 10, 11 and 13. Under the Programme Task 10, a number of cities from the Organisation for Economic Cooperation and Development (OECD) countries including Malaysia were selected for a study on the opportunities for large-scale PV system implementations in urban areas. The study compared 2 types of PV applications which were the roof type PV system and the façade type PV systems. Standard polycrystalline silicon modules and standard GC inverters were used in the study. The results of the study showed that the cities in Malaysia were able to get annual energy output between (1170 – 1600) kWh for the roof type systems meanwhile the façade type systems were able to produce an output of between (630 – 830) kWh annually. These results were seen to be upper side of the annual energy output spectrum amongst all the other cities investigated [10], [11]. These studies completely support the idea that Malaysia would really benefit from completely utilising as much solar energy as possible.

There are many benefits for the Malaysian people if they were to install these solar PV systems whether for their household or businesses. The current cost of energy in Malaysia is very expensive standing at $0.048/kWh for a household and $0.128/kWh for a business [12]. If the people were to install their own solar PV system, this would enable the household to reduce a significant amount of electricity bought from the grid thus reducing their spending on the electricity bill every month. If any excess energy is generated and the household is self-consumed (the energy generated from the PV system is able to completely offset the energy consumption of the house), the energy could be sold back to the grid for extra money. If more households are self-consumed in such a way, the amount of electricity produced by the fossil fuel plants would be reduced significantly which then would reduce the amount of carbon dioxide being produced daily.

Since Malaysia was producing its power from fossil fuels, the carbon dioxide production was also on a very high level. From 1972 to 2021, Malaysia's CO2 emissions has gone up from 1.3 tons of CO2 per capita to 7.56 tons of CO2 per capita [13]. As the world seems to be moving away from fossil fuels in an attempt to reduce their carbon footprint, Malaysia seem to be moving in the opposite direction in that matter. Although more renewable power is being generated, it is insufficient to offset the increasing generation power from fossil fuels.

In an attempt to drive Malaysia forward towards a greener country, a case study was made. An electrical components manufacturing factory with a PV system installed is being looked into. An optimisation plan was looked at to make the factory self-sufficient with any excess energy sold back to the grid or stored for reuse.

1.1 Aims & Objectives

The aims of this project are:

1. Design an optimised PV system for Jabil factory with validation of design with real time output
2. Design a plan for the factory to be self-sufficient or self-sufficient (the energy generated is able to offset the energy consumption of the factory)
3. Design a plan for an energy storage system to be integrated into the PV system for self-consumption
4. Check for feasibility of the proposed plan economically

The methodology needed to achieve the aims set for this paper are:

1. Investigate the existing PV system set up by Jabil
2. Optimise that PV system to increase the energy generation value by looking into what factors within a PV system can be changed for optimisation
3. Look into other optimisation procedures to optimise the factory itself in terms of increasing the overall energy generation whilst reducing the overall energy consumption of the factory

4. Investigate energy storage technologies required during non-daylight hours to allow the factory to function as usual

5. Size the chosen energy storage system and choose commercially available technologies that could be used for the purpose of this project. Then, integrate this system into the factory's ecosystem

6. Carry out an economic assessment to ensure the proposed plan is feasible economically

If the economic assessment of the project deemed viable, this project would be a futuristic plan for Jabil to become the first commercial self-sufficient factory in Malaysia and would act as a steppingstone and a varied approach for self-consumption for other companies in Malaysia and possibly companies around the world.

2.0 Literature Review

2.1 Solar PV

2.1.1 PV Physics

Solar Photovoltaics (PV) is a technology that converts solar radiation into electricity. It uses the photoelectric effect by which an electron is released when a photon is absorbed into the atom of a semiconductor material. The released electron flows into an external circuit resulting in the increase of current within the circuit. The efficiency of a PV device is dependent on various factors primarily the material used within the PV cell and the construction of the PV device itself. The efficiency of a PV device would be relatively low between (4 to 25)% where the generic efficiency lies about 15%. A lot of research and development has been carried out and still continuing to achieve higher efficiency with lower costs.

To understand how a PV device would work and how the efficiency of the device could be further improved, the physics behind the device has to be understood. The device ideally roots from the photoelectric effect. This is the key concept behind the PV device. The photoelectric effect is described as when the atom of a material absorbs a photon and in return releases an electron. The electron absorbs the energy from the photon and gets knocked out of its stable energy level band. This electron now has higher energy, so it moves to a higher energy level band. [14], [15]. As the electron is released from the atom, it creates a hole that gets left behind. It is also known as an electron-hole pair. This is said to be the foundation to the PV device because it is this released higher energy electron that is made to flow into an external circuit. As current is described as the flow of electrons, an increase in the number of electrons in the flow results in the increase in current of the circuit and as such the PV device generates electricity. However, as the device is based on this physics phenomenon, it comes with a limitation which affects the PV device's efficiency [15].

Following the equation $E = hv$, the energy of the photon is related to its frequency. Due to this, only a fraction of the solar radiation falling upon the solar cell can be used. This leads to the efficiency of the cell to be relatively low. One photon only creates one electron-hole pair so extra photon energy is lost as heat. As mentioned previously, the PV device has limitations which would be that if $v < E/h$, the photons did not enough have enough energy to promote the electron whereas if v > E/h, the extra photon energy is lost as heat. Due to this limitations, only a fixed amount of energy can be converted into electricity.

Normally, the electrons and holes quickly combine back together which would stop the increase in flow of current. To prevent this from occurring, a special material is chosen with specific properties that prevents this combination from occurring. This material choice also affects the efficiency of the PV cell.

2.1.2 PV Cell & Panels

To complete the PV cell with the fundamentals understood, a metal contact is connected to the silicon. This metal is the enabler for the released higher energy electrons to flow around the cell within the external circuit. This can be seen in the figure below.

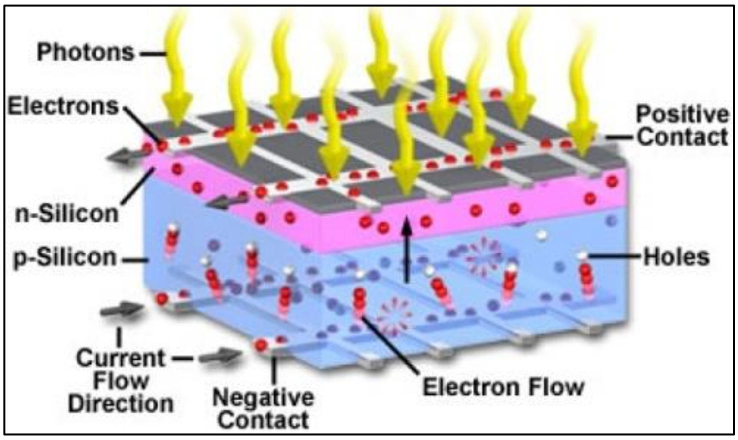


Figure 1 - Electron and current flow in a solar cell [15]

Cells are usually combined together with glass covers, substrate and power circuits which then forms a solar panel or module. A combination of panels forms an array. This can be seen in the figure below.

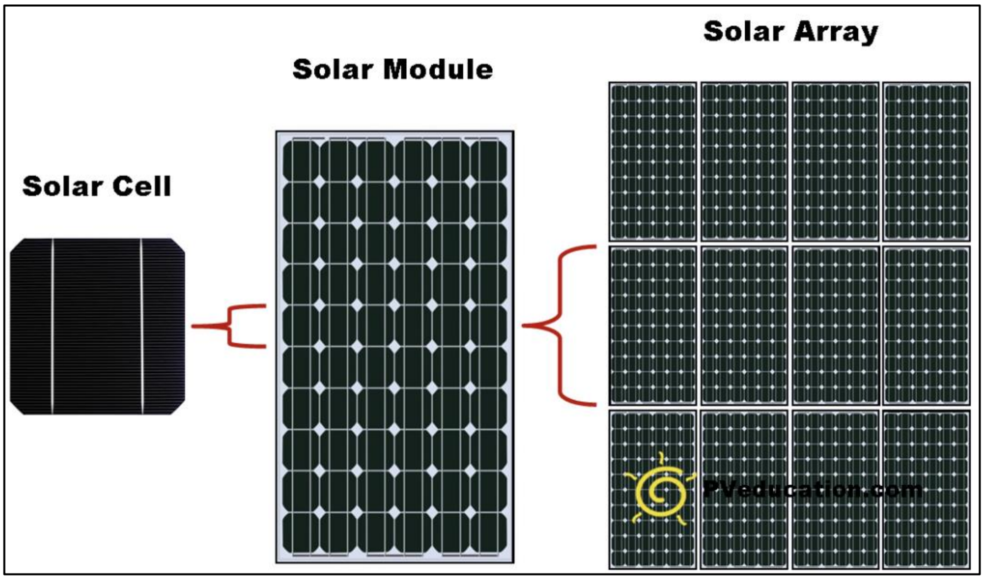


Figure 2 - Solar cell, module/panel, and an array [16]

2.1.3 PV Orientation

To further improve the power generation obtained from the PV panels, the orientation of the panels can be optimised. The tilt angle of the panels to the Sun can be optimised to constantly generate maximum power available throughout the day. This can be done by ensuring the tilt angle constantly changes throughout the day with the position of the Sun. For this, the panel has to move with the position of the Sun as the day progresses. Talebizadeha et al., published a paper on the different tilt angle optimization techniques done by other researchers. Numerous similar mathematical models were used to create the optimum tilt angle with respect to the altitude and locations with one of the previous research showing the optimum tilt angle for Malaysia to be 10° [17].

The are 2 main types of mounting structures for PV panels which are fixed and tracking systems. The fixed mounting structure would have the PV panel fixed at the best tilt angle for that particular location. To optimise the power generation, a tracking system would be implemented. The tracking system would track and follow the position of the Sun throughout the day and adjust the tilt angle of the panel to the intended optimised angle for maximum generation.

Within tracking systems, there are 2 types of systems which are single and double axis tracking systems. The single-axis systems follow the position of the Sun in only one axis which could either be the vertical or horizontal axis depending on the location. The dual-axis systems however can the PV panel in both the vertical and horizontal (azimuth and zenith) axes. This further improves the efficiency of panels. The efficiency of the panels could increase by (30-45)% [18]. Despite the higher efficiency, dual-axis systems are implemented less compared to single-axis systems due to its cost-effectiveness.

2.1.4 PV Material

2.1.4.1 P-N Material

A typical PV cell consist of 2 opposing semiconducting materials. The P-type is the material that has an electron deficit whereas the N-type is the material with an electron surplus. The usual material choice for the PV cell would be silicon. In order to create the P-N silicon semiconductor, the silicon has to be doped with different impurities. This is essential since without the P-N typing within the silicon semiconductor, the current level would not be able to increase. This can be seen in the figure below.

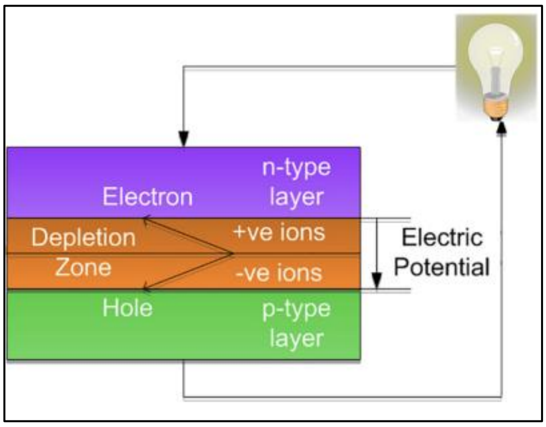


Figure 3 - PV cell with both P-N type layers [19]

Other materials have been used in the construction of PV cells such as Amorphous Silicon (a-Si) , Crystalline Silicon (c-Si), Hybrid cells (fabricated with P3HT Nanostructure Oxide), Cadmium Sulphide (CdS), Cadmium Telluride (CdTe), Organic and Polymer cells. These different materials have been used instead of the conventional Silicon solar PV cells where the efficiencies of the different material solar cells also vary with the materials [19].

2.1.5 PV Technologies

With the different materials that had been introduced from the conventionally silicon solar PV cells, various PV technologies have been introduced with these materials. Each of these different PV cell technologies have different characteristics as well. These technologies have been separated by generations showing the different years at which a different kind of PV technology was developed as the world progressed towards a more renewable society.

The 1st generation PV cells were based on crystalline-silicon or monocrystalline which include both the p and m crystalline solar cells. Monocrystalline silicon is grown from a specific type of crystal. Most of the world's PV cells currently being used are either of this generation's solar cells. Although it has been widely used, the efficiency of these panels in terms of power conversion has been recorded as between (15-20)% [19], [15].

Due to the expensive cost of the 1st generation PV cells, a new type of solar cells was researched and looked into. The 2nd generation PV cells are comprised of the amorphous silicon (a-Si) thin film or binary semiconductors cells such as gallium arsenide (GaAs), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). The efficiencies of these generation panels are roughly about 20%. With slightly more promising efficiencies, these panels have been introduced into the world and being used commercially [19].

The 3rd generation solar cells are the "conjugated polymers and organic semiconductors". The materials used in this generation have been accepted and known to be advanced materials. The organic solar cells can be broken down further into dye-sensitised organic solar cells (DSSC), photoelectro-chemical solar cells, plastic polymer cells and organic photovoltaic devices (OPVD). The difference between all these different cells would be their working mechanisms. These technologies are yet to be introduced commercially and are still under research and further studies [19]. These generation solar cells are cheaper and much more solar absorbent with less amount of material [15].

The 4th generation of PV cells would be nano cells which uses nanotechnology as the material choice for power generation. An example of this type of nano solar cell would be the quantum dot-sensitised solar cell (QDSSC), hybrid bulk-heterojunction solar cells and CdSe nanoparticles. Due to issues with the stability and efficiency of these cells, these technologies are still being researched and developed [19].

Another variation to the PV panels would be the floating solar panels. This ideally is the same as the PV panels installed on the ground but as its name suggests, these panels are installed on top of a body of water such as lakes or seas. It works by the same principle as the conventional land solar panels but have a much better efficiency compared to the land solar cells due to the presence of water. The water acts as a cooling component within the system which in reduces the temperature of the panels. Due to this reduction in panel temperature, the floating solar cells have an efficiency increase of about (1.5-2)% [20]. If the dual axis tracking system was introduced into the floating PV, its efficiency would be further improved.

Other types of PV technologies that are similar the conventional PV panels would be the bi-facial panels, concentrating solar panels and cylindrical panels. Bi-facial panels are exactly the same as the conventional panels with the difference being that with the bi-facial panels, the panels absorb radiation from both the sky and the ground. The bi-facial panel has shown to have an increase of 23% in power generation meaning better efficiency compared to the conventional panels [21].

Concentrating solar panels work by the principle of reflecting solar radiation onto a single solar receiver. The panels work as heliostats where a lot of them are arranged at various angles to reflect the radiation onto the receiver. The efficiency of this system is about 20% but could decrease to the gradual increase of temperature. With the increasing temperature, the efficiency of the system decreases [18].

The cylindrical solar panels are cylindrical panels with the PV cells wrapped around the cylinder in a 360°. It also has a reflector on its surface which allows both direct solar radiation and reflected radiation from the reflector to generate power. The efficiency of this panel would be about 17% and mostly used on lamp posts around the world [18], [22].

2.1.6 PV Cell Parameters & Characteristics

2.1.6.1 MPPT

In order to for the PV cell to maintain its performance at the best level, an electronic component is needed to be installed into the solar cell’s system known as maximum power point tracking (MPPT). This component ensures the power generation is always optimised as the current (I_{tot}) and temperature (T) varies with time. Without the power point tracking, the performance of the PV cell would be far from optimum. This can be seen in the figure below.

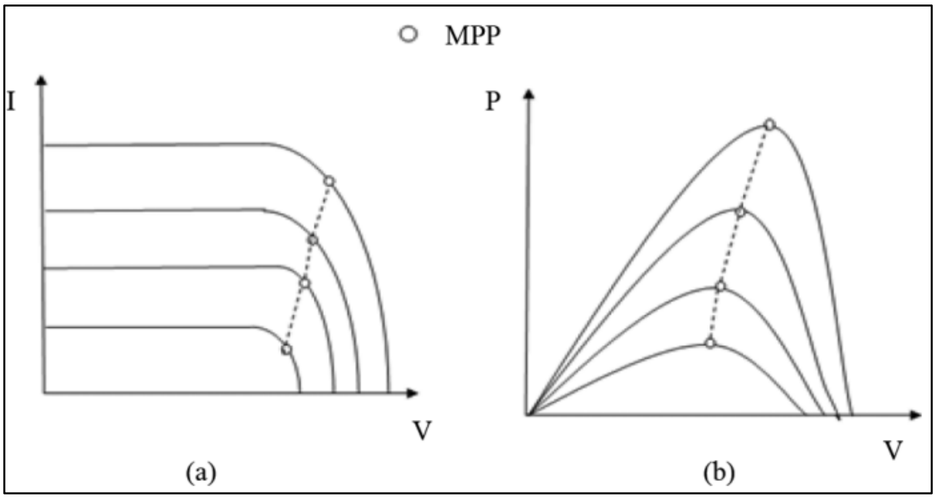


Figure 4 - (a) I-V characteristics with MPPT (b) P-V characteristics with MPPT [23]

2.1.6.2 Open-Circuit Voltage

Open-circuit voltage (V_{OC}) is the maximum voltage available from the PV solar cell which only occurs when the current in the cell is 0. The open-circuit voltage compares the amount of forward bias in the solar cell because the bias is created by the solar cell junction with the current produced from the cell converting light into electricity process. It is dependent on the way the solar cell is manufactured as well as the temperature the panel is at. Normally the V_{OC} of solar cells has been known to be between (0.5-0.6)V. The open-circuit voltage is shown in the figure below [19], [24].

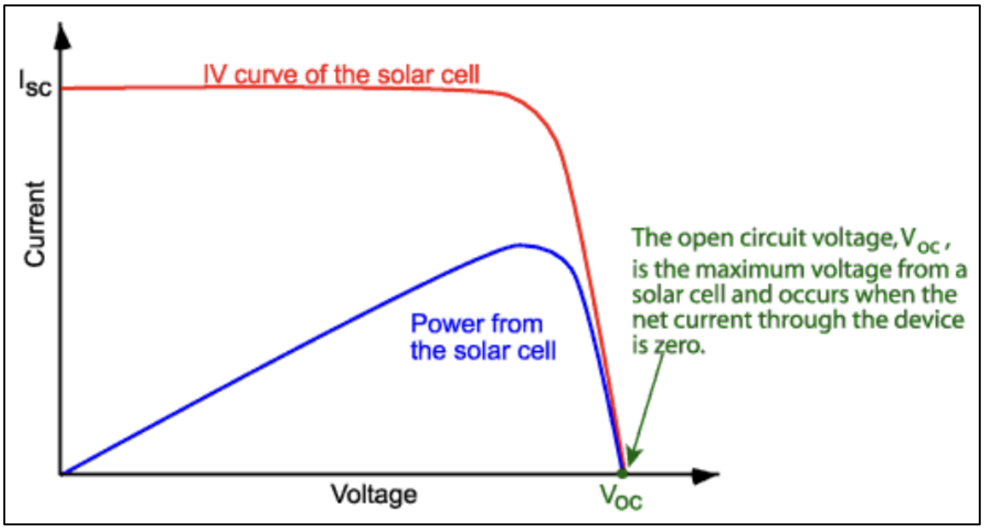


Figure 5 - I-V curve of solar cell showing open-circuit voltage [24]

V_{OC} can be calculated using equation (1) below.

$$\mathbf{Voc} = \frac{\mathbf{nkT}}{\mathbf{q}} \ln\left(\frac{\mathbf{IL}}{\mathbf{I0}} + 1\right) \qquad \textbf{(1)}$$

where, $\mathbf{V_{OC}}$ is the open-circuit voltage, **n** is the ideality factor, **T** is temperature, $\mathbf{I_L}$ is the light generated current and $\mathbf{I_0}$ is the dark saturation current.

2.1.6.3 Short-Circuit Current

The short-circuit current (I_{SC}) is the maximum current within the PV solar cell when the voltage in the cell is 0. It is the maximum current the cell produces without damaging the cell itself. An example of this scenario is when the solar cell has short circuited. The short-circuit voltage is shown in the figure below [19], [25].

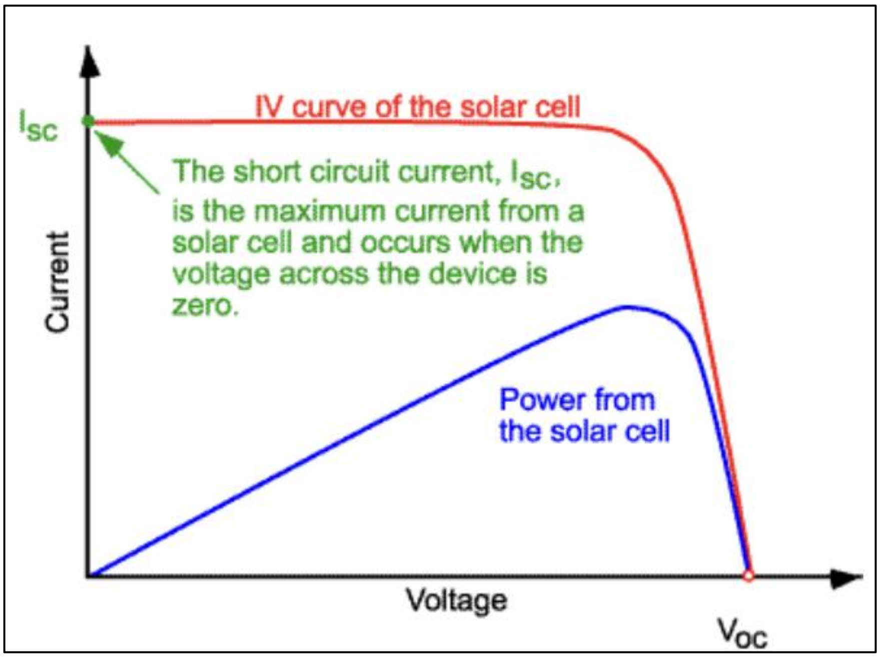


Figure 6 - I-V curve of solar cell showing short-circuit current [25]

The short-circuit current is dependent on a few factors such as [25]:

- Area of the solar cell
- Number of photons
- Spectrum of the incident light
- Absorption and reflection abilities of the solar cell
- Minority-carrier collection probability

This current can be calculated using the equation (2) below.

$$\mathbf{I_{SC} = J_{SC}A} \qquad \mathbf{(2)}$$

where, $\mathbf{I_{SC}}$ is the short-circuit current, $\mathbf{J_{SC}}$ is the short-circuit current density and **A** is the area of the solar cell [25].

2.1.6.4 Fill factor

At short-circuit current and open-circuit voltage, the power generated by the solar cell would be 0. The fill factor (FF) is a parameter which determines the maximum power generated by the solar cell during either VOC or ISC. The fill factor on an I-V curve would be the square area below the curve with high fill factor having a larger area and vice versa. This can be seen in the figure below [19], [26].

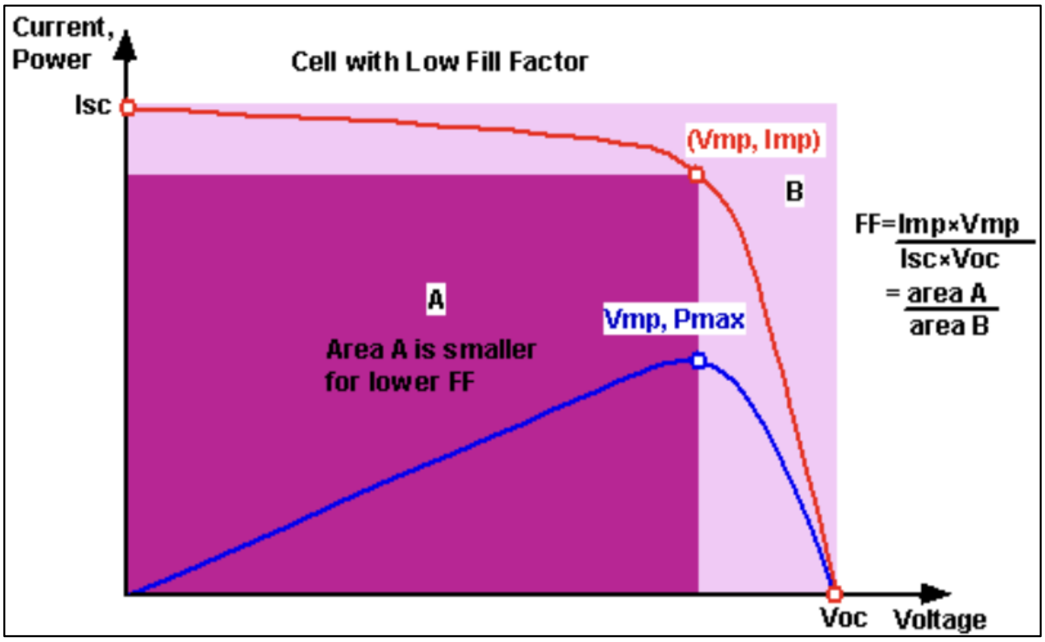


Figure 7 - I-V curve for solar cell with low fill factor

The fill factor can be calculated using equation (3) below.

$$\mathbf{FF} = \frac{\mathbf{Imax \times Vmax}}{\mathbf{Isc \times Voc}} = \frac{\mathbf{Pmax}}{\mathbf{Isc \times Voc}} \qquad \mathbf{(3)}$$

where, $\mathbf{I_{MAX}}$ is the maximum current and $\mathbf{V_{MAX}}$ is the maximum voltage [26].

2.1.6.5 PV Efficiency

The efficiency of the PV solar cell is the most important parameter when looking at the performance and function of the PV cell. It is widely used as a comparison factor and final test to assess the performance of the cell. The efficiency is defined as the ratio of the power generation output by the solar cell to the energy received by the cell from the Sun. The efficiency of a solar cell is dependent on a few other factors such as [19]:

- Spectrum and Intensity of the light from the Sun

- Temperature of the solar cell with time

The value of efficiency of a solar cell can be calculated by using equation (4).

$$\mathbf{PCE\ (\eta)} = \frac{\mathbf{Pmax}}{\mathbf{Pin}} \times \mathbf{100} = \frac{\mathbf{Imax\,.Vmax}}{\mathbf{Pin}} \times \mathbf{100} = \frac{\mathbf{Isc\,.Voc\,.FF}}{\mathbf{Pin}} \times \mathbf{100} \qquad \mathbf{(4)}$$

where, **PCE (η)** is the power conversion efficiency, $\mathbf{P_{MAX}}$ is the power output by the solar cell and $\mathbf{P_{IN}}$ is the power of the sunlight from the Sun [19].

2.1.6.6 PV Power Performance

The power performance is simply the amount of power generated by the PV solar cell. This can be calculated using equation (5) [15]:

$$\mathbf{P = Pstc\ \frac{Itot}{1000}\ (1 - \beta[T - 25]) \times p} \qquad \mathbf{(5)}$$

where, **P** is the power generated, $\mathbf{P_{STC}}$ is the power at test conditions, $\mathbf{I_{tot}}$ is the total incident solar, **β** is the loss coefficient, **T** is the operating temperature and **p** is the number of panels [15].

2.1.7 PV Temperature and Irradiance Effects

The radiation from the Sun falls upon the PV cells but only a certain percentage of this radiation is absorbed and used by the solar cell. This is also referred to as the efficiency of the PV cell. The remaining energy from the radiation would be converted into which in return heats up and increases the temperature of the PV solar cell. This reduces the efficiency of the solar cell [27].

One particular study done by T.T. Chow., (2003), found that the section of the panel that was cooler had a 3% increase in electrical efficiency. Hence proving that a cooler temperature was required by the PV panel in order to achieve better efficiencies [28]. Another study by Naveed et al., (2006), found that a reduction in the temperature of the PV panel of about (3-9)℃, an increase in the solar panel's performance was seen [29]. This ultimately confirms the theory of higher temperatures are not favoured in order to achieve greater yield from the PV solar cell since at higher temperatures, less current is produced which in return reduces the power generated by the solar cell. This can be seen in the figures below [30].

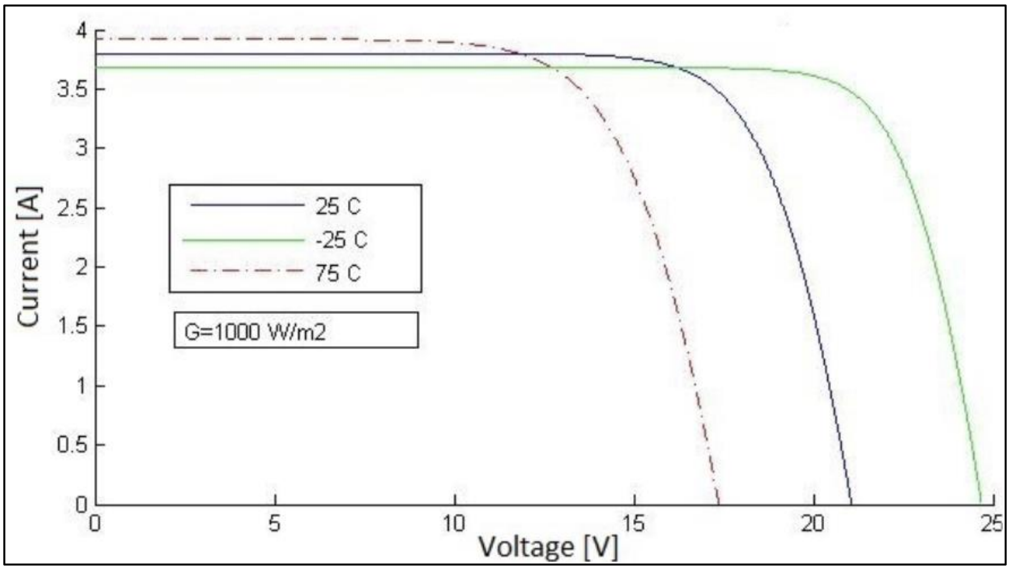


Figure 8 - Temperature effects on I-V curve [30]

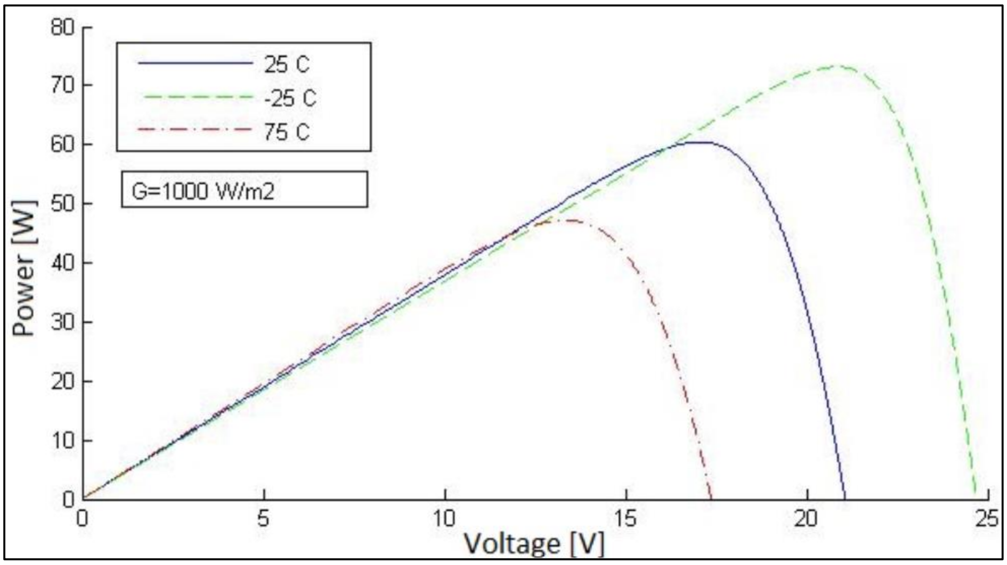


Figure 9 - Temperature effects on P-V curve [30]

The same way temperature has a significant effect on the performance and yield of the solar cell, irradiance also plays a big role in these values. When all the other parameters affecting the performance of the solar cell is kept constant, a greater level of irradiance, increases the output of the current produced by the cell thus increasing the power generated by the solar cell. This can be seen in the figures below [31].

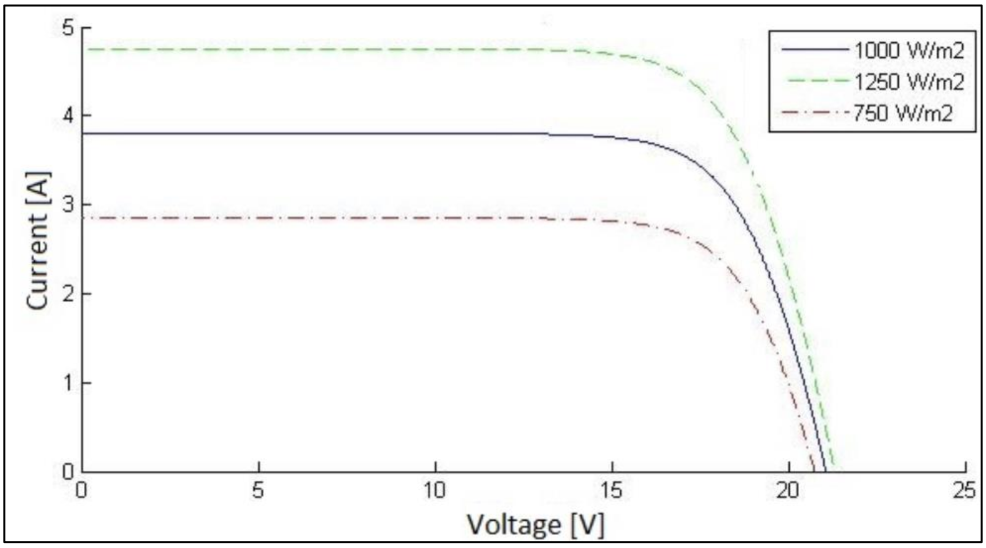


Figure 10 - Irradiance effects on I-V curve [31]

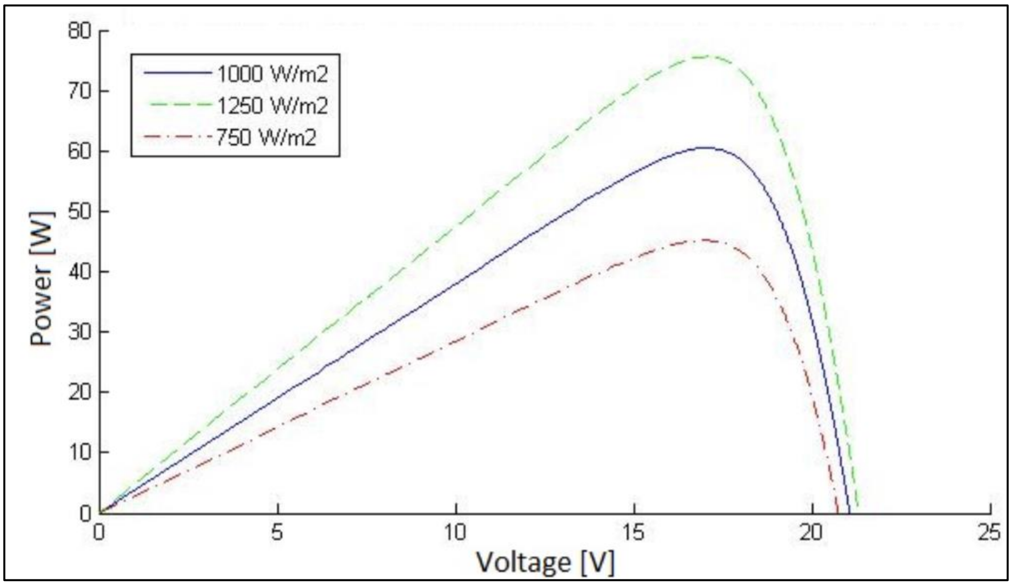


Figure 11 - Irradiance effects on P-V curve [31]

2.1.8 PV Mismatch Effects

2.1.8.1 Hotspots

Hot spot is a phenomenon that occurs when the greater values of current from the unshaded cells tries to pass through the shaded cells but rather than just passing through it becomes a load on the other cells and increases the temperature of the cells. This occurs as the shaded cells have lower voltage resulting in the opposite direction. The current restriction creates a power loss within the cells. Hot spots can increase the temperature of the cells until physical damages to the panels itself. There are chances of the cells to melt, the glass of the panels to crack or even changing the characteristics of the cells. Hot spots can really destroy not only the solar cells and panels but also terribly affect the performance of the solar cells. In order to prevent this phenomenon from occurring, the arranged cells should be installed in areas where there is no shade or very minimum shade [32].

2.1.8.2 Shadings

Shading is a phenomenon that occurs naturally all over the world. It is when an area that has been blocked or covered and does not receive any sunlight. This could occur due to the trees, buildings or clouds that are within the environment of the PV panels installation site. Another factor that could cause the cells to be shaded could also be the dust that forms on top of the cells after long periods of time. This can be prevented by cleaning the surface of the panels after a certain period of time constantly until the panels are no longer under commission [32].

When the cells are shaded, as previously mentioned, the cells experience a power loss due to the current restriction thus reducing the performance of the panels or even worse damaging the panels themselves. This could lead to hot spots forming within the solar cells. The panels might lose about 30% of its voltage and power due to the shading and hot spot effects [32].

2.1.9 PV String

PV string is formed when multiple panels are connected in series. PV strings can consist of one panel or a large number of panels. A PV system consists of just one string or multiple strings. The number of strings within a PV system is dependent on the size of the PV system itself [33].

2.1.10 PV System Inverters

A PV system would not be complete without the presence of the inverters. An inverter is a device that converts the direct current (DC) generated from the PV panels into alternating current (AC) used within the grid. Without the use of the inverter, the electricity generated from the PV panel, would not be able to be put into the grid for nationwide use as intended. This therefore makes the inverter a very important component within a PV system for successful power generation [34].

There are several types of inverters that could be used within the PV system depending on the configuration of the PV plant. Existing inverter types are [35]:

- Module Integrated Inverters/Microinverters: This inverter is used in very small PV system plants where the range of power generation is about (50-400) W. This would be the choice of inverter if the PV system is as small as one solar panel where one inverter is installed and fitted to each PV panel. Though its small size and capacity, this inverter has an efficiency of greater than 90% [36].

- String inverters: String inverters are used for PV systems slightly bigger such as small roof-tops where the panels are connected in a string. Ideally the limit of this inverter would be one string of panels. The power generation range for this inverter type would be about (0.4-2)kW.

- Multistring Inverters: As the name of inverter suggests, this particular type of inverter is used for PV systems with a much larger size area. This inverter would be used when the PV system consist of a maximum of 2 strings. The range of power generation for this inverter would be within the range of (1.5-6)kW.

- Mini Central Inverters: This inverter is used when the range of power generation is (>6)kW. This inverter introduces the 3-phase topology and modular design meaning this inverter would normally be installed in small scale PV solar plants or larger roof-tops. The limit for this inverter would be around the figure of 100kW.

- Central Inverters: Central inverters are similar to mini central inverters with same topology and design. The difference between these two inverters is that this particular inverter has a power generation range of (100-1000)kW. Normally large scale solar power plants would install inverters of this capacity.

2.2 System Optimisation, Modelling & Simulation

2.2.1 Case Study

As previously mentioned in the introduction, a case study of an existing PV system for an electronic components production factory in Malaysia has been selected. This site was selected to be assessed with the thought that an industrial building would provide a better understanding of the influence of having a PV system on a large commercial scale. Another reason behind the selection of an industrial site was due to the lack of studies done for PV systems on a factory. Most studies have been conducted on office buildings or residential buildings. This study would provide a better understanding of the PV system's impact onto the national power generation since the amount of power being used by industrial buildings would be significantly higher than office or residential buildings.

The selected factory is called Jabil Penang (Plant 1) factory and is located in the state of Penang which is a very industry heavy state with many companies and factories set up there. According to S.C. Chua et al., (2012), this is one of the states in Malaysia with the highest solar potential within the Peninsular region of the country [10]. With the best potential available, the potential for Malaysia to generate large amounts of power increases and possibly reflecting its upper limits of solar power generation. This created the best case study for this project as with the best solar potential available alongside the large number of factory sites available there.

In order to fulfil the criteria of the case study, a factory with an existing PV system was chosen. This choice was made because an existing PV system would be able to provide much more accurate real life date in terms of energy generation. This allows the software model to be much more accurate as it would be based on a real life PV system. With access to the factory's average monthly load profile and generation data, the current PV system was assessed and optimised. The case study also attempted to make the factory self-sufficient. The chosen factory can be seen in the figure below has an installed capacity of 3771.75 kWp. Throughout the year, the system after considering the efficiency of the system and its losses, the system was able to generate around 1917.2 MWh/year. The initial power demand for the factory was about an average of 54 655.7 MWh/year. In order to make the factory self-sufficient, optimisation to both the PV system as well as the factory itself had to be made. The approach to the optimisation was that the energy generated from the PV system would be increased but an effort would also be made to reduce the energy consumption of the factory in order to achieve self-sufficiency.

Figure 12 - Jabil Penang (Plant 1) factory site [37]

2.2.2 Modelling & Simulation Software

Before the PV system was installed onto the Jabil Plant site, a detailed analysis study was done on the site with its potential solar generation capacity. The software used by Jabil Penang was PVsyst. This is a PV system based powerful tool which enables its users to design, simulate and analyse all types of solar energy systems. It allows designs of small scale all the way up to large scale projects with an extensive database for meteorological data as well as equipment library such as PV modules, inverters, pumps and more.

The software also provides a complex system design choices such as grid connected systems, stand-alone systems or pumping systems which would mostly be used for agriculture. There are multiple tools that is also available within the software categorised as solar and electrical tools. These tools are listed below:

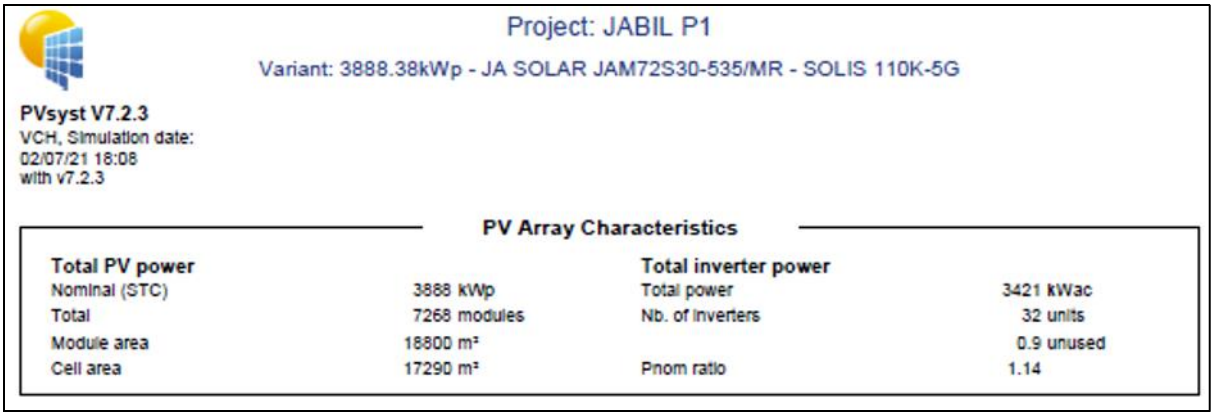
1. Solar Toolbox
    a. Tables/Graphs for solar geometry and models
    b. Transposition Factor, Plane Orientation Optimisation
    c. Monthly Meteo Computation – quick meteo calculations with specific conditions
2. Electrical Toolbox

a. Electrical behaviour of PV Arrays – mismatch, shaded cell (hot-sp.), I-V characteristic of shaded cells
b. Operating Voltage Optimisation – fixed voltage optimisation by MPP over the full year

With all these tools available within the software, a system could be designed, and further optimisation could be done to the design to maximise the power generation at that particular site. The software would be able to provide an economic study of the site and predict its payback period and such with the designed system.

2.2.3 Recreation

In order to further analyse and understand the system designed and installed at the Jabil site, a detailed study of the site and its system had to be done. To accomplish this, the system design done by Jabil was recreated as accurately as possible following the information provided by Jabil. A 3-D model of the site and the orientation of the panels installed were replicated. The type of PV module and inverter were also replicated as accurately as possible. The purpose of the recreation would be to validate the designed model. As Jabil has been able to produce generation values close to what was simulated by PV Syst. This proves that the recreated model would be fairly accurate in presenting the new values of energy production with the optimised system. The process and breakdown of the recreation could be seen in the figures below.



Project: JABIL P1

Variant: 3888.38kWp - JA SOLAR JAM72S30-535/MR - SOLIS 110K-5G

PVsyst V7.2.3
VCH, Simulation date:
02/07/21 18:08
with v7.2.3

PV Array Characteristics

Total PV power		**Total inverter power**	
Nominal (STC)	3888 kWp	Total power	3421 kWac
Total	7268 modules	Nb. of inverters	32 units
Module area	18800 m²		0.9 unused
Cell area	17290 m²	Pnom ratio	1.14

Figure 13 - Jabil's PV system summary

Project summary

Geographical Site	Situation		Project settings	
Jabil	Latitude	5.30 °N	Albedo	0.20
Malaysia	Longitude	100.29 °E		
	Altitude	13 m		
	Time zone	UTC+8		

Meteo data
Jabil
Meteonorm 8.1 (1991-2009) - Synthetic

System summary

Grid-Connected System — **Sheds on a building**

PV Field Orientation		Near Shadings	User's needs
Fixed planes	4 orientations	Linear shadings	Unlimited load (grid)
Tilts/azimuths	4 / 49.1 °		
	4 / -131 °		
	4 / -41 °		
	4 / 139.8 °		

System information

PV Array		Inverters	
Nb. of modules	7268 units	Nb. of units	33.5 units
Pnom total	3888 kWp	Pnom total	3685 kWac
		Pnom ratio	1.055

Results summary

Produced Energy	5768358 kWh/year	Specific production	1483 kWh/kWp/year	Perf. Ratio PR	82.15 %

Figure 14 - Recreated PV system summary

From Figures 10 and 11, it can be observed that the power generation for both the module and inverter as well as the number of modules were successfully replicated. The number of inverters in the recreation study however without exact knowledge to how the inverters were sized, the recreated model had a slightly different value with a 1.5 increase to the number of inverters to the original study made. Another comparison can be seen in the figure below.

Compatibility with Orientation and System parameter

	Orient./System	3D scene
Active area	**18775 m²**	**18867 m²**
Fields tilt	**in 4 orient.**	**in 4 orient.**
Fields azimuth	**See "Overview"**	

Figure 15 - Recreated PV system and the building's area

Comparing Figures 10 and 12, the area of the recreated study was replicated. Although the areas are not exactly the same the values are close enough to be accepted. To achieve the most accurate recreation possible, the shadings and losses of the original study was also replicated. This would be seen in the figures below showing the loss diagrams from the Jabil report and recreation report respectively.

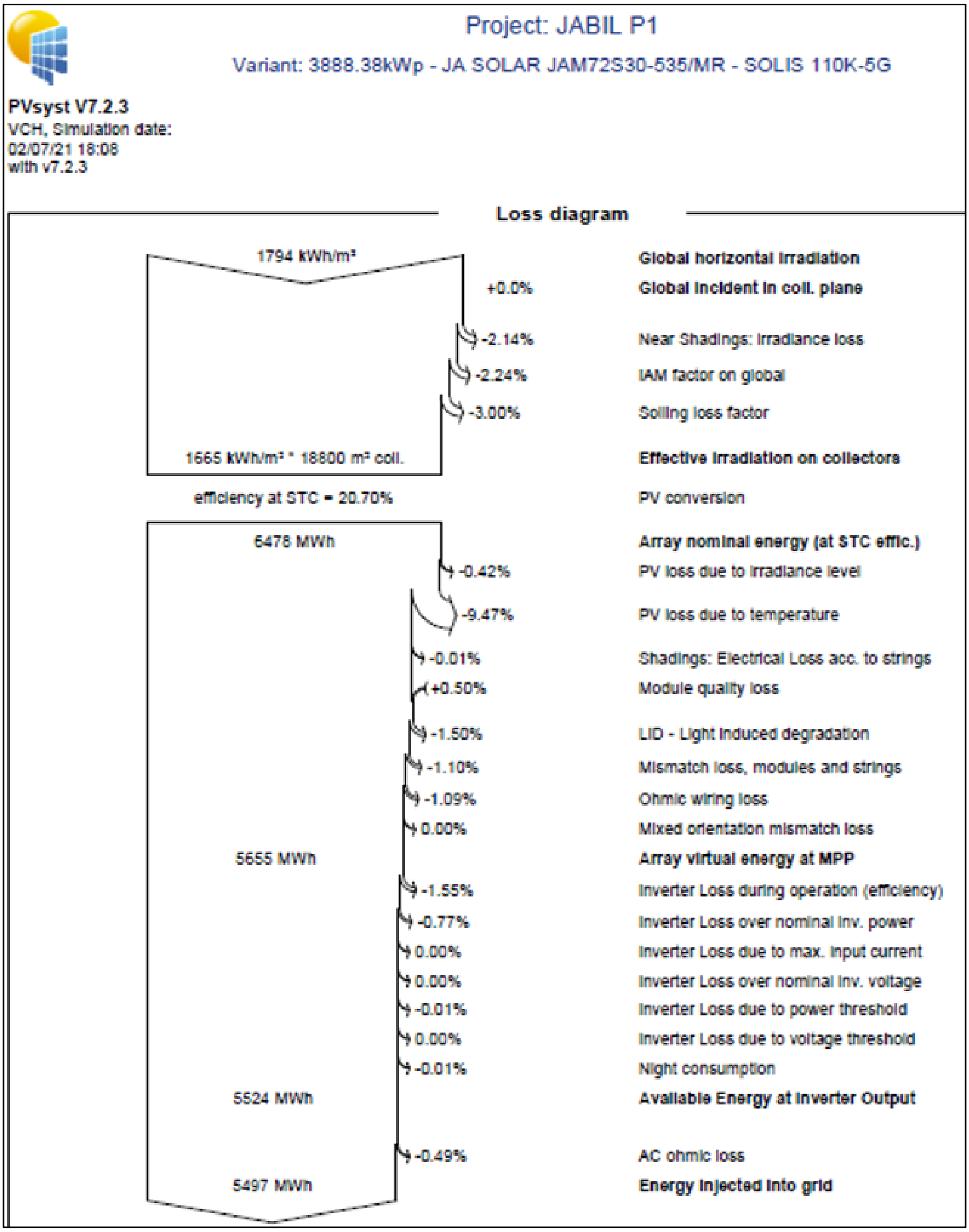


Figure 16 - Jabil's PV system loss diagram

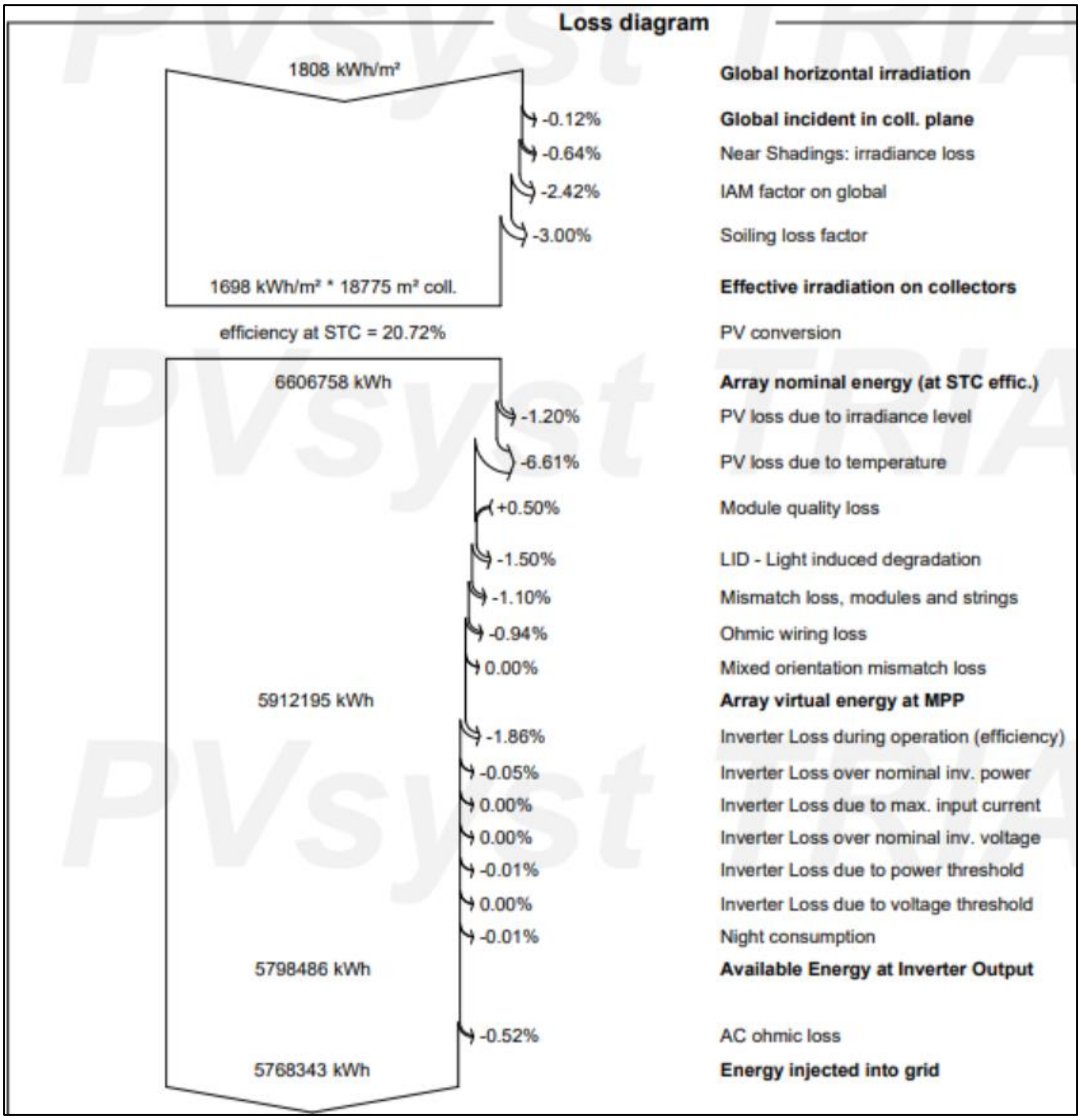


Figure 17 - Recreated PV system's loss diagram

From Figures 13 and 14 above, it can be seen that the loss diagrams present the same losses with mostly exact values. There are some differences in certain losses due to the slight difference in the system design as mentioned in the sections above. But the loss values are accepted considering the difference in the values as well as any missing losses were of very small values which were considered as negligible. An example of this would be the shadings loss which would be the electrical loss according to the strings which in the original system had a loss value of -0.01. This value was not present in the recreation system but since the value was very small, this loss was neglected.

2.2.4 System Optimisation

Considering that the PV system was unable to make the factory self-sufficient, optimisation was to be introduced into the factory setup and design. To achieve this, several changes could be made such as the optimisation of the PV system, introducing a heat pump system (technology that functions similarly to an air conditioner unit providing cold air into the factory with the difference being the efficiency of the technology itself; it would reduce the energy consumption of the factory), implementing piezo-electric tiles (technology which is able to convert mechanical energy from steps made by people walking into electrical energy; it provides additional energy generation) and extra PV generation upon site selection. These factors would be looked into and analysed to see the extend of optimisation that would be achievable by these factors.

2.2.4.1 PV Optimisation

The PV system installed at Jabil Penang could be further optimised in certain aspects. Using the PVsyst software, the system could be optimised using the tools within the software. Under the advanced simulation options, the optimisation tool could be used to make these changes. Some optimisations could also be done by manually changing the type of PV module and inverter. The factors that would be optimised for this project were:

- Pitch
- Ground Coverage Ratio (GCR)
- PV Module & Inverter
- Tilt Angle
- Azimuth

2.2.4.2 Other Forms of Optimisation

Heat Pump

Malaysia is a very warm and humid country with high temperatures throughout the year. Due to the weather conditions being as such, majority of the buildings in the country uses an air conditioning (AC) system. But due to the cost and efficiency of the AC system being relatively poor, the AC system has not the favoured option. However, due to the lack of technological advancement within the country, the use of AC systems has still been very dominant. The factory also uses this AC units to provide cold air within the building.

An alternative to using the AC system would be the use of heat pumps. Heat pumps are devices that use the concept of heat transfer to heat up or cool down an area of space. This is done by circulating the heat from inside the space to the environment if the space is to be cooled and vice versa to heat up the space area. The figure below shows the types of heat pump systems available.

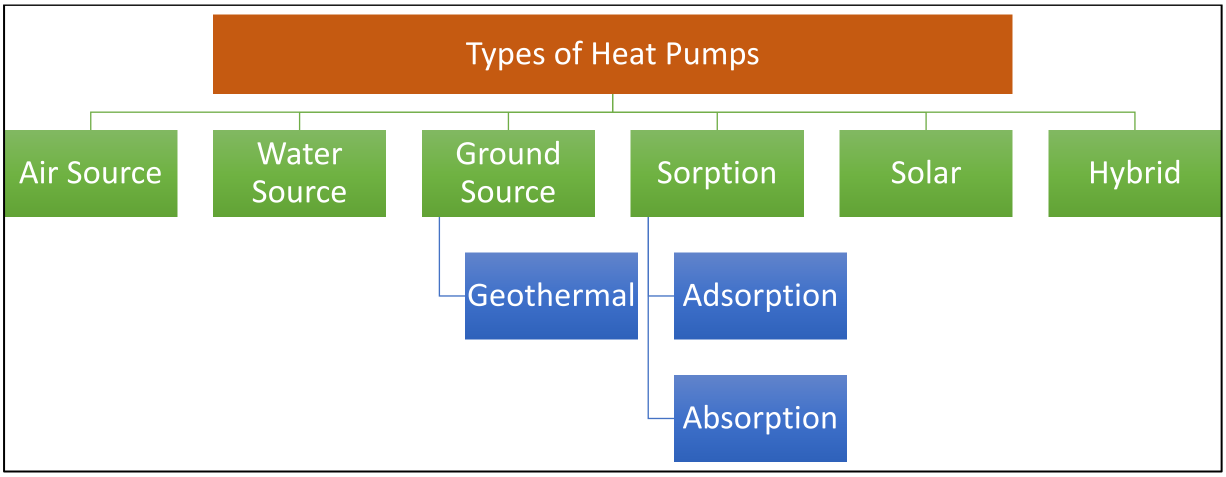


Figure 18 - Types of heat pumps [38]

Although there are various different types of heat pumps, there are only 3 main types of heat pumps commonly available in the market which are the air source, water source and ground source heat pumps [38]. As the name suggests, an air source heat pump (ASHP) takes low grade heat from the air and converts it to high grade heat which then would be used for heating. However, in this instance, the heat pump would be removing the heat from the building and transferring it out to the environment to reduce the temperature within the building. A working fluid acts as the medium of heat transfer and removes the heat from inside the building to the air outside [38]. This can be seen in the figure below.

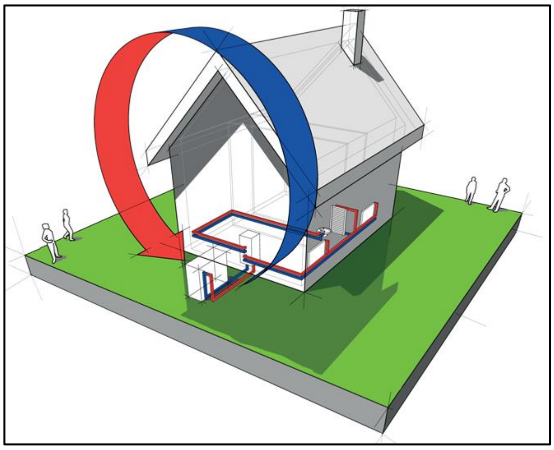


Figure 19 - Diagram of an air source heat pump system [39]

Water source heat pumps (WSHPs) use water bodies such as ponds, lakes, rivers, seas or even groundwater as a source of heat. They extract the low grade heat from these water bodies and convert them into useful heat which would be used for heating for buildings. In order to utilise the heat pump for cooling, the water bodies would act as the source of cooling. A working fluid which could be water from the water body, would be used to extract heat from the building and dumped into the water bodies. As heat always travels from hot to cold, the water from the water bodies would be of a lower temperature which then enables the heat to be transferred into the fluid from the building and back out to the water body. There are 2 ways of going about these which would be categorised as a closed loop system or an open loop system. This can be seen in the figure below [38].

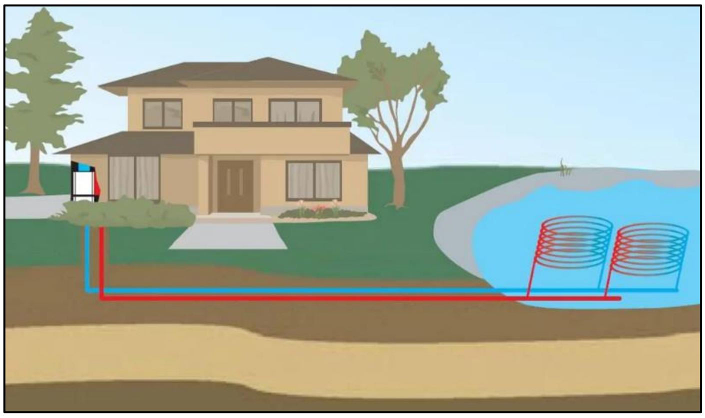


Figure 20 - Diagram of water source heat pump system [40]

An open loop system means that the system is left open at the water body by which the water entering the building for the 1st cycle might not be the same water entering the 2nd cycle. In order for this system to work well, a large source of water body must be present. Water is constantly extracted and deposited to the water bodies at the same time. An open loop system tends to be more economical considering it requires no additional machinery or installations such as drilling of holes and installations of pipes, etc. These additional work and cost generally falls under the closed loop system.

A closed loop system simply is a system that reuses the same volume of water to extract heat from the building as well as dumping that heat. This system is easier to install as open loop systems tend to require a huge source of water in order to keep the cycle going. With the closed loop system, another set of pipes might be needed alongside a heat exchanger in order to extract the heat from the closed loop water. This may result in additional costs for the entire system making this option less economical. Depending on the economic situation or the company and suitable geographical location of the building, the choice between an open or closed loop system would be made.

Another type of commonly used heat pumps would be the ground source heat pump (GSHP). From figure 22, it can be seen that one type of GSHP was the geothermal heat pump. Both these heat pumps generally use the ground as a source of heat. According to A.S. Gaur et al., (2021), sometimes both the GSHP and the geothermal heat pump could be referred to as the same type of heat pump. The GSHP in this case would be utilising the ground as the heat sink. A working fluid such as water would be used to extract the heat from the building and dumping the heat into the ground. This can be seen in the figure below.

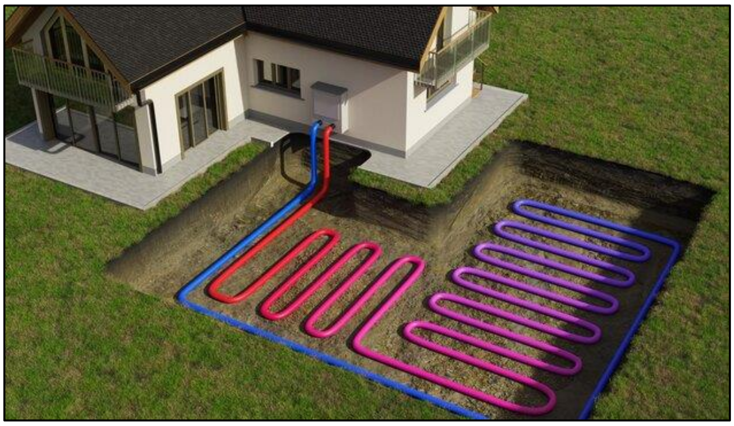


Figure 21 - Diagram of ground source heat pump system [41]

Considering the geographical location of the Jabil Penang factory site which can be seen below, there are equal opportunities for all the 3 types of heat pumps.

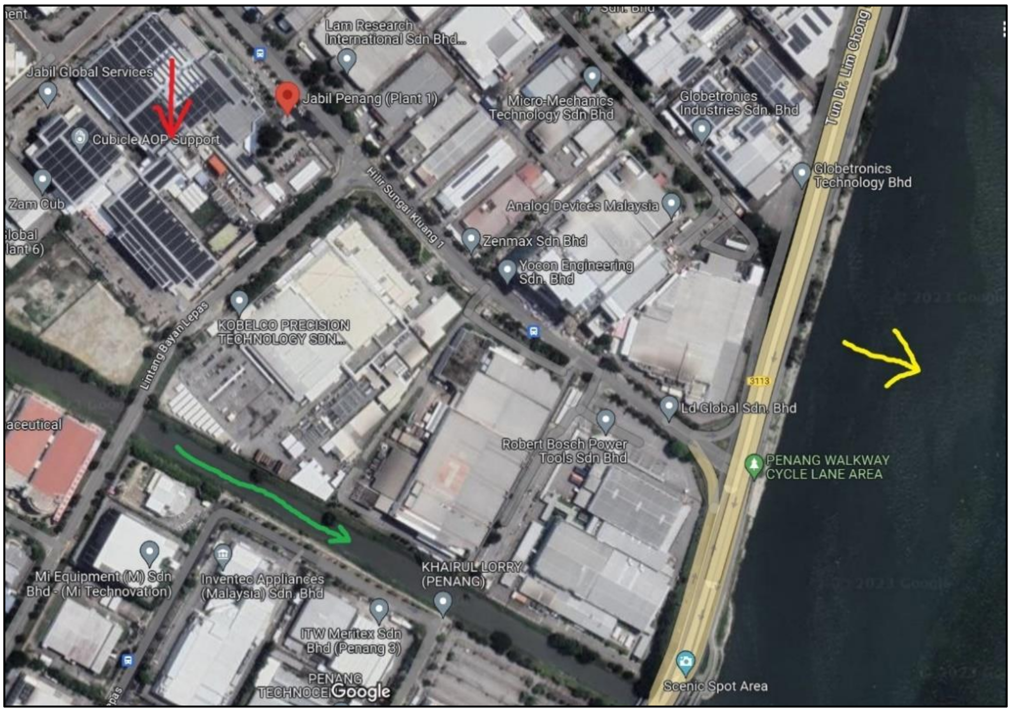


Figure 22 - Geographical location of Jabil factory site [42]

From the figure above, the red arrow marks the location of the factory. The green arrow shows the river which then connects into the sea which is shown by the yellow arrow. The presence of the river and sea enables the factory to implement a WSHP system if necessary. With this, all 3 types of heat pumps are available to the company. To find out which system would be most viable, a separate study would be needed to be done. Therefore, to obtain a rough value of energy reduction of the factory's total energy consumption, a thorough literature review was conducted. These papers were able to give a rough estimated percentage value of energy reduction.

One literature by K.Yasukawa et al., (2019), titled Space Cooling by Ground Source Heat Pump in Tropical Asia, mentioned that 30% of energy reduction was achieved in a test site in Bangkok, Thailand. The paper also mentions that a survey was conducted in Chao Phraya plain, Thailand which showed that subsurface temperature is lower than the daytime atmospheric temperature. This suggested that the underground could be used as a cold heat source in other tropical countries. A thorough survey was done in 6 other regions in Thailand and Vietnam to further prove the underground for depths 20 - 50m could be used as a cold heat source for the tropical countries. The paper concluded with the 30% energy reduction for a site in Thailand [43]. This literature was accepted as part of the estimation because Thailand is a country that borders Malaysia and has very similar weather conditions as well as the atmospheric temperatures.

Another literature by Y. Shimada et al., (2020), titled A Study on the Operational Condition of a Ground Source Heat Pump in Bangkok Based on a Field Experiment and Simulation, summarised that a 40% energy reduction was achieved with the proposed operational conditions. The paper looked into the implementation of a borehole heat exchangers vertically and horizontally to see the significance it plays in the percentage of energy reduction. Analysis of the difference in efficiency between a GSHP and ASHP was also conducted to investigate which system was more efficient. From the results of this paper, it was determined that the GSHPs with vertical and horizontal type of borehole heat exchangers were able to save approximately 30% and 18% of energy respectively compared to an ASHP [44]. This paper was included in the estimation process because it not only gave a value of energy reduction but was also helpful in determining the better option between a GSHP and ASHP.

As mentioned in the previous paragraph, this literature by A. Widiatmojo et al., (2019), titled Ground-Source Heat Pumps with Horizontal Heat Exchangers for Space Cooling in Hot Tropical Climate of Thailand, provided a detail insight to how a GSHP is more efficient to an ASHP with energy reductions of between 17 – 18% [45].

This paper was important in the estimation process as it proves that a GSHP is more efficient than a traditionally used AC system considering an AC system works on the same principle as the ASHP for cooling. Therefore, a WSHP or GSHP would be the choice to be made for the factory to reduce the total energy consumption. Most literatures in relation to heat pumps used for space cooling in tropical Asia, were using GSHP as the technology of choice. This made the energy reduction by a WSHP unable to be determined.

In order to make the estimation process more realistic for the purpose of this paper, only 25% energy reduction was assumed. This was done to underestimate the real value of energy reduction achievable by the factory if a GSHP system was installed to replace the AC systems.

Piezo-electric Tiles

In order to achieve the goal of making the factory self-sufficient, more energy needed to be generated. One technology that has been progressively making its way up the market would be the piezoelectric tiles. There are several literatures mentioning various different types of piezoelectric technology for one flooring tile and their respective energy or power produced.

Using the information about the potential power produced, a rough undervalued estimate of the total energy generation by the tiles was made.

A literature conducted by R.R. Moussa et al., (2022), titled Energy Generation in Public Buildings Using Piezoelectric Flooring Tiles; A Case Study of a Metro Station looked into and reviewed the application of piezoelectric tiles in other case studies of public buildings and summarised the different technologies used in 7 other literatures. From the 14 different technologies mentioned by R.R. Moussa et al., (2022), several of them were selected to be further looked into for the purpose of the Jabil Penang factory. The selection criteria were to select technologies with the highest energy generation. This can be seen in the table below [46].

Table 1 - Details of the different types of piezoelectric tiles [51], [52]

Product Type		Size of Tiles	Power Produced (W)	Cost/tile (UK £)	Estimated Lifespan (years)
1	Waynergy Floor [47], [48]	(40 x 40) cm	10W/step	371.29	20
2	Sustainable Energy Floor (SEF) [49]	(75 x 75) OR (50 x 50) cm	Up to 30W of continuous output. Typical output by a person is between (1 – 10)W with the average being 7W	399.96	15
3	Pavegen Tiles [50]	(50 x 50) cm	5W continuous power	325.08	20
4	PZT Ceramic [51]	Diameter range: (10 – 250) µm	8.4mW	30.00	20
5	Parquet PVDF Layers [51]	Layers with thickness of 10 µm	2.1mWs per pulse with rough load of 70kg	NA	20

6	Drum Harvesters – Piezo buzzer, Piezoelectric Ceramics [52]	Between (25 – 40) mm	2.463mW	13.33/tile	20
7	Power Leap [53]	(60 x 60) cm	0.5mW/step	Project Stopped	20
8	Hybrid Energy Floor (HEF) [49]	(75 x 75) OR (100 x 200) cm	Up to 250 kWh/year per tile	399.96	20

Another literature by S.Sharma at al., (2022), titled A Review of Piezoelectric Energy Harvesting Tiles: Available Designs and Future Perspective, also looked into the currently available technologies. This literature was able to validate the information found from the paper by R.R. Moussa et al., (2022) shown in the table above [54].

One other literature by P. Shariffudin., (2021), titled Piezoelectric Energy Floor Tiles Performance and Effectiveness as Building Energy Conservation Measures for Different Types of Buildings in Malaysia, had done an analysis of the potential energy generation by various different types of buildings in Malaysia including a manufacturing factory using the Pavegen piezoelectric tiles. Although the factories looked into are of different capacities, it would be beneficial to include this paper into the literature review as it would give a much better estimate value of potential energy generation from the tiles [55].

From the table above, the best options in terms of highest power produced per step would be the Waynergy Floor, SEF and Pavegen tiles with the Waynergy tiles producing the most power. Another important factor when considering the choice of technology would be the cost. However, in this case, the cost of the 3 technologies appears to be very similar. The recommended option of technology for Jabil Penang factory would be the Waynergy Floor tiles solely due to the fact that it would be able to generate more power than the rest and at a slightly more reasonable price compared to the other 2 technologies.

Extra Generation from Available Land Areas

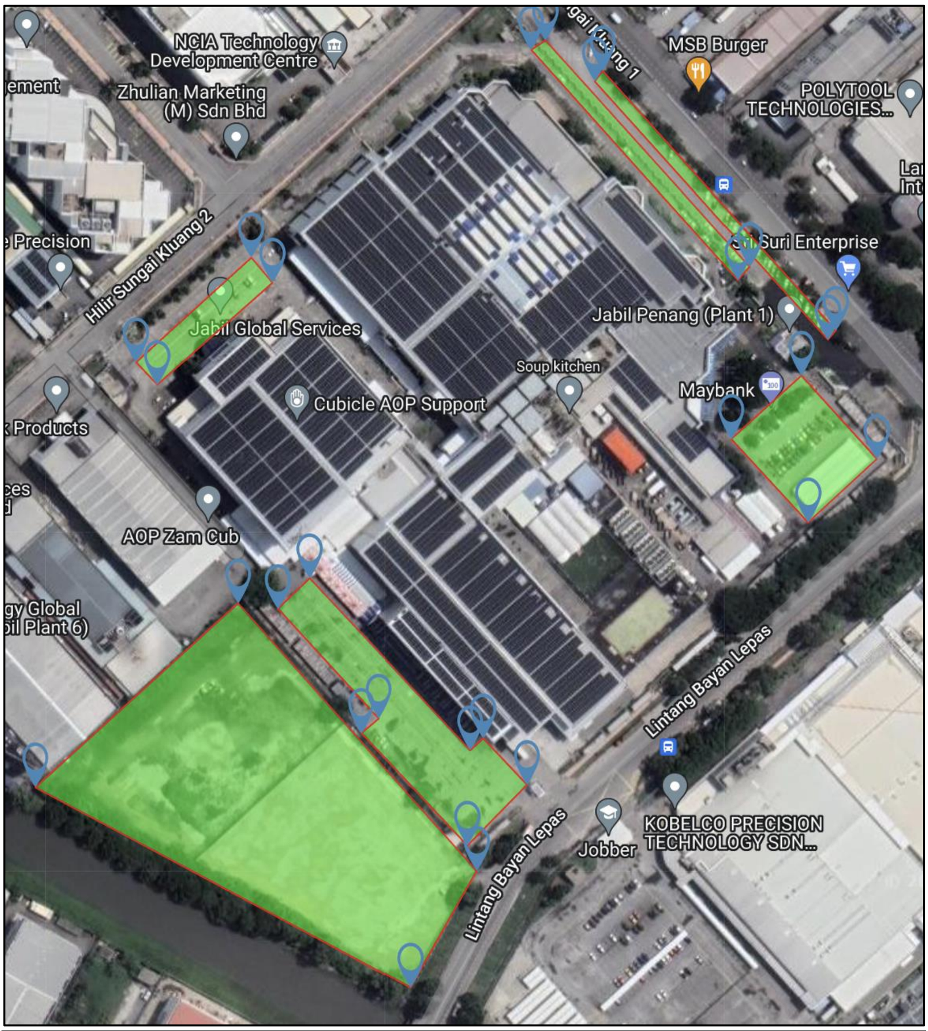


Figure 23 - Derelict and available land for extra energy generation [56]

Total Area Output

24277.604 m²
0.025 km²
5.999 Acres
2.429 Hectares
261321.96099999998 Feet²

Figure 24 - Total area available [56]

From the figures above, there are more available land that Jabil Penang could utilise for extra energy generation. Just like the piezoelectric tiles, this additional energy generation would contribute to the factory becoming self-sufficient. The energy generation using the available area would be calculated the same it was done in the PVsyst software to ensure the value obtained would be as accurate as possible.

2.3 Integration of Energy Storage

2.3.1 Types of Energy Storage Systems

A very integral part of the whole renewable energy system development process would be the integration of an energy storage system. As the factory becomes self-sufficient, any surplus energy generated needs to be stored or sold back to the grid. Not only that, if the factory is to rely solely on the PV system installed, a storage system would be very crucial for off-peak hours which would be the hours without sunlight. More than enough energy would need to be generated during the daytime with all the surplus stored. This stored energy would then be reused the following day. A surplus of energy has to be generated as the factory runs for 24 hours with very minimal reduction in power consumption after work hours. All these factors would be considered in the design of the energy storage system.

However, before the system was designed, the type of energy storage technology that would be used needed to be decided. There are various types of energy storage technologies currently available. There are also many new technologies still being researched and developed. Although many new technologies are being proposed and researched, a lot of the older technologies are still being researched to further enhance the technology's efficiency amongst other criteria.

Energy storage technologies can be divided into 5 main categories which are Mechanical, Electro-chemical, Chemical, Thermal and Electrical. Each category can then be sub-divided into different types of technologies under each main category. This can be seen in the figure below [57].

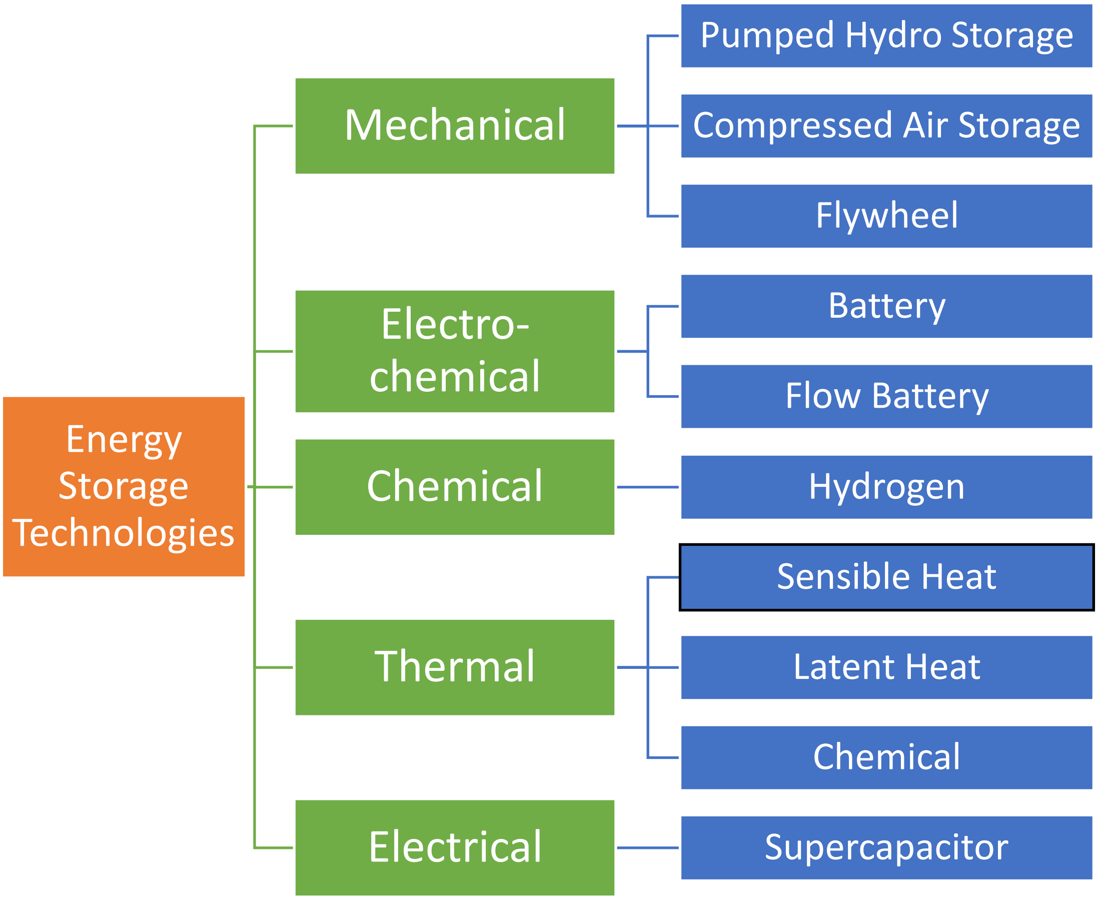


Figure 25 - Types of energy storage technologies [57]

2.3.1.1 Mechanical Energy Storage

Under the mechanical energy storage, the pumped hydro storage (PHS) is said to be the most developed commercial storage technology contributing to 94% of the world's total energy storage. PHS is set up with 2 water reservoirs at different elevations. The water from the top reservoir is dropped down to the bottom reservoir with a turbine placed in between them. The water passes through the turbine with great potential energy depending on the height difference of the 2 reservoirs and generates electricity. Once the electricity has been generated, during the off peak time, a pump is utilised to send the water back to the top reservoir for further energy generation. That is the concept of this energy storage technology. After much development, it was able to achieve high efficiencies, long discharge durations and cycle life making it a suitable choice for long term use. This can be seen in the figure below [57], [58].

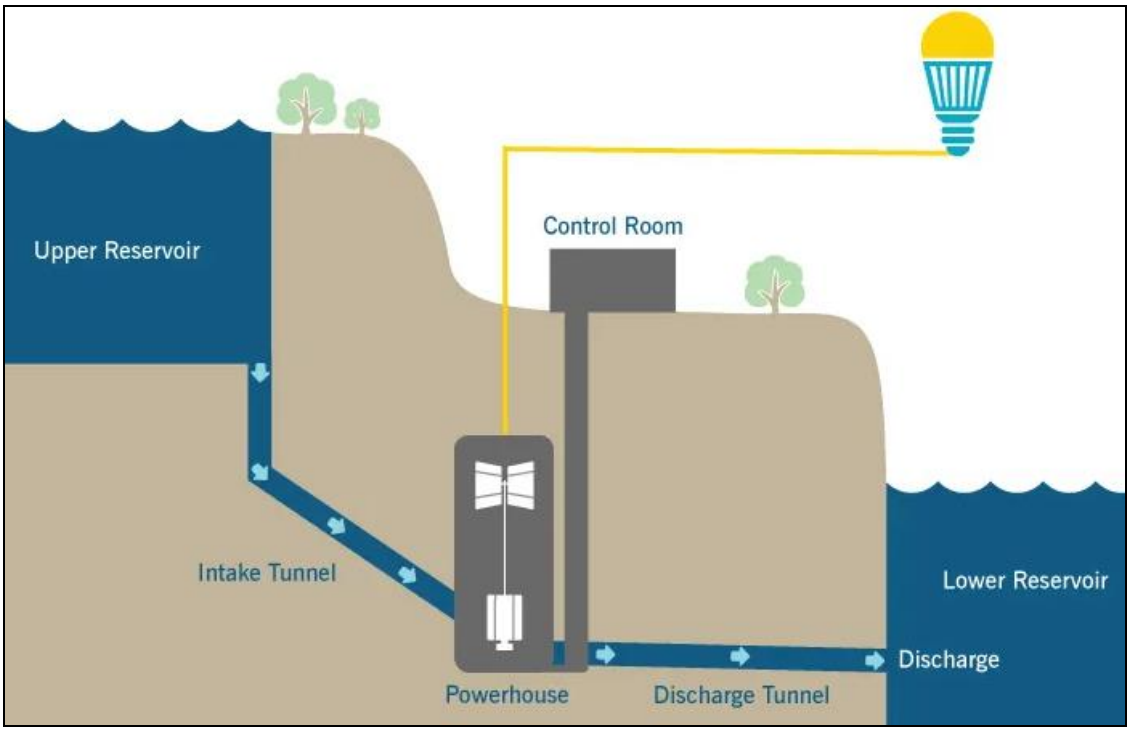


Figure 26 - Diagram of pumped hydro storage [59]

Another type of mechanical storage would be the compressed air energy storage (CAES). It is still a developing and researched type of storage system. CAES can be separated into 2 types which are conventional and above ground. The conventional CAES uses underground caverns such as excavated salt caverns as the storage vessel whereas the above ground uses man-made storage vessels. There are a few commercial CAES systems already deployed in countries such as Germany, United States, Canada, and Australia. The concept of CAES is fairly straight forward. Excess energy would power the compressor to compress air from the environment and stored into either a cavern or vessel. This process is known as the charging and occurs when the power demand is low. During the discharge process, the compressed air would pass through an expander and then into a turbine to generate electricity. The discharge process occurs when the demand for energy is high. This can be seen in the figure below [57], [60].

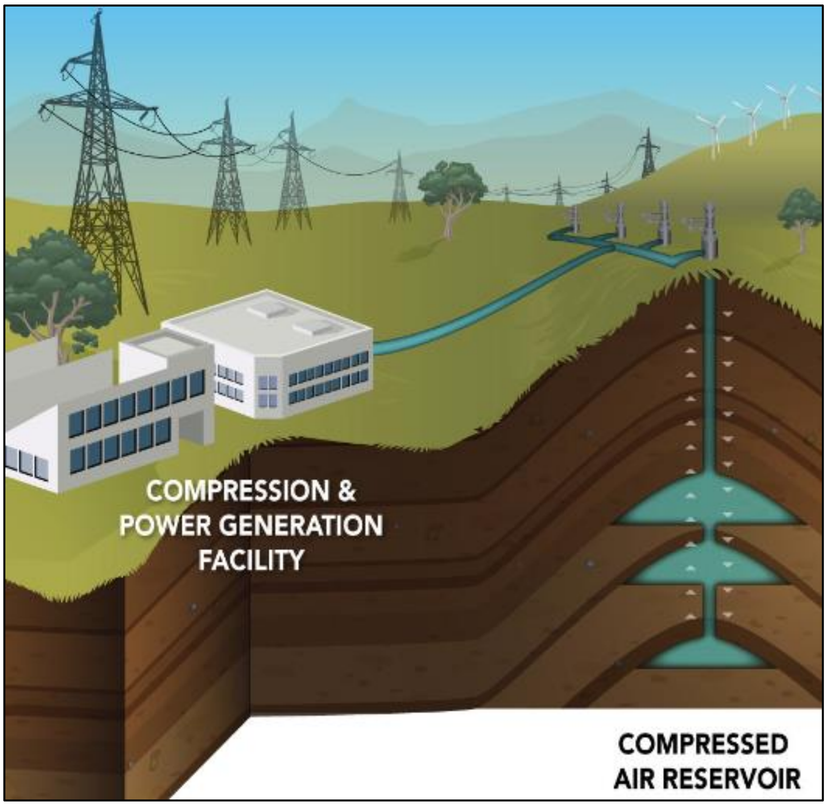


Figure 27 - Conventional CAES system [61]

The flywheel energy storage (FES) system is another type of mechanical energy storage. The FES stores energy using the rotating mass principle. It converts electrical energy into mechanical energy whereby the energy stored is in the form of rotational kinetic energy. This means that the more energy stored, the faster the flywheel rotates. The flywheel is driven by an electrical motor-generator which converts the electrical energy into mechanical energy. This can be seen in the figure below [57], [62].

Figure 28 - Flywheel used in FES [63]

2.3.1.2 Electro-chemical Energy Storage

The electro-chemical energy storage can be split into 2 categories which are the rechargeable batteries and flow batteries. This type of energy storage has the 3rd highest installed capacity in the world. Batteries store the energy in an electrochemical form. The input into and output from the battery would be in the form of electrical energy. The common types of batteries used for storage are the Pb-A, Na-S, Li-ion, Ni-Cd, etc with the Li-ion battery dominating the world's energy storage market. Batteries are able to provide high efficiencies, long life cycles, high power and energy density. These properties have led to the development of batteries. This can be seen in the figure below [57], [64], [65].

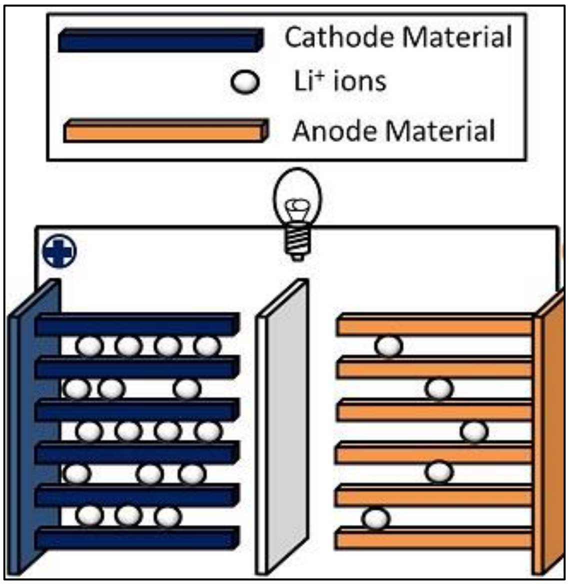


Figure 29 - Schematic of lithium ion battery [66]

Another variation to the common batteries mentioned above would be the flow batteries. The internal part of a flow battery consists of 2 chemical components separated by a membrane. The charging and discharging process of the flow battery occurs by the transfer of ions from one chemical component to the other through the membrane. Flow batteries store the excess electricity in liquid electrolyte tanks which was pumped through the electrodes to extract the electrons. During the charging process, the electrolyte is recharged with the electricity generated and then stored in the tank but during the discharging process, the electrolyte is the pumped through the electrodes which then removes and extracts the electrons. Common types of flow batteries are vanadium redox and Zn-Br. This can be seen in the figure below [57], [65].

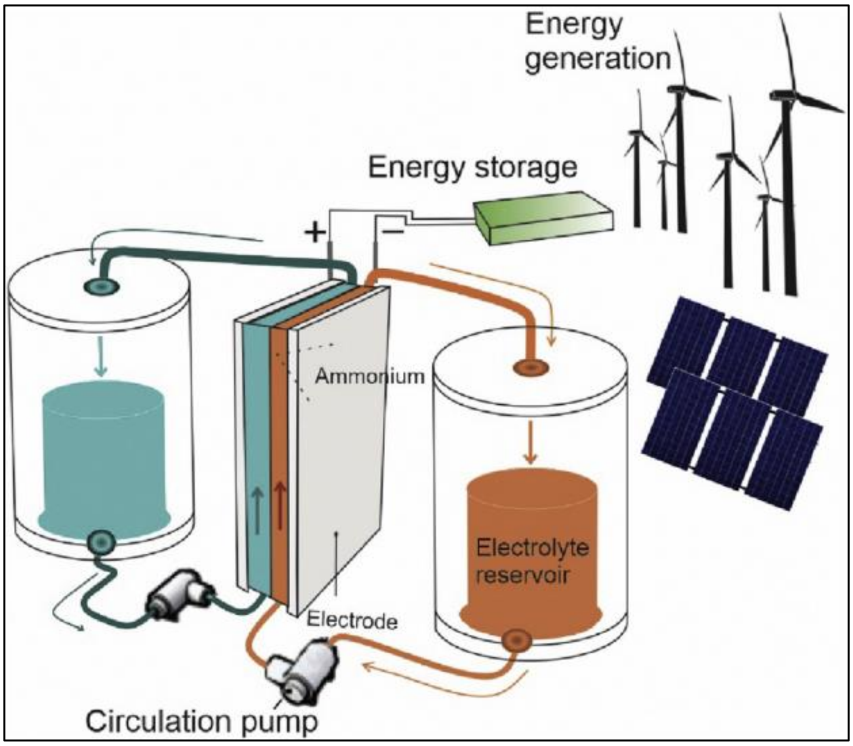


Figure 30 - Schematic of flow battery [65]

2.3.1.3 Chemical Energy Storage

Hydrogen storage is a very well-known chemical energy storage. Hydrogen can be obtained by performing electrolysis on water. This is a process of splitting the water molecules into its respective element using an electrolyser. According to A. Züttel., (2004), performing this process at ambient pressure and temperature requires minimum voltage therefore requiring minimum energy of approximately 39.7 kWh/kg of hydrogen. The hydrogen molecule H2 can also be found in many different forms depending on the pressure and temperature. At very low temperatures, hydrogen can be found as a solid with liquid hydrogen being found at slightly higher temperatures. This then shows that hydrogen can also be stored in all the 3 different state of matter [67].

At a gaseous state, hydrogen can be stored in high pressure vessels to store more volume of the gas. This process works similarly to the compressed air energy storage system. The hydrogen needs to be compressed and stored in a pressure vessel. This would be the charging process which occurs when the demand for power is low. During the discharge process, the hydrogen would be expanded and passed through an engine which has been retrofitted to use hydrogen as the fuel source [67].

Hydrogen can also be stored in liquid state. This involves a process known as liquefaction which liquifies the hydrogen. This liquid hydrogen is then stored in special tanks called cryogenic tanks. These tanks were specially made to maintain the pressure and temperature of the liquid hydrogen to maintain it in its current state of matter. With the hydrogen in liquid state, more volume of hydrogen could be stored but the disadvantage to this would be the cost of the liquefaction unit and its process. During the discharging process, the liquid hydrogen is then converted back to gaseous state and goes through the same discharging process mentioned above [67].

Hydrogen can also be stored in the solid state in a form of metal hydrides. Metal hydrides are metals that have been bonded to hydrogen forming a new compound. Most metals would be able to bond with hydrogen to form the metal hydride. The metal hydride would be easier to store as large volumes of hydrogen can be stored in this form [67].

Another method of storing hydrogen could be storing water itself. Adding a metal to water would form an oxide or hydroxide along with hydrogen gas. Water is freely available and easy to store. The only cost here would be the cost of the metals itself. The cost of procuring the metals might be slightly expensive but the cost of the process of producing hydrogen could be economically viable. The reaction is not reversible, but the hydroxide could be removed and returned to the metallic form with the by-product being water. This allows the water to be reused, further saving up the additional costs [57], [67].

2.3.1.4 Thermal Energy Storage

There are 3 types of thermal energy storage technologies which are sensible heat storage (SHS), latent heat storage (LHS) and chemical heat storage (CHS). Thermal energy storage has the 2nd highest number of installed capacity in the world. A SHS system stores energy in the form of heat energy either by heating or cooling the liquid or solid storage medium.

During the charging process the storage medium is heated whereas during the discharging process, the medium is then cooled. The amount of heat energy stored depends on the specific heat of the medium, the change in temperature of the medium and the amount of storage material present in the medium. It follows the specific heat capacity equation (6) shown below.

$$\mathbf{Q = \int_{ti}^{tf} mCpdt = mCp(tf - ti)} \qquad \mathbf{(6)}$$

where **Q** is the amount of heat stored in joules (J), **m** is the mass of heat storage medium in (kg), **Cp** is the specific heat capacity in (J/kg.K), **tf** is the final temperature in (°C) and **ti** is the initial temperature in (°C) [57], [68], [69].

Latent energy storage (LHS) stores heat energy by absorbing or releasing heat when the storage material itself goes through a phase change from solid to liquid or liquid to gas or vice versa of both. The heat is absorbed or released at constant temperature during the phase change process occurs. During the charging process, the heat is absorbed and vice versa for the discharging stage. This storage technology follows the specific latent heat equation (7) shown below [57], [68], [69].

$$\mathbf{Q = mL} \qquad \mathbf{(7)}$$

where **Q** is the amount of heat stored in joules (J), **m** is the mass of heat storage material in (kg) and **L** is the specific latent heat in (J/kg).

Another type of thermal storage is the chemical heat storage (CHS). CHS stores heat from endothermic or exothermic reactions. During the charging process, heat from the reactions is absorbed and stored. The heat is then released for the discharging process. An example reaction would be the thermal decomposition of metal oxides [57], [68], [69].

2.3.1.5 Electrical Energy Storage

Supercapacitor energy storage (SCS) is known for being a short term energy storage technology. It stores energy using static charge where a voltage difference across the positive and negative plates charges the capacitor. With its ability to quickly store and release energy, it is more suitable as a temporary storage system for short term power demands. It can be used as either a stand alone or in combination with other storage technologies such as batteries [57], [70].

2.3.2 Energy Storage for the Jabil Factory

All the energy storage technologies mentioned above have their unique characteristics in terms of system efficiency, cycle duration, self-discharge, etc. The suitability of the particular type of storage technology depends on these characteristics. For this study, the compressed air energy storage (CAES) was the choice of storage technology. CAES has been researched a lot but not many commercially available therefore making the possibility of implementing this system more interesting rather than the usual battery storage. The CAES system looked in this paper would be an aboveground system due to the geographical location of the factory.

2.3.2.1 Types of Compressed Air Energy Storage (CAES)

There are 3 main types of above ground CAES systems. These are:

- Adiabatic

An adiabatic system is one where the transfer of heat and mass does not occur. This means heat is not lost or gained throughout the system. Any heat produced during the compression is assumed to be completely stored and not lost to the environment. The same heat is then released during the expansion process [60], [71]. This means that the air storage unit would also play the role of a thermal energy storage system which greatly increases the efficiency of the entire system. According to A.G. Olabi et al., (2021), adiabatic systems tend to have RTE of between 60 to 75% [60], [72]. Another paper by B. Cheung et al., (2012), the efficiency of this system was enhanced by reducing the pressure losses which then gave RTE of between 62 to 65% [60], [73].

- Diabatic

A diabatic system is one where the transfer of heat occurs in the system. Heat can be gained or lost throughout any process within the system. Heat produced during the compression stage of the charging process can be lost to the environment with intercoolers within the structure of the system to improve overall efficiency. This means that less heat is released during the expansion stage of the discharging process [60]. A paper by H. Jafarizadeh et al., (2020), looked into the currently large scale CAES system in Huntorf, Germany under enhanced modifications which achieved a RTE of 42% [74]. The 2nd commercialized CAES plant in McIntosh, USA was also modified with the implementation of a recuperator to recover waste heat which increased the RTE from 42% to 54% [74].

- Isothermal

An isothermal system is one where the temperature within the entire system remains constant. This occurs because any changes within the system occurs very slowly [71]. Isothermal systems are still under development and would require special machinery to achieve this ideal state for the system. According to A.G. Olabi et al., (2021), the RTE of this system is said to be much higher than any other types of CAES systems since any heat produced during the compression or expansion is taken to be negligible in the equations [60].

2.3.2.2 CAES System Components

A CAES system consists of 4 main components. Off the shelf available components would be used to design this CAES system to ease the information gathering process such as energy intake, cost, efficiency, power output, etc. The 4 components are:

- Compressor

The compressor is the machine responsible for pressurising the air from the environment. With the help of the compressor, a greater volume of air would be able to be stored. According to K. Herriman., (2013), the RTE of the air compressor is around the range of 85 to 95% [71].

The chosen air compressor is a 2-stage V shaped diaphragm compressor which can be seen in the figure below. This is a positive displacement compressor which is able to compress any kinds of gas. The characteristics of the air compressor can be seen in the table below [75].

Table 2 - Air compressor characteristics [75]

Structure Type	V type
Piston Travel (mm)	70 – 130
Max. Piston Force (kN)	10 – 30
Max. Discharge Pressure (MPa)	50
Flow Rate Range (m3/h)	2 – 100
Motor Power (kW)	2.2 – 30

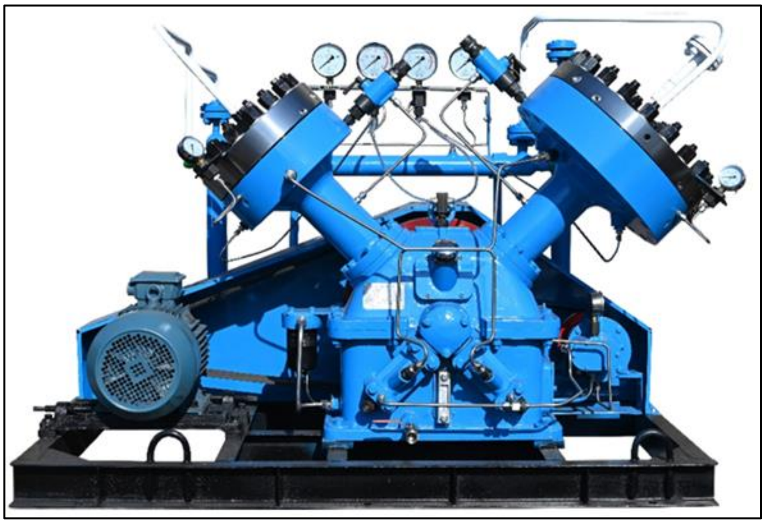


Figure 31 - Sollant's diaphragm air compressor [75]

This compressor was chosen with the maximum discharge pressure in mind. The intended pressure of the air stored was set at 50 MPa. This was because it enabled a great volume of air to be stored within a reasonable sized pressure vessel. An air pressure regulator would also be included into the system to ensure that constant pressure is maintained.

- <u>Storage Unit</u>

The storage unit is the most important component within the entire energy storage system. The sizing of the storage unit could be calculated using the ideal gas equation (8) shown below [71].

$$\boldsymbol{W = RT\left[\ln\frac{Pf}{Pi}\right]} \qquad \textbf{(8)}$$

where **W** is the energy in (J/kg), **Pf** is the final pressure in (kPa), **Pi** is the initial pressure (kPa), **R** is the gas constant which is (287 J/kg.K) and **T** is the absolute temperature which is (273 K).

- <u>Turbo Expander Generator</u>

An expander mostly known as a pneumatic motor or compressed air engine is responsible for expanding the compressed air before the air reached the inlet of the gas turbine. However, with modern turbines being built, a combination of an expander and turbine technology is available known as a turboexpander. A turboexpander expands high pressured gas and releases the energy. The specific type of turboexpander would be the generator loaded expander which is an expander system connected to an electric generator which then generates electricity. The turboexpander is said to achieve RTE of 84% to 86% [76].

The chosen turboexpander for this project is the EG L6000 from L.A. Turbine. The characteristics of this turboexpander is shown in the table below [77].

Table 3 - Turboexpander characteristics [77]

Turboexpander Configurations	EG (Expander Generator)
Frame Sizes	L6000
Bearing Types	Oil Bearings/Active Magnetic Bearings
Max. Inlet Flow (ACMH)	16,000
Max. Inlet Pressure (bars)	206
Temperature (℃)	-195 to 260
Max. RPM	15,000
Seal Types	Labyrinth Seal/Dry Gas
Max. Wheel Power (MW)	14

Figure 32 - Turboexpander [78]

- <u>Generator</u>

The proposed turbo expander also encompasses a generator within the entire structure. However, if the component is not able to do so, an electric generator would be included to complete the CAES system.

3.0 Results & Discussion

3.1PV System Optimisation

As mentioned in the literature review section, the 5 possible optimisation variables were looked into and optimised.

3.1.1 Pitch

Using the optimisation tool in the software, the optimal pitch was determined. The software defined the term pitch as the distance between 2 rows of solar panels. No change was achieved in terms of power generation because when the analysis was done, the optimal pitch value was already set. The optimal range for the pitch was roughly between (1-7)m. The pitch set during the design of the system was already set at 5m therefore having no effect on the power generation. The analysis range and the number of steps between the range was set to be relatively large to get a more accurate result and optimisation for the analysis. The steps were set at 50 where the analysis was measuring the energy generated at the array for every meter of increase in pitch length. The figure below shows the graph for the changing pitch and its effects on the energy generated at the array.

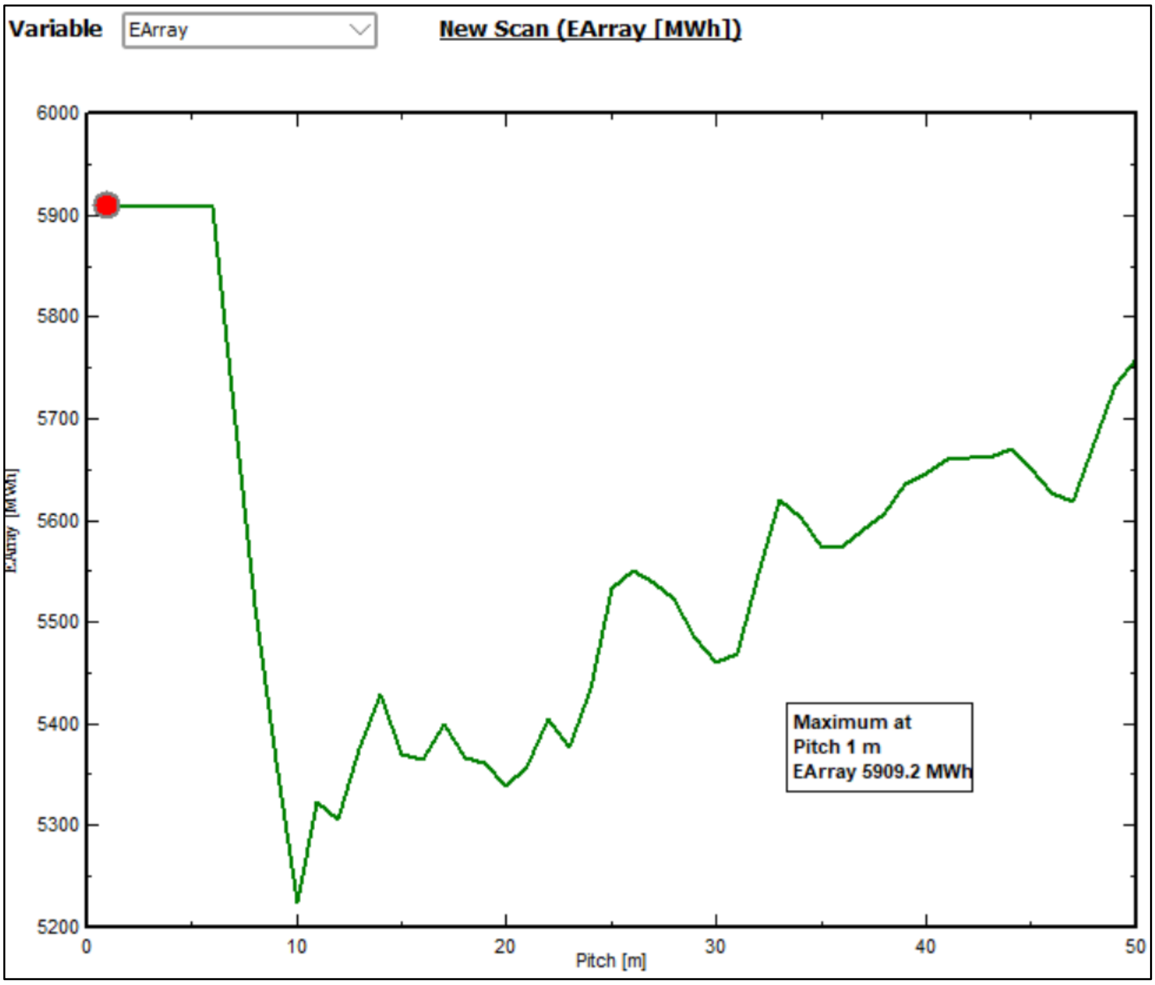


Figure 33 - Varying Pitch vs Energy at array

3.1.2 GCR

GCR also known as the ground coverage ratio is defined as the ratio of the module or system area to the available land area. This was an important factor to consider when designing a PV system as shading between the rows of the solar panel could occur which would result in the reduction in global irradiance on the panel which further leads to the reduction in power generated by the system itself. The module area for this design was about 18775m^2 while the available land area was approximately 18867m^2. This can be calculated with equation (9).

$$\mathbf{GCR} = \frac{\mathbf{Module\ Area}}{\mathbf{Land\ Area}} \times \mathbf{100\%}$$

$$\mathbf{GCR} = \frac{\mathbf{18775}}{\mathbf{18867}} \times \mathbf{100\%}$$

$$\mathbf{GCR} = \mathbf{100.04\%} \qquad \mathbf{(9)}$$

Using the optimisation tool with the software, a graph for the optimal GCR was produced. The graph can be seen below.

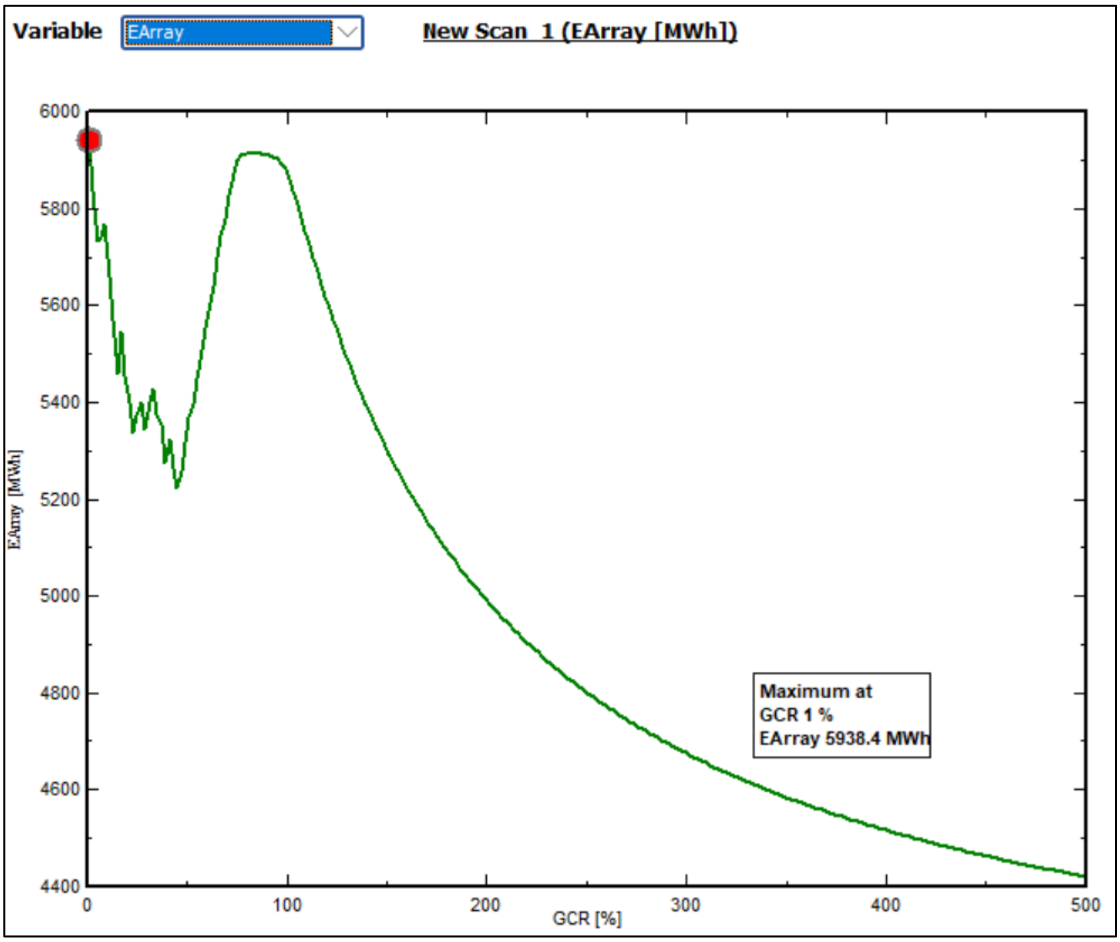


Figure 34 - Varying GCR vs Energy at array

From Figure 16 above, it can be seen that the optimal GCR value stands at 1%. The calculated value for the GCR based upon the module and land areas was 100%. Although the calculated value was a lot different, as seen in the figure above, the 100% GCR value would still be able to produce close to optimal amount of energy at the array. Not only that, in order to achieve the 1% GCR value, but the module area for the design would have to be 188.67m2. This would be very unrealistic since the area utilised for the PV system would be too small resulting in very little potential energy generation. This would defeat the purpose of the PV system itself. Therefore, the value of 100% was accepted to be the optimal GCR value for the PV system.

3.1.3 PV Module & Inverter

So far, the changes made to the system have not made any large changes to the power generation output as the values have already been at or very close to the optimal values for the PV system. A major change to the power generation would be seen by optimising the type of PV module and inverter being used in the system.

The change made to the type of module was fairly straightforward. A module with a much greater rated maximum power was chosen. The initial module was the JAM72S30 525-550/MR by the company JA Solar. This was a silicon monocrystalline module with a rated capacity of 535W with an efficiency of 20.7%. With the fixed land area available, the amount of energy generated with this module was estimated to be around 5768 MWh/year.

The optimised module was the RHA66HDGDC-715 by the company Winhitech. This was a bifacial type of solar panel which as mentioned before, has proven that bifacial modules are slightly more efficient than the regular silicon monocrystalline module. It had a rated capacity of 715W with an efficiency of 23.1%. Since the modules are of different rated capacities, the module area also differed. In order to restore the GCR back to 100%, the number of modules were reduced significantly from 7268 to 5971 . With the same land area available, the amount of energy generated increased to 6483 MWh/year.

The next change that was made to the system was the inverter used. The initial inverter used by Jabil was the Solis-110K-5G 3-phase inverter by the company Ginlong Solis. It had a maximum efficiency of 98.7% with 10MPPts. As the system was generating more power, the size of the inverter had to be increased slightly to accommodate this increase in power to allow the system to run smoothly. With the caution of not oversizing the inverter, another inverter was chosen.

The optimised inverter was the SG125CX-P2 by the company Sungrow. It had a maximum efficiency of 98.5% with 12 MPPTs. With the help of the larger sized inverter, the number of inverters that was used by the system was successfully reduced which not only is an optimisation to the system itself but also to the economic aspect of the system. In summary, optimising the type of PV module and inverter, had increased the generation from the PV system from 5768 to 6483 MWh/year.

3.1.4 Tilt Angle

The tilt angle for the design done by Jabil Penang was kept constant. For all 4 orientations present within the layout of the site and PV panels, the tilt angle was set at 4°. The tilt angle option using the optimisation tool was not available to the detailed and specific location and layout of the PV panels on the site.

Analysis of the tilt angle with respect to all 4 different orientations was still carried out by changing the tilt angle by 1° and comparing the changed in the tilt angle to the amount of irradiance captured by the panel at each angle. Graphs of the these was also presented by the software. A separate table alongside much more readable graphs were made by noting down the changes in angle with respect to the irradiance which can be seen in the figure below.

Orientation 1			Orientation 2			Orientation 3			Orientation 4		
Tilt (°)	Global Irradiance on Plane (kWh/m2)	Loss with respect to Optimum (%)	Tilt (°)	Global Irradiance on Plane (kWh/m2)	Loss with respect to Optimum (%)	Tilt (°)	Global Irradiance on Plane (kWh/m2)	Loss with respect to Optimum (%)	Tilt (°)	Global Irradiance on Plane (kWh/m2)	Loss with respect to Optimum (%)
1	1811	-0.2	1	1808	-0.4	1	1811	-0.2	1	1807	-0.4
2	1813	-0.1	2	1807	-0.4	2	1813	0	2	1806	-0.4
3	1814	0	3	1805	-0.5	3	1815	0	3	1805	-0.5
4	1816	0	4	1806	-0.6	4	1817	0	4	1803	-0.6
5	1817	0	5	1802	-0.7	5	1818	0	5	1800	-0.7
6	1817	0	6	1799	-0.8	6	1818	0	6	1798	-0.9
7	1817	0	7	1796	-1	7	1819	0	7	1794	-1.1
8	1817	0	8	1793	-1.2	8	1819	0	8	1791	-1.3
9	1816	0	9	1789	-1.4	9	1818	0	9	1787	-1.5
10	1815	0	10	1785	-1.6	10	1817	0	10	1782	-1.7
11	1813	-0.1	11	1780	-1.8	11	1816	0	11	1778	-2
12	1811	-0.2	12	1776	-2.1	12	1814	0	12	1772	-2.3
13	1809	-0.3	13	1771	-2.4	13	1812	-0.1	13	1767	-2.6
14	1807	-0.4	14	1766	-2.7	14	1809	-0.2	14	1761	-2.9
15	1804	-0.6	15	1760	-3	15	1807	-0.4	15	1755	-3.2
16	1801	-0.7	16	1754	-3.3	16	1804	-0.6	16	1749	-3.6
17	1797	-0.9	17	1748	-3.6	17	1800	-0.8	17	1742	-3.9
18	1794	-1.1	18	1741	-4	18	1797	-1	18	1735	-4.3
19	1789	-1.4	19	1734	-4.4	19	1792	-1.2	19	1728	-4.7
20	1785	-1.6	20	1727	-4.8	20	1788	-1.4	20	1720	-5.2

Figure 35 - Tilt angle and corresponding irradiance for all 4 orientations

From Figure 15 above, the green highlighted values are the optimal tilt angle for each orientation. Graphs representing the tables could be seen below.

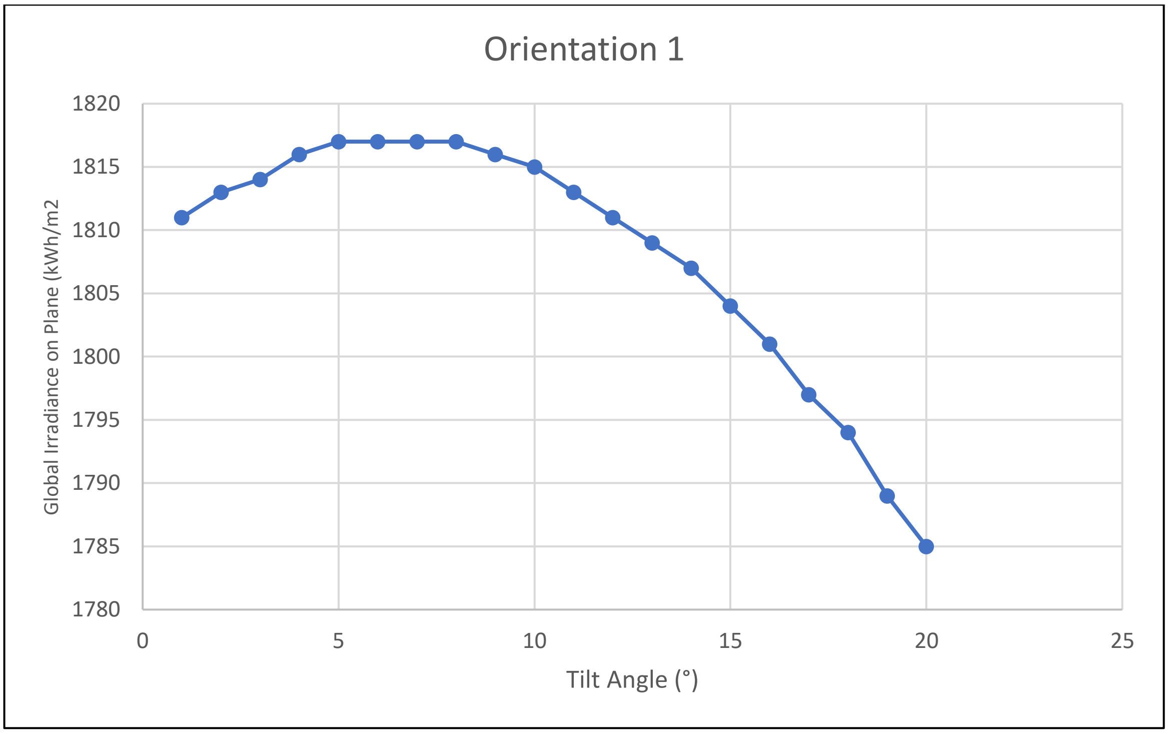


Figure 36 - Irradiance vs Tilt angle for Orientation 1

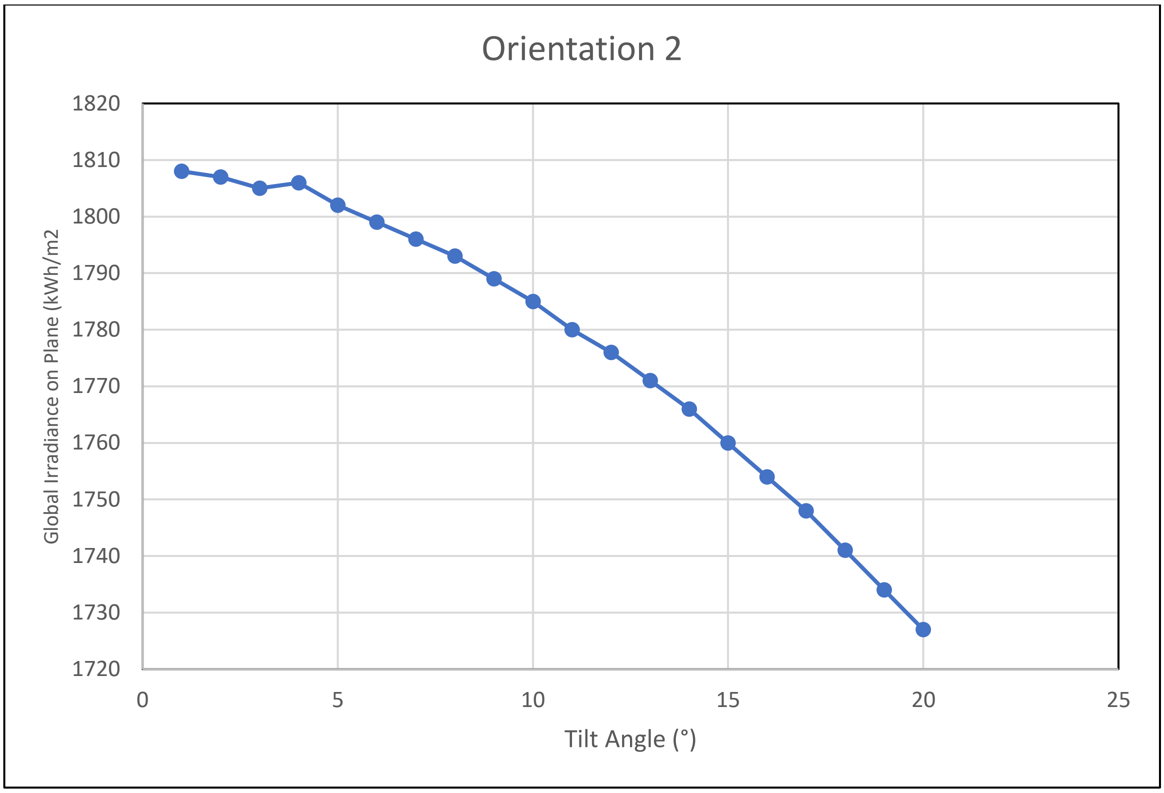


Figure 37 - Irradiance vs Tilt angle for Orientation 2

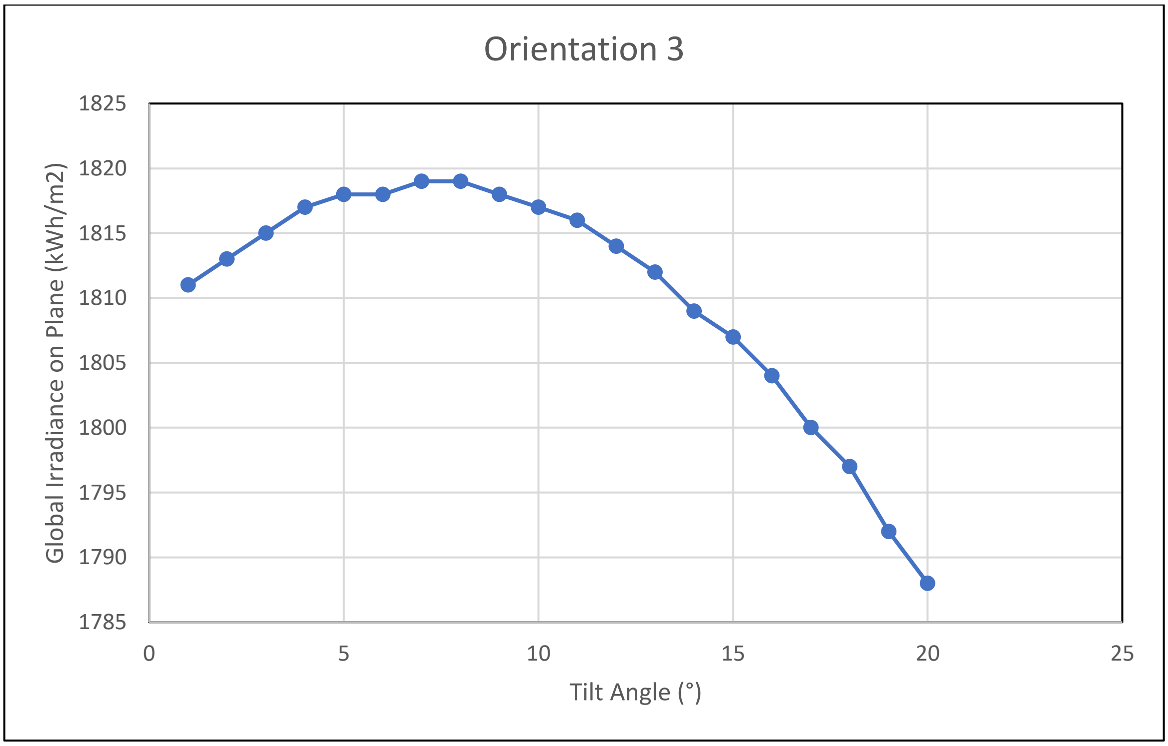


Figure 38 - Irradiance vs Tilt angle for Orientation 3

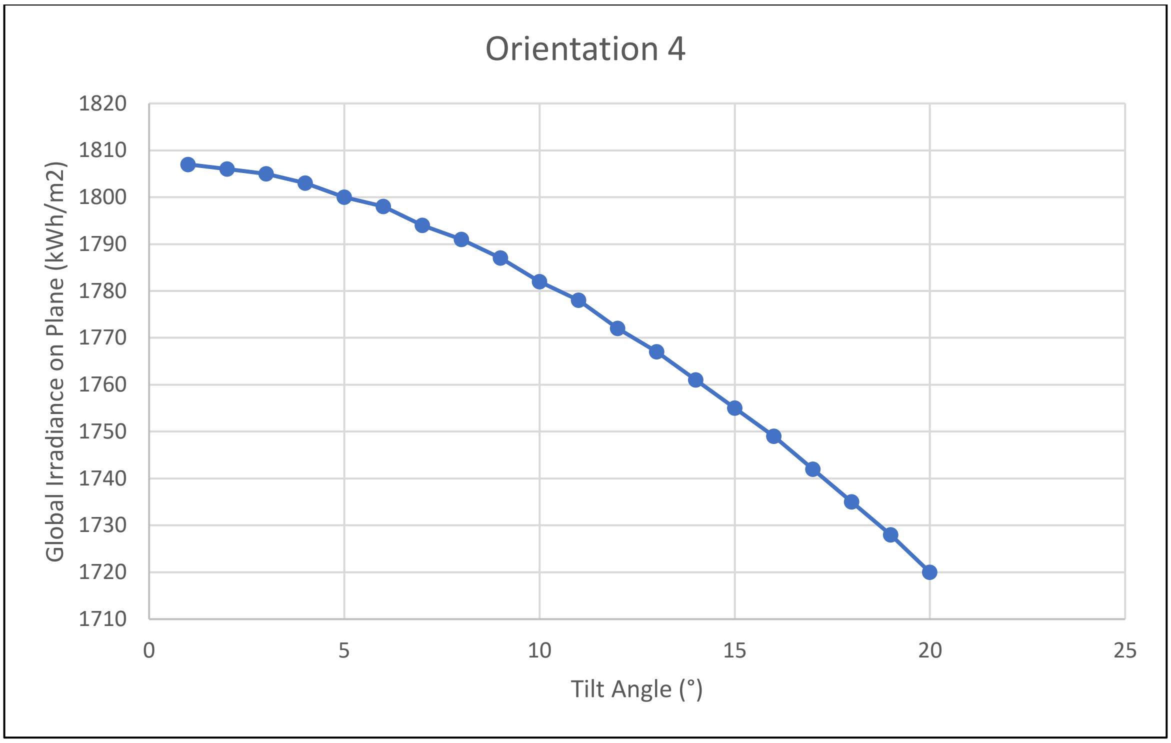


Figure 39 - Irradiance vs Tilt angle for Orientation 4

From the figures above, the optimal tilt angle with the highest global irradiance on the plane for all 4 orientations are listed below:

- Orientation 1: Tilt angle – (5-8)° ; Irradiance – 1817 kWh/m2
- Orientation 2: Tilt angle – 1° ; Irradiance – 1808 kWh/m2
- Orientation 3: Tilt angle – (7-8)° ; Irradiance – 1819 kWh/m2
- Orientation 4: Tilt angle – 1° ; Irradiance – 1807 kWh/m2

Changing the tilt angle although very minimal, had a slight increase in the system's yearly power generation. The value increased from 6483 MWh/year to 6489 MWh/year. Although the increase may appear small, any increase in power generation is appreciated considering the massive difference between the factory's energy consumption and PV system energy generation.

3.1.5 Azimuth

Due to the very specific positioning and layout of the Jabil Penang site, the azimuth was not altered since the recreation model was made to imitate the original layout and plan of the PV system present at Jabil Penang. Due to this, the azimuth was not optimised, and it is assumed that prior to the PV system's installation at Jabil, the optimal azimuth was analysed and used.

3.1.6 PV Calculations

The table below shows the increase in energy generation with each optimisation step taken discussed previously. It also shows the offset each step makes in regard to the factory's total energy consumption. The calculations to the values presented in the table can be viewed in the appendix.

Table 4 - Energy generation increase with optimisation and resulting decrease in factory's energy consumption

<table>
<tr><th>Optimisations Made</th><th>Energy Generation (MWh/year)</th><th>Total Energy Generated (MWh/year)</th><th>Energy Consumption Reduction (MWh/year)</th><th>Total Energy Consumption Reduction (MWh/year)</th></tr>
<tr><td>Initial Values</td><td>1917.2</td><td rowspan="3">1917.2</td><td>54,655.7</td><td rowspan="3">54,655.7</td></tr>
<tr><td>Pitch</td><td>0</td><td>0</td></tr>
<tr><td>GCR</td><td>0</td><td>0</td></tr>
<tr><td>PV Module & Inverter</td><td>417.2</td><td>2334.4</td><td>2334.4</td><td>52,321.3</td></tr>
<tr><td>Tilt Angle</td><td>149</td><td rowspan="2">2483.4</td><td>149</td><td rowspan="2">52,172.3</td></tr>
<tr><td>Azimuth</td><td>0</td><td>0</td></tr>
</table>

As seen in the table above, the optimised PV system was unable to offset the factory's energy consumption. Therefore, further generation and overall system optimisation had to be done.

3.2 Other Optimisation

The table below shows the additional energy generated and reduction in energy consumption from the 3 other system optimisation steps taken. The calculations to the values presented in the table can be viewed in the appendix.

Table 5 - Energy generation & resulting decrease in factory's energy consumption

Optimisations Made	Energy Generation (MWh/year)	Total Energy Generated (MWh/year)	Energy Consumption	Total Energy Consumption

<table>
<tr><td></td><td></td><td></td><td>Reduction (MWh/year)</td><td>Reduction (MWh/year)</td></tr>
<tr><td>Initial Values</td><td>2483.4</td><td>2483.4</td><td>52,172.3</td><td>52,172.3</td></tr>
<tr><td>Extra PV Generation</td><td>2817.4</td><td rowspan="2">5300.8</td><td>2817.4</td><td>49,354.9</td></tr>
<tr><td>Heat Pump</td><td>0</td><td>25% energy reduction</td><td>37,016.2</td></tr>
<tr><td>Piezo-electric Tiles</td><td>190,530</td><td>195,830.8</td><td>190,530</td><td>-153,513.8</td></tr>
</table>

The -153,513.8 MWh/year seen in table 5 above, shows that this is the surplus energy available after offsetting the energy consumption of the factory.

3.3Jabil's CAES System

For the CAES system to function, the components within the system requires energy. This then increases the energy consumption of the factory again by which the surplus energy would offset as seen previously. The calculations to the values presented in the table can be viewed in the appendix.

Table 6 - Energy consumption of the CAES system components

<table>
<tr><th>CAES System Components</th><th>Energy Consumption Reduction (MWh/year)</th><th>Total Energy Consumption Reduction (MWh/year)</th></tr>
<tr><td>Total Energy Generated (MWh/year)</td><td colspan="2">153,513.8</td></tr>
<tr><td>Compressor</td><td>87.6</td><td>153,426.2</td></tr>
<tr><td>Storage</td><td>27,272.8</td><td>126,153.4</td></tr>
<tr><td>Turboexpander Generator</td><td>96,360</td><td>29,793.4</td></tr>
</table>

In order to complete the CAES system for the Jabil factory, the pressurised storage vessel was looked into. The energy required by the factory during non PV generation hours was calculated as seen in the appendix. Using equation (8) mentioned above, the volume of the pressure vessel was calculated to be 865.5 m^3. This size of this vessel although seemingly large, could be split into smaller vessels for safety and economic measures. An important assumption is that the efficiency of the CAES system to recover the stored energy is close to 100% since the system is considered to be isothermal.

To ensure more than enough energy is able to support the factory during bad weather days and such, the proposed pressure vessel volume would be 2600m^3. This volume would be able to provide energy for 2 whole days. This is equivalent to 3 units of the pressure vessel. In any event where insufficient energy was produced, the factory could still resort to purchasing energy from the grid. This would be a last resort backup plan for the factory. A simple schematic of the proposed system can be seen in the figure below to show how the CAES system would function.

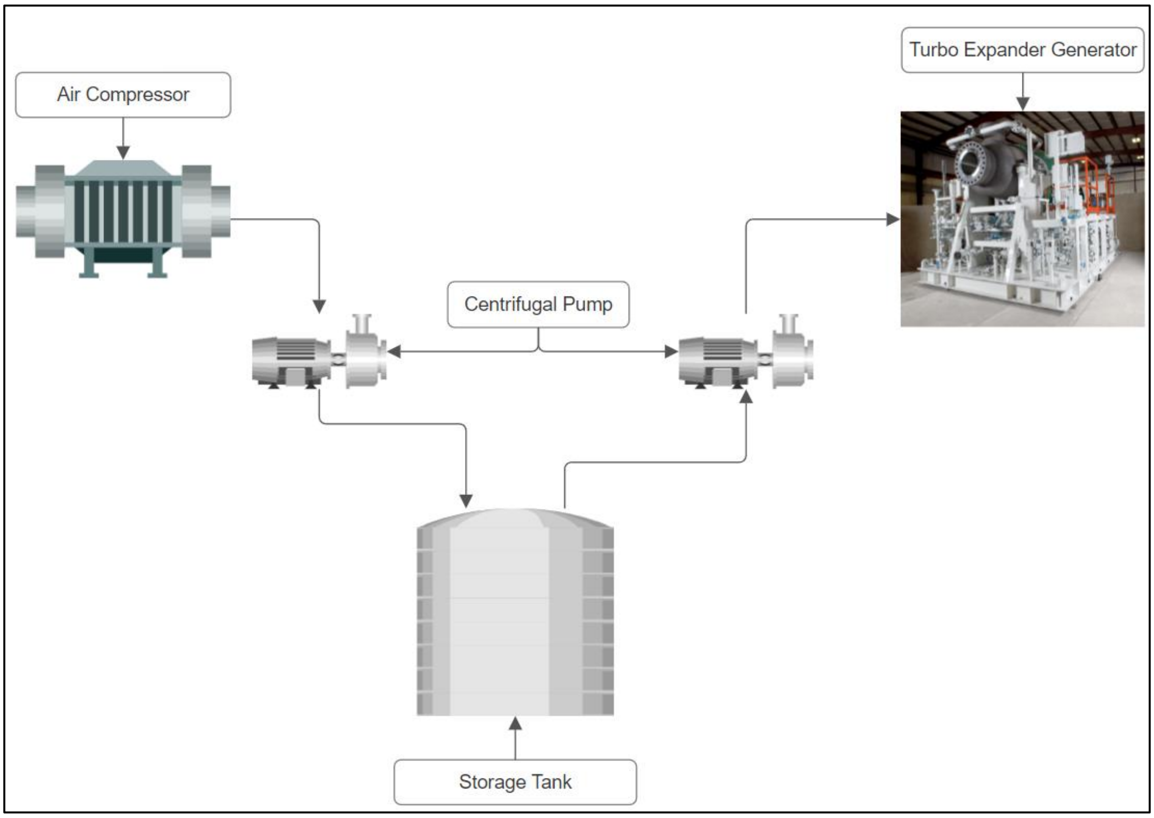


Figure 40 - Schematic of the proposed CAES system

During the day, the PV systems would be generating energy alongside the piezo-electric tiles with the workers walking over them throughout the office hours. The PV system would be able to generate energy for 8 hours leaving the remaining 16 hours without any energy being generated. This is where the storage system comes into place. The energy generated by the PV system and tiles would not only offset the entire factory's energy consumption but power the CAES system components in order to store the excess energy into the pressurised storage vessel. The energy consumption of the CAES components were calculated to understand how much energy would be required by the system to store the energy as well as approximately how much energy was needed for the factory to run without the PV system.

The energy for the CAES system would first power the compressor where air from the environment would be compressed to the intended pressure and pumped into the pressure vessel. A pressure regulator would be attached to the system to ensure the pressure within the vessel is maintained. During the 8 hours of the day, air would constantly be compressed and stored.

During the remaining 16 hours, the energy would need to be extracted to power the factory and other machinery. The pressured air inside the vessel would be let out through controlled valves. This air would go through the turbo expander generator and expand reducing its pressure. This air would then pass through the turbine section of the turbo expander generator. The air would rotate the blades of the turbine converting mechanical energy into electricity with the help of the generator attached to the turbo expander generator. This in return produces the electricity required by the factory to function as usual. The stored air would be able to produce more than enough energy before the PV system comes into play again.

The turbo expander generator chosen for Jabil was designed to carry out both the expanding and generating processes giving electricity as the output. It also contains a turbine where the expanded air would go to rotate the blades within the turbine section. This explains the large energy consumption of the machine itself.

After powering the entire factory, an approximate value of 29,793.4 MWh/year as seen in table 6 would be the surplus energy available. This would be used to power the pumps, valves, etc or sold back to the grid yielding a significant amount of profit. Since the energy generation by the piezo-electric tiles were underestimated, more energy could be sold but for this paper, only 29,793.4 MWh/year would be accounted for in the project's cost.

3.4Project Cost

A simple economic assessment was made to check the feasibility of this proposed plan. This includes the PV system, heat pumps, piezo-electric tiles, additional PV generation, the CAES system, etc. The economic assessment would give an approximate costing to set up the proposed plan following Malaysia's market prices for the technologies. Most of the information was provided by Jabil (Malaysia) with their access to quotes and the current market prices to technologies. The costs are shown in US Dollars ($) after the conversion from the Malaysian Ringgit (RM).

A graph of the net present value against the lifetime of the project was made to show this. This can be seen in the figure below.

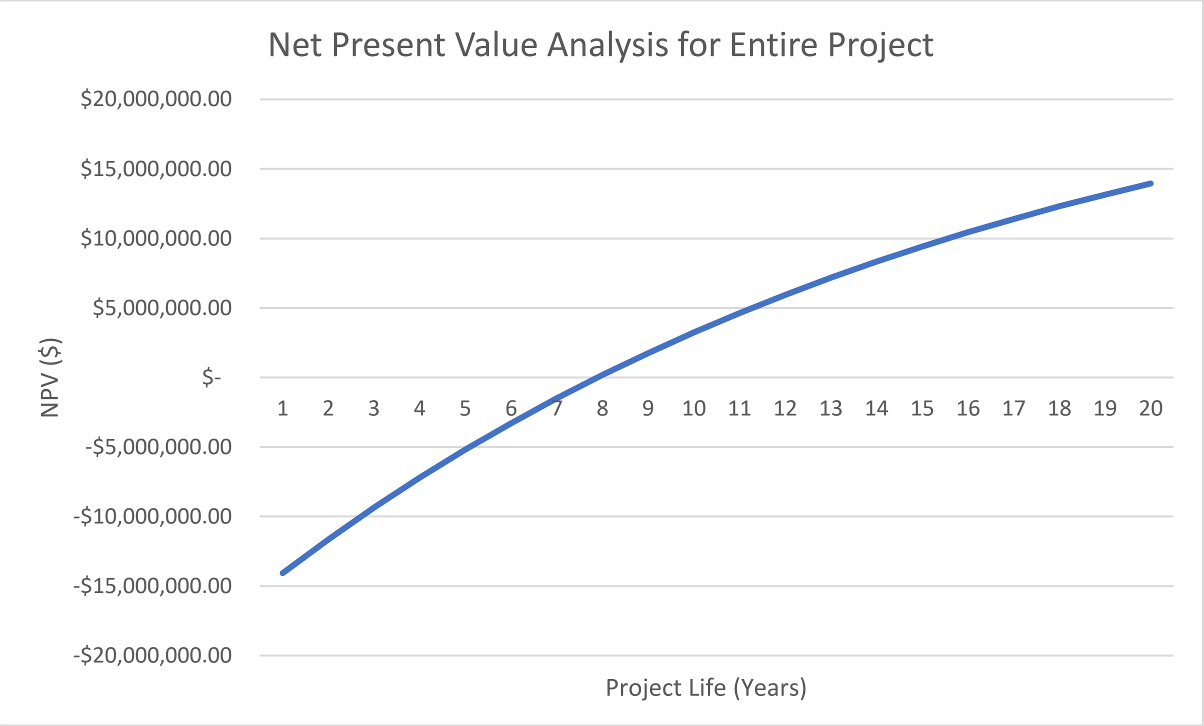


Figure 41 - NPV vs Project Life

From the figure above, it can be seen that the NPV becomes positive in the 8th year. This shows Jabil that the project is worth undertaking as an investment. Although achieving the break even in almost 8 years can be seen as very long and discouraging the future prospect beyond that can be seen to be quite fruitful considering that from the implementation of this proposed plan, there would be no money lost in the purchase of energy making this a feasible plan. It was also seen that the payback period for this plan would be approximately 7 – 8 years. This plan would be a much more beneficial plan in the long term.

3.5 CO_2 Savings

The amount of CO_2 reduction achievable by this project was calculated. The whole purpose of investing in renewable energy technologies was to move away from fuel sources that produce greenhouse gases primarily CO_2. The value provided by Jabil was 0.78 kg of CO_2/kWh of energy. A source from the US used the value of 1.025 kg of CO_2/kWh which was fairly similar to the value provided by Jabil [79]. Using 0.78 kg of CO_2/kWh and considering the demand of the factory was at 54,655.7 MWh/year, an approximate total of 42,631.5 tonnes of CO_2 was reduced since the factory is running completely on renewable sources and not using the energy from the grid.

4.0 Conclusions

4.1Achievement of Project Aims & Objectives

- Optimising the PV system at the Jabil factory

The PV system at Jabil was successfully optimised with more energy being generated as discussed in the results section of the paper. This optimisation highlighted that more energy needed to be generated to become self-sufficient.

- Optimise the overall factory to make it self-sufficient

Integrating the use of heat pumps, additional rooftop generation and piezo-electric tiles, the factory was able to become self-sufficient. However, the absence of PV generation for 16 hours of the day meant that an energy storage system had to be integrated.

- Research all the possible types of energy storage technologies and selecting one

Research into all the different types of energy storage technologies available was carried out where the CAES system was chosen as the preferred choice of energy storage system due to the interesting prospect it holds to be implemented for industrial buildings. With the lack of research for a CAES system for a factory, it had an interesting prospect to it.

- Design a CAES system using commercially available components

A bigger view design was made with the approximate values of energy needed to run for the 16 hours and the corresponding volume of storage needed for this design to work. Further research in this section of this paper would be needed to analyse the entire system with more accuracy.

- Checking the feasibility of the plan economically

An NPV against the entire project life was made to show that the plan would be worth considering and implementing as more cost would be saved from purchasing energy from the grid which is also heavily dependent on fossil fuel.

4.2Future Work

A more in depth analysis of the CAES system could be done using modelling software’s to find out the time taken for the CAES system take to charge and discharge. One limitation within this project was the data provided by Jabil. The energy demand of the factory was given as an average rather than an hourly demand profile. This made it slightly difficult to calculate the exact sizing required for the storage vessel. With more information on the charging and discharging cycle of the CAES systema more in depth design of the energy storage system could be put in place.

Further research could be done in the optimisation processes that occurred throughout the project. A better choice of expander, compressor, PV module, PV inverter, etc could be done with more analysis on the individual component itself. This paper provided the larger picture of the entire design for this self-sufficient plan with prospect for future work and improvements within the individual component itself.

An interesting future research could be the effects of reheating the compressed air and what effects that has onto the CAES system in terms of efficiency, the other components of the system, etc [71].

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6.0 Appendices

Jabil Penang factory had an initial demand value of **54 655.7 MWh/year**. Jabil Penang had already installed a rooftop PV system with an installed capacity of 3772 kWp. Before installing this system, they had used the PV Syst software to model and simulate this system. Therefore, to make the optimisation of this system possible, a recreation of Jabil's PV Syst model was made. To validate Jabil's model, a comparison between the model's potential generation vs the actual generation was made. The comparison was calculated as shown below.

- Jabil's PV Syst Model

$$\boldsymbol{Potential\ Energy\ Generation}$$
$$\boldsymbol{= Installed\ Capacity\ \times Hours\ of\ Operation\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 3888\ \times 8\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 11352960\ kWh/year}$$

$$\boldsymbol{Potential\ Energy\ Generation = 11,353\ MWh/year}$$

- Multiply STC of 20.70% so then,

$$\boldsymbol{= 11,353\ MWh/year \times 20.70\%}$$

$$\boldsymbol{= 2350\ MWh/year}$$

- After losses,

$$\boldsymbol{= 2350\ MWh/year \times 84.09\%}$$

$$\boldsymbol{= 1976\ MWh/year}$$

- Jabil Real Generation

$$\boldsymbol{Potential\ Energy\ Generation}$$
$$\boldsymbol{= Installed\ Capacity\ \times Hours\ of\ Operation\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 3772\ \times 8\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 11014240\ kWh/year}$$

$$\boldsymbol{Potential\ Energy\ Generation = 11,014.24\ MWh/year}$$

- Multiply STC of 20.70% so then,

$$= \boldsymbol{11,014.24\ MWh/year} \times \boldsymbol{20.70}\%$$

$$= \boldsymbol{2280\ MWh/year}$$

- After losses,

$$= \boldsymbol{2280\ MWh/year} \times \boldsymbol{84.09}\%$$

$$= \boldsymbol{1917.2\ MWh/year}$$

Comparing the two values, they were very similar which was enough to validate that the PV Syst model was accurate enough to predict the actual generation values. The main aim of this project was to optimise this system by several means. By optimising the PV system, itself, the new values were calculated as shown below.

- <u>Jabil's PV Syst Model</u>

$$\boldsymbol{Potential\ Energy\ Generation}$$
$$\boldsymbol{= Installed\ Capacity\ \times Hours\ of\ Operation\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 4269\ \times 8\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 12465480\ kWh/year}$$

$$\boldsymbol{Potential\ Energy\ Generation = 12,465.5\ MWh/year}$$

- Multiply STC of 23.09% so then,

$$= \boldsymbol{12,465.5\ MWh/year} \times \boldsymbol{23.09}\%$$

$$= \boldsymbol{2878\ MWh/year}$$

- After losses,

$$= \boldsymbol{2878\ MWh/year} \times \boldsymbol{88.69}\%$$

$$= \boldsymbol{2552.5\ MWh/year}$$

- Jabil Real Generation

$$\boldsymbol{Potential\ Energy\ Generation}$$
$$\boldsymbol{= Installed\ Capacity\ \times Hours\ of\ Operation\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 4153\ \times 8\ \times 365}$$

$$\boldsymbol{Potential\ Energy\ Generation = 12126760\ kWh/year}$$

$$\boldsymbol{Potential\ Energy\ Generation = 12,126.8\ MWh/year}$$

- Multiply STC of 23.09% so then,

$$\boldsymbol{= 12,126.8\ MWh/year \times 23.09\%}$$

$$\boldsymbol{= 2800\ MWh/year}$$

- After losses,

$$\boldsymbol{= 2800\ MWh/year \times 88.69\%}$$

$$\boldsymbol{= 2483.4\ MWh/year}$$

After the optimisation process, the demand for Jabil's factory would be calculated as shown below.

$$\boldsymbol{New\ Demand = 54,655.7\frac{MWh}{year} - 2483.4\frac{MWh}{year}}$$

$$\boldsymbol{New\ Demand = 52,172.3\ \frac{MWh}{year}}$$

For the factory to be self-sufficient, further generation needed to be added to the entire system. The easiest way to do this was to utilise any nearby available derelict land as well as all the carparks for additional roof PV systems. As seen above, the total available area is 24,277.6 m^2. The additional generation value was calculated using another equation used in the loss diagram of the PV Syst software to ensure the estimate was kept accurate and constant.

$$\boldsymbol{Potential\ Generation = Irradiance\ after\ losses\ \times Available\ Area}$$

$$\boldsymbol{Potential\ Generation} = \mathbf{1700}\,\frac{\boldsymbol{kWh}}{\boldsymbol{m2}} \times \mathbf{24,277.6\ m2}$$

$$\boldsymbol{Potential\ Generation} = \mathbf{41271920\ kWh/year}$$

$$\boldsymbol{Potential\ Generation} = \mathbf{41,271.9}\ \boldsymbol{MWh/year}$$

$$\boldsymbol{Potential\ Generation} = \mathbf{41,271.9}\,\frac{\boldsymbol{MWh}}{\boldsymbol{year}} \div \mathbf{24}\ \boldsymbol{hours}$$

$$\boldsymbol{Potential\ Generation} = \mathbf{1719.7}\ \boldsymbol{MW/year}\ (\boldsymbol{Value\ is\ in\ Power})$$

$$\boldsymbol{Potential\ Generation} = \mathbf{1719.7}\ \boldsymbol{MW/year}\ \times \mathbf{8}\ \boldsymbol{operational\ hours}$$

$$\boldsymbol{Potential\ Generation} = \mathbf{13,757.6}\ \boldsymbol{MWh/year}$$

- Multiply STC of 23.09% so then,

$$= \mathbf{13,757.6}\ \boldsymbol{MWh/year} \times \mathbf{23.09}\%$$

$$= \mathbf{3176.6}\ \boldsymbol{MWh/year}$$

- After losses,

$$= \mathbf{3176.6}\ \boldsymbol{MWh/year} \times \mathbf{88.69}\%$$

$$= \mathbf{2817.4}\ \boldsymbol{MWh/year}$$

This further reduces the energy demand of the factory as shown below.

$$\boldsymbol{New\ Demand} = \mathbf{52,172.3}\,\frac{\boldsymbol{MWh}}{\boldsymbol{year}} - \mathbf{2817.4}\,\frac{\boldsymbol{MWh}}{\boldsymbol{year}}$$

$$\boldsymbol{New\ Demand} = \mathbf{49,354.9}\ \frac{\boldsymbol{MWh}}{\boldsymbol{year}}$$

The next optimisation step was aimed towards reducing the energy consumption of the factory. The first optimisation was to retrofit the factory with heat pumps. As mentioned above, in order to not overestimate the potential energy reduction, only 25% energy savings was taken. The new demand was calculated as shown below.

$$\boldsymbol{New\ Demand} = \mathbf{75}\%\ \times \mathbf{49,354.9}\,\frac{\boldsymbol{MWh}}{\boldsymbol{year}}$$

$$\boldsymbol{New\ Demand = 37,016.2\ \frac{MWh}{year}}$$

To increase the factory's total energy generation, the use of piezoelectric tiles was looked into. An estimate value of the potential energy generated by the tiles were calculated as shown below. The generation value was calculated as not to overestimate the true potential of the tiles.

$$\begin{aligned}\boldsymbol{Potential\ Generation}&\\ &\boldsymbol{= Power\ Produced\ per\ Tile \times Number\ of\ Tiles}\\ &\boldsymbol{\times Average\ Number\ of\ Steps\ per\ Person}\\ &\boldsymbol{\times Number\ of\ People\ in\ the\ Factory\ \times Operational\ Hours}\\ &\boldsymbol{\times 365\ days}\end{aligned}$$

$$\boldsymbol{Potential\ Generation = \frac{8W}{step} \times 1500 \times 10 \times 2175 \times 4 \times 365\ days}$$

$$\boldsymbol{Potential\ Generation = 381,060\ MWh/year}$$

- After including estimate efficiency of 50%,

$$\boldsymbol{Potential\ Generation = 381,060\frac{MWh}{year} \times 50\%}$$

$$\boldsymbol{Potential\ Generation = 190,530\ MWh/year}$$

To calculate the total energy available after the final optimisation process is calculated as seen below.

$$\boldsymbol{Available\ Energy = Energy\ Generated - Energy\ Demand}$$

$$\boldsymbol{Available\ Energy = 190,530\frac{MWh}{year} - 37,016.2\frac{MWh}{year}}$$

$$\boldsymbol{Available\ Energy = 153,513.8\ MWh/year}$$

This is the surplus energy available to be stored. However, the components that make up the energy storage system also require energy. Therefore, the amount of energy required to run the system needs to be removed. The compressor needs to be working at maximum capacity to achieve the 50 MPa intended pressure target. Therefore, the compressor's power usage would also be at its maximum. The compressor's yearly energy consumption can be calculated as shown below.

$$\boldsymbol{Energy\ Required = Max\ Rated\ Power\ \times Operational\ hours}$$

$$\boldsymbol{Energy\ Required = 0.03\ MW\ \times 8}$$

$$\boldsymbol{Energy\ Required = 0.24\frac{MWh}{day} \times 365\ days}$$

$$\boldsymbol{Energy\ Required = 87.6\ MWh/year}$$

The PV generation only occurs for 8 hours therefore, the energy surplus should be sufficient for the remaining 16 hours. This can be calculated as shown below.

$$\boldsymbol{New\ Demand = 75\%\ \times 54,655.7\frac{MWh}{year}}$$

$$\boldsymbol{New\ Demand = 40,991.2\ \frac{MWh}{year}}$$

$$\boldsymbol{New\ Demand = 40,991.2\ \frac{MWh}{year} \div 365}$$

$$\boldsymbol{New\ Demand = 112.3\ \frac{MWh}{day} \div 24}$$

$$\boldsymbol{New\ Demand = 4.67MW \times 16\ operational\ hours \times 365}$$

$$\boldsymbol{New\ Demand = 27,272.8\frac{MWh}{year}}$$

The same way, the turboexpander would require energy. From the characteristics table shown above, the energy required for this machine can be calculated as shown below.

$$\boldsymbol{Energy\ Required = Max\ Rated\ Power\ \times Operational\ hours}$$

$$\boldsymbol{Energy\ Required = 16.5\ MW\ \times 16}$$

$$\boldsymbol{Energy\ Required = 264 \frac{MWh}{day} \times 365\ days}$$

$$\boldsymbol{Energy\ Required = 96360\ MWh/year}$$

- therefore, final energy surplus available is,

$$\boldsymbol{Available\ Energy = 41,736.2 \frac{MWh}{year} - 87.6 \frac{MWh}{year} - 27,272.8 \frac{MWh}{year} - 96,360 \frac{MWh}{year}}$$

$$\boldsymbol{Available\ Energy = 29,793.4\ MWh/year}$$

This additional surplus energy can either be stored but would need a larger size pressure vessel or could be sold back to the grid which would bring in profit to the company. It could also be used to provide energy to other components that was not looked into such as the generator, etc.

The equations used for this section is only valid because the CAES system is assumed to be isothermal. Now the volume of pressure vessel can be calculated [71].

$$\boldsymbol{W = RT \left[\ln \frac{Pf}{Pi}\right]}$$

$$\boldsymbol{W = 287 \frac{J}{kg.K} \times 293\ K \left[\ln \frac{50000\ kPa}{100\ kPa}\right]}$$

$$\boldsymbol{W = 522,593 \frac{J}{kg}}$$

- **1 WH/kg = 3600 J/kg so,**

$$\boldsymbol{W = \frac{522,593}{3600}}$$

$$\boldsymbol{W = 145.2 \frac{Wh}{kg}}$$

- Rearrange the ideal gas law (PV=mRT) to give litres/kg so,

$$\frac{V}{m} = \frac{RT}{P}$$

$$\frac{V}{m} = \frac{287 \times 293}{(50000 \times 10^3)}$$

$$\frac{V}{m} = 1.682 \times 10^{-3} \frac{m^3}{kg}$$

$$\frac{V}{m} = 1.682 \ \frac{litres}{kg}$$

- Energy Density:

$$\frac{W}{V} = \frac{Wh}{litre} \quad so,$$

$$\frac{W}{V} = \frac{145.2 \frac{Wh}{kg}}{1.68 \frac{litres}{kg}}$$

$$\frac{W}{V} = 86.4 \frac{Wh}{litres} \quad OR,$$

$$\frac{W}{V} = \frac{145.2 \frac{Wh}{kg}}{(1.682 \times 10^{-3}) \frac{m^3}{kg}}$$

$$\frac{W}{V} = 86,335 \ \frac{Wh}{m^3}$$

- Rearranging the equation and units around,

$$Energy\ Surplus\ (Wh) = Energy\ Density\ \left(\frac{Wh}{m^3}\right) \times Volume\ (m^3)$$

$$(74.72 \times 10^6) Wh = 86,335\ \left(\frac{Wh}{m^3}\right) \times Volume\ (m^3)$$

$$\underline{Volume = 865.5\ m^3}$$

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