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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

Study of the installation of a PV Plant with an integrated battery energy storage system (BESS) connected to the grid in Queensland, Australia

Author: Jorge Mullor Martínez

Supervisor: Ignacio Oleaga Ballester

Madrid

June, 2020

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Analysis of a PV Plant with an integrated battery energy storage system (BESS) connected to the grid in Queensland, Australia

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EL DIRECTOR DEL PROYECTO

Fdo.: Ignacio Oleaga Ballester Fecha: 24/08/2020

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I would like to thank Ignacio Oleaga for offering and supervising such an interesting project as this one, and for introducing me to the engineering world. Your dedication and commitment have made me consider you a model in the professional aspect and in life in general.

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STUDY OF THE INSTALLATION OF A PV PLANT WITH AN INTEGRATED BATTERY ENERGY STORAGE SYSTEM (BESS) CONNECTED TO THE GRID IN QUEENSLAND, AUSTRALIA

Author: Mullor Martínez, Jorge.
Supervisor: Oleaga Ballester, Ignacio.
Collaborating Entity: GRANSOLAR

ABSTRACT

This paper analyses the viability of the construction of a PV Plant in Queensland, Australia with an integrated battery energy storage system (BESS). The procedure followed consists on calculating the profitability of the plant as a standalone, choosing all elements that take part in a solar plant, and then, comparing it with the extra benefit obtained by the BESS, having developed an algorithm that simulates the functioning of the battery.

Keywords: PV Plant, Battery Energy Storage System (BESS), Battery, Energy Storage, Renewable Energy, Australia.

1. Introduction

The Australian's energy needs have been successfully met by fossil fuels up to date. Australia is the largest producer and exporter of black and brown coal, and its energy production has been significantly dependant on their exploitation (IEA Key World Energy Statistics, 2017). However, the importance of renewable energies in Australia has been increasing in the last 20 years because of two different factors: First, the development and research on technologies related to solar panels and windmills have made renewable energies a real competitor to fossil fuels in the Australian spot market. Second, the Australian government is subsidizing progressively the creation of new renewable plants, with the clear intention of making the country less reliant on coal.

The contribution of both factors has made renewable energies projects to be increasingly profitable in the long term. The different opportunities created by this industry have contributed to achieving a 20% of renewable energy production out of the total fuel mix in 2019 (Department of Energy of Australia, 2019). According to this, the aim of the project is to take advantage of this situation by analysing the profitability of the construction of a solar plant in Australia, apart from continuing contributing to a more sustainable fuel mix.

2. Description of the project

This project will analyse the feasibility and potential upsides of the installation of a specific PV plant with an integrated battery energy storage system (BESS) - connected to the grid in the state of Queensland, Australia. The proposal for the PV plant is to be located in an available site near the town of Jericho, Queensland with a nameplate capacity of 3 MW_{AC} and peak power of 3,155 MW_{DC}. This proposal has been developed with the partnering company Gransolar.

The project will analyse all different components of a solar plant and choose them according to their characteristics and long-term profitability. Once chosen, the production of the designed solar plant will be simulated through a PVSyst simulation, and an economic study will be developed.

Having completed the economic study of the plant standalone, the same procedure will be followed for the BESS. An algorithm will be developed to simulate the functioning of the battery, and another economic study will be completed for the PV Plant and BESS. The feasibility of both projects will be then discussed.

3. Methodology

The methodology developed is divided in three different stages: First, the technical description of the plant is completed. Second, the simulation of the energy production and the economic study of the PV Plant is developed. Last, the optimal battery is chosen, alongside with the creation of an algorithm that controls it.

The block diagram that describes the developed plant can be seen in Figure 1:

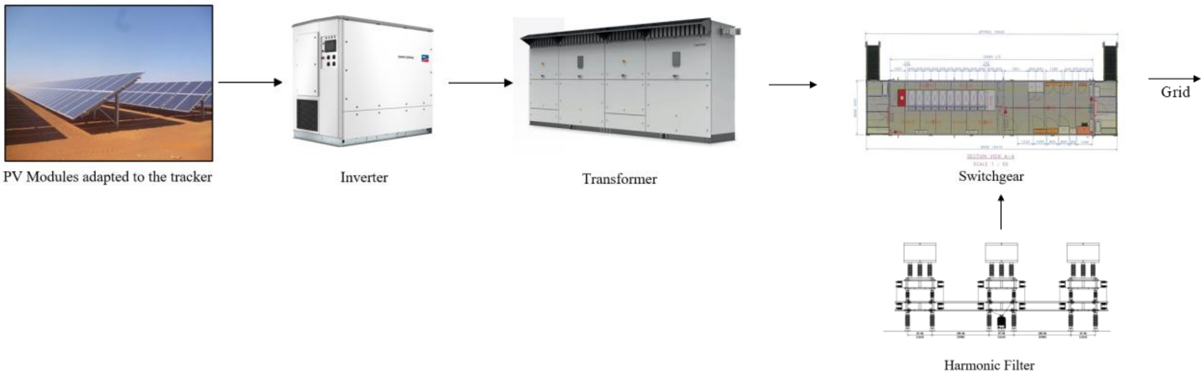

Figure 1: Block diagram of the plant

A total of 7250 PV modules have been used to provide the desired power, which are fitted into 250 single-axis trackers. A 3 MVA inverter has been fitted to transform the electricity from the solar panels (DC) to AC, which is then fed into a step-up transformer that elevates the voltage produced to the transmission network voltage value. The switchgear acts as the interconnection to the grid, installing a harmonic filter to fulfil the network code requirements. The chosen models are specified in the body of the project, and the plant layout has been as well defined.

In the second stage, the production of the plant is simulated according to the elements chosen. For calculating the revenue, this project does not consider any PPA but rather 100% of electricity to be sold to the spot market. Accordingly, an approximation of the behaviour of the spot market in the future years must be made. It has been shown that the prices of 2019's spot market are a reliable approximation for the future years. As so, the revenue is calculated by multiplying the energy production times the spot prices for 2019. Considering this revenue, all costs associated with the construction and maintenance of the solar plant (CAPEX and OPEX), the inflation and degradation of the components, the 25-year IRR of the PV plant standalone has been calculated.

In the third stage, the behaviour of the battery is studied. It has been assumed that the most profitable mode for a BESS is working as a peak-hours battery: charging the battery when the prices are low and selling that stored energy when the prices are higher (known as arbitrage). This mode allows the battery to obtain other revenue sources, such as taking part in the contingency market (known as grid services) and by the signature of a virtual cap contract. As the prices of Queensland's spot market are set every half an hour, this results in small periods of charging and discharging. Lithium-ion rechargeable batteries have shown better performance than Vanadium redox batteries when the activity cycles are shorter, therefore a Lithium-Ion battery has been chosen for the project.

A study of the volatility of the price-demand curve for Queensland has been completed, and shows that two price-peaks appear: one in the early morning (around 7:00) and one in the evening (around 18:30). As a complement, it has been checked that the higher the penetration of renewable energies, the further away are those peaks from the production hours (Simshauser, 2020). Consequently, the algorithm developed for the battery charges it in the production hours and discharges it after those hours, to take advantage of both price-peaks. The revenue obtained from the battery can then be calculated, and the optimal one is chosen.

It must be noted that this algorithm only simulates the arbitrage's revenue of the battery. The revenue obtained by taking part in the contingency market and by the signature of a cap contract is not possible to simulate with the available resources. However, a technical report of a battery of the same characteristics as the project's (Wilson, Esterhuysen and Hains, 2020) has been used to create different scenarios about how much revenue could be obtained from these sources. Once all revenue sources have been considered, the 25-year IRR of the PV plant with BESS is calculated.

4. Results

The economic study shows that the PV plant itself presents a 25-year IRR of 4.91%. According to the algorithm developed, the BESS that best fits the characteristics of the project is a 0.5MW/0.25MWh lithium-ion battery. For the project of PV plant and BESS, if the battery only functioned for arbitrage, the resultant IRR is 4.4%. However, the technical report of the University of Queensland's battery, which has similar characteristics as the project's battery, shows that the revenue from contingencies and cap contract could suppose a 767% higher benefit than only the arbitrage. Three different scenarios have been studied to simulate this additional revenue, which can be seen in the result's table below:

	Scenario 1: 15% increase from arbitrage's revenue	Scenario 2: 100% increase from arbitrage's revenue	Scenario 3: 250% increase from arbitrage's revenue
CAPEX Base	3.604.925,57	3.604.925,57	3.604.925,57
Total Benefit	336.267,34	347.557,58	367.481,52
OPEX	143.500	143.500	143.500
Project's IRR	4,49%	5,01%	5,90%

Table 1: Results of the different scenarios

5. Conclusions

The obtained results show that the PV plant itself can be profitable, as a 4,90% IRR is a reliable value for similar long-term projects. It has been proved that the installation of the BESS is feasible when working in arbitrage mode, as it obtains similar profitability as the PV plant itself. Also, by the participation in the contingency market and the signature of a cap contract, the profitability of the battery can be largely increased. It is impossible to simulate these incomes, but based on real data from other similar projects, in a standard scenario, the whole project of PV plant and battery is able to obtain a 5,90% IRR when considering all revenue sources.

6. References

[1] IEA Key World Energy Statistics 2017. International Energy Agency. 2017. p. 17.

[2] www.energy.gov.au. (2019). Australian electricity generation - fuel mix | energy.gov.au. [online] Available at: https://www.energy.gov.au/australian-electricity-generation-fuel-mix. [Accessed 25 Mar. 2020]

[3] Wilson, A., Esterhuysen, D. and Hains, D. (2020). The business case for behind-the-meter energy storage. [online] Available at: https://sustainability.uq.edu.au/files/11868/EPBQtyRptq12020.pdf [Accessed 16 Jul. 2020].

ESTUDIO DE LA INSTALACIÓN DE UNA PLANTA FOTOVOLTAICA CON UN SISTEMA INTEGRADO DE ALMACENAMIENTO DE ENERGÍA POR BATERÍA (BESS) CONECTADO A LA RED EN QUEENSLAND, AUSTRALIA

Autor: Mullor Martínez, Jorge
Director: Oleaga Ballester, Ignacio.
Entidad Colaboradora: GRANSOLAR

RESUMEN DEL PROYECTO

Este artículo analiza la viabilidad de la construcción de una planta fotovoltaica con un sistema integrado de almacenamiento de energía por batería (BESS) en Queensland, Australia. El procedimiento seguido consiste en calcular la rentabilidad de la planta de forma autónoma, eligiendo todos los elementos que intervienen en una planta solar, y comparándola después con el beneficio extra obtenido por la BESS, habiendo desarrollado un algoritmo que simula el funcionamiento de la batería.

Palabras clave: Planta Fotovoltaica, Sistema de almacenamiento de energía por batería (BESS), Batería, Almacenamiento de energía, Energía Renovable, Australia.

1. Introducción

Hasta la fecha, las necesidades energéticas de Australia se han satisfecho con éxito gracias a los combustibles fósiles. Australia es el mayor productor y exportador de carbón, y su producción de energía ha dependido significativamente de su explotación (IEA Key World Energy Statistics, 2017). Sin embargo, la importancia de las energías renovables en Australia ha ido aumentando en los últimos 20 años debido a dos factores: Primero, el desarrollo y la investigación de tecnologías relacionadas con paneles solares y molinos de viento han convertido a las energías renovables en un verdadero competidor de los combustibles fósiles en Australia en el mercado. En segundo lugar, el gobierno australiano está subvencionando progresivamente la creación de nuevas plantas renovables, con la clara intención de hacer que el país dependa menos del carbón.

La aportación de ambos factores ha hecho que los proyectos de energías renovables sean cada vez más rentables a largo plazo. Las diferentes oportunidades creadas por esta industria han contribuido a lograr un 20% de producción de energía renovable del total de la mezcla de producción de energía en 2019 (Departamento de Energía de Australia, 2019). Así, el objetivo del proyecto es aprovechar esta situación analizando la rentabilidad de la construcción de una planta solar en Australia, además de seguir contribuyendo a una mezcla de producción de energía más sostenible.

2. Definición del proyecto

Este proyecto analizará la viabilidad y las posibles ventajas de la instalación de una planta fotovoltaica con un sistema integrado de almacenamiento de energía por batería (BESS), conectado a la red en el estado de Queensland, Australia. La propuesta estudiada es la de una planta fotovoltaica con una capacidad nominal de 3 MW_{AC} y una potencia máxima de 3,155 MW_{DC}, situada en un terreno disponible cerca de la ciudad de Jericho, Queensland. Esta propuesta ha sido desarrollada con la empresa colaboradora Gransolar.

El proyecto analizará todos los componentes de una planta solar y los elegirá según las características necesarias y su rentabilidad a largo plazo. Una vez elegidos, la producción de la planta solar diseñada se simulará mediante el programa PVSys,t y posteriormente se desarrollará su estudio económico. Finalizado el estudio económico de la planta, se seguirá el mismo procedimiento para el BESS. Se desarrollará un algoritmo para simular el funcionamiento de la batería y se completará otro estudio económico para la planta fotovoltaica y BESS, conjuntamente. Por último, se discutirá la viabilidad de ambos proyectos.

3. Descripción del modelo

La metodología desarrollada se divide en tres etapas diferentes: Primero, se completa la descripción técnica de la planta. En segundo lugar, se desarrolla la simulación de la producción de energía y el estudio económico de la planta fotovoltaica. Por último, se elige la batería óptima, junto con la creación de un algoritmo que la controla. El diagrama de bloques de la planta se puede observar en la Figura 1:

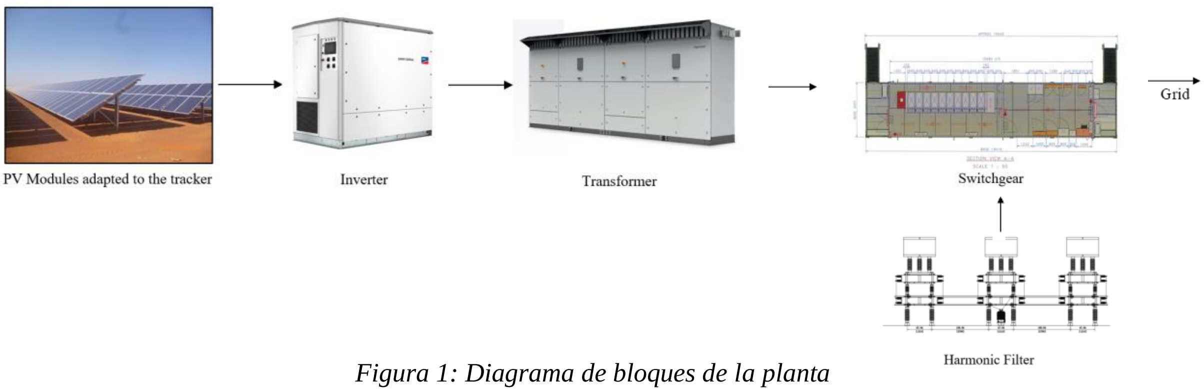

Figura 1: Diagrama de bloques de la planta

Se han utilizado un total de 7250 módulos fotovoltaicos para proporcionar la potencia deseada, que se instalan en 250 seguidores de un eje. Se ha instalado un inversor de 3 MVA para transformar la electricidad de los paneles solares (CC) en CA, que luego se alimenta a un transformador elevador que eleva la tensión producida al valor de tensión de la red de transmisión. El switchgear actúa como interconexión a la red, y se ha instalado un filtro de armónicos para cumplir con los requisitos del código de red. Los modelos elegidos se especifican en el cuerpo del proyecto, junto con la descripción de la distribución de la planta.

En la segunda etapa se simula la producción de la planta según los elementos elegidos. Para el cálculo de los ingresos, este proyecto no considera ningún PPA sino que el 100% de la electricidad se venderá al mercado spot. En consecuencia, se debe realizar una aproximación del comportamiento del mercado spot en los próximos años. Se ha demostrado que los precios del mercado spot de 2019 son una aproximación fiable para los años futuros. Por lo tanto, los ingresos se calculan multiplicando la producción de la planta por los precios spot de 2019. Considerando estos ingresos, se ha calculado la TIR a 25 años con todos los costes asociados con la construcción y mantenimiento de la planta solar (CAPEX y OPEX), la inflación y degradación de los componentes.

En la tercera etapa se estudia el comportamiento de la batería. Se ha asumido que el modo más rentable para un BESS es trabajar como batería en horas pico: esto es, cargando la batería cuando los precios son bajos y vender esa energía almacenada cuando los precios son más altos (lo que se conoce como arbitraje). Este modo permite a la batería obtener otras fuentes de ingresos, como la participación en el mercado de contingencia (conocido como servicios de red) y mediante la firma de un contrato de límite virtual. Como los precios del mercado al contado de Queensland se establecen cada media hora, esto da lugar a pequeños períodos de carga y descarga. Las baterías recargables de iones de litio han mostrado un mejor rendimiento que las baterías de flujo de vanadio cuando los ciclos de actividad son más cortos, por lo que se ha elegido una batería de iones de litio para el proyecto.

Se ha completado un estudio de la volatilidad de la curva de precio-demanda de Queensland, y se ha demostrado que aparecen dos picos de precios: uno temprano en la mañana (alrededor de las 7:00) y otro por la tarde (alrededor de las 18:30). Además, se ha comprobado que cuanto mayor es la penetración de las energías renovables, más alejados están esos picos de las horas de producción (Simshauser, 2020). Consecuentemente, el algoritmo desarrollado para la batería la carga en las horas de producción y la descarga después de esas horas, para aprovechar ambos picos de precios. A continuación, se pueden calcular los ingresos obtenidos de la batería y se elige la capacidad óptima de la batería.

Cabe indicar que este algoritmo solo simula los ingresos por arbitraje de la batería. Los ingresos obtenidos por participar en el mercado de contingencias y por la firma de un contrato de tope no son posibles de simular con los recursos disponibles. Sin embargo, se ha utilizado un informe técnico de una batería de las mismas características que la del proyecto (Wilson, Esterhuysen y Hains, 2020) para crear diferentes escenarios sobre cuántos ingresos podrían obtenerse de estas fuentes. Una vez que se han considerado todas las fuentes de ingresos, se calcula la TIR a 25 años de la planta fotovoltaica con BESS.

4. Resultados

El estudio económico muestra que la planta fotovoltaica presenta una TIR a 25 años del 4,91%. Según el algoritmo desarrollado, la BESS que mejor se adapta a las características del proyecto es una batería de iones de litio de 0,5MW/0,25MWh. Para el proyecto de planta fotovoltaica y BESS, si la batería solo se programa para modo arbitraje, la TIR resultante es del 4,4%. Sin embargo, el informe técnico de la batería de la Universidad de Queensland, que tiene características similares a la batería del proyecto, muestra que los ingresos por contingencias y contrato de tope podrían suponer un beneficio 767% mayor que solo el arbitraje. Se han estudiado tres escenarios diferentes para simular estos ingresos adicionales, que se pueden ver en la tabla de resultados a continuación:

	Scenario 1: 15% increase from arbitrage's revenue	Scenario 2: 100% increase from arbitrage's revenue	Scenario 3: 250% increase from arbitrage's revenue
CAPEX Base	3.604.925,57	3.604.925,57	3.604.925,57
Total Benefit	336.267,34	347.557,58	367.481,52
OPEX	143.500	143.500	143.500
Project's IRR	4,49%	5,01%	5,90%

Tabla 2: Resultados de los diferentes escenarios

5. Conclusiones

Los resultados obtenidos muestran que la planta fotovoltaica en sí puede ser rentable, ya que una TIR del 4,90% es un valor fiable para proyectos de este tipo a largo plazo. Se ha comprobado que la instalación del BESS es factible cuando se trabaja en modo arbitraje, ya que obtiene una rentabilidad similar a la de la propia planta fotovoltaica. Además, mediante la participación en el mercado de contingencias y la firma de un contrato de tope, la rentabilidad de la batería se puede incrementar en gran medida. Es imposible simular estos ingresos, pero en base a datos reales de otros proyectos similares, en un escenario estándar, el proyecto de planta fotovoltaica y batería puede obtener una TIR del 5,90% al considerar todas las fuentes de ingresos.

6. Referencias

[1] IEA Key World Energy Statistics 2017. International Energy Agency. 2017. p. 17.

[2] www.energy.gov.au. (2019). Australian electricity generation - fuel mix | energy.gov.au. [online] Available at: https://www.energy.gov.au/australian-electricity-generation-fuel-mix. [Accessed 25 Mar. 2020]

[3] Wilson, A., Esterhuysen, D. and Hains, D. (2020). The business case for behind-the-meter energy storage. [online] Available at: https://sustainability.uq.edu.au/files/11868/EPBQtyRptq12020.pdf [Accessed 16 Jul. 2020].

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Chapter 1. INTRODUCTION AND BACKGROUND

1.1 PROJECT INTRODUCTION

This project will analyse the feasibility and potential upsides of the installation of a specific PV plant with an integrated battery energy storage system (BESS) - connected to the grid in the state of Queensland, Australia. The main application of the BESS will be to store part of the energy produced by the PV plant and feed it into the grid when spot prices are higher, with the objective of optimizing the income of the power plant. The design of the battery will consider several aspects, such as the type of battery to be installed by analysing the two prevailing types: Vanadium flow batteries or Lithium-Ion batteries.

1.2 FUNCTIONING OF THE AUSTRALIAN ELECTRICITY SYSTEM

In order to understand the context of the project, it is important to describe the functioning of the Australian Electricity System. The Australian National Electricity Market (NEM) is a wholesale market where electricity is traded in Australia. It covers the states of Queensland, New South Wales, ACT, Tasmania, Victoria, and South Australia, delivering around the 90% of Australian total consumption (the remaining 10% comes from off-grid installations). The NEM is one of the world's largest interconnected power systems. The total distance between the two furthest points of the network (Port Lincoln, South Australia and Port Douglas, Queensland) is more than 5,000 km. This network can be observed in Figure 2.

The NEM supplies around 9 million end customers, with a total demand of 200 TWh (Terawatts per hour) per year. The total registered capacity is 57 GW (Gigawatts), including 3 GW of utility-scale solar and 8 GW of rooftop solar energy, being the country with more installed power of rooftop solar energy in the world. As at March 2020, more than 2.37 million household solar systems have been installed around Australia (Department of Energy of Australia, 2020).

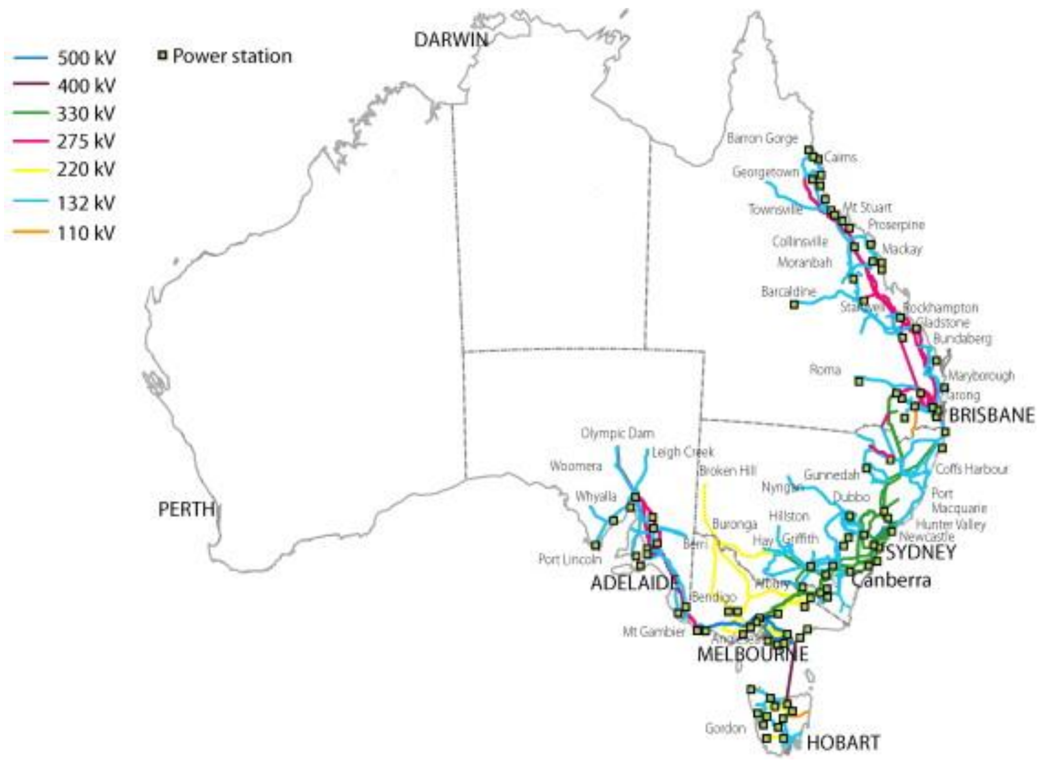

Figure 2: Representation of the Australian NEM

The system operation is based on a spot market, where energy is produced and sold to this market by generators, and retailers buy electricity from it and resell it to the end consumers. Despite the Australian Energy Market Commission (AEMC) decided in 2017 that the time interval for settlement in the NEM will be of five minutes, the spot price is still calculated as the average of each 30-minute period. Also, the spot market is divided into the different states that compose the NEM, having different spot prices depending on the location. Therefore, the spot market works on a 30-minute basis and with different prices for each state.

It must be noted also that the most extended arrangement that support the financial feasibility of renewable power plants in Australia (and worldwide) is the Power Purchase Agreement

(PPA). This is a private contract by which the retailers (offtaker) directly buy the electricity to the generator (independent power producer - IPP) at a fixed price and for a certain period.

The case study included in this project does not consider any PPA but rather 100% of electricity will be sold to the spot market. Based on this, the project will provide the most profitable solution for the development of a PV Plant with the battery storage system integrated.

1.3 CURRENT SITUATION OF ENERGY SOURCES IN AUSTRALIA

The main source of energy of Australia is coal. Every single state in the country (excepting Tasmania) has coal mining as their principal energy source, which has made Australia the biggest exporter of coal in the world (IEA Key World Energy Statistics, 2017). At the beginning of the 1990 decade, black and brown coal provided the 81% of the total energy of the country, leaving renewable energies in a 10%. However, nowadays coal only contributes in the 60% of the total energy supply, with the renewable energies gaining importance to approximately 20% (Department of Energy of Australia, 2019). The fuel mix in Australia in 2019 can be seen in Figure 3.

This progress has mainly occurred because of two different factors: First, the development and research on technologies related to solar panels and windmills has made the renewable energies a real competitor to fossil fuels in the Australian spot market (phenomenon known as *grid parity*). Secondly, the Australian government is subsidizing progressively the creation of new renewable plants, with the clear intention of making the country less reliant on coal. Consequently, the number of projects involving renewable energies, and more concretely, PV plants, have been multiplied in recent years, as it is progressively becoming a more profitable investment. Nowadays, there are over 2.2 million solar PV rooftop installations in the country, 3 GW utility-scale installed capacity and other 3 GW of solar PV plants under construction. These make a combined capacity of almost 14 GW. This progress is meant to continue increasing in the future years. AEMO has introduced a 20-year plan period, which objective is to have an installed around 75.5 GW of renewable energy for 2040, dispatched in 28 GW of solar, 10.5 GW of wind, 17 GW of storage and 20 GW of rooftop solar. The detailed forecast NEM capacity throughout the next years can be observed in Figure 4.

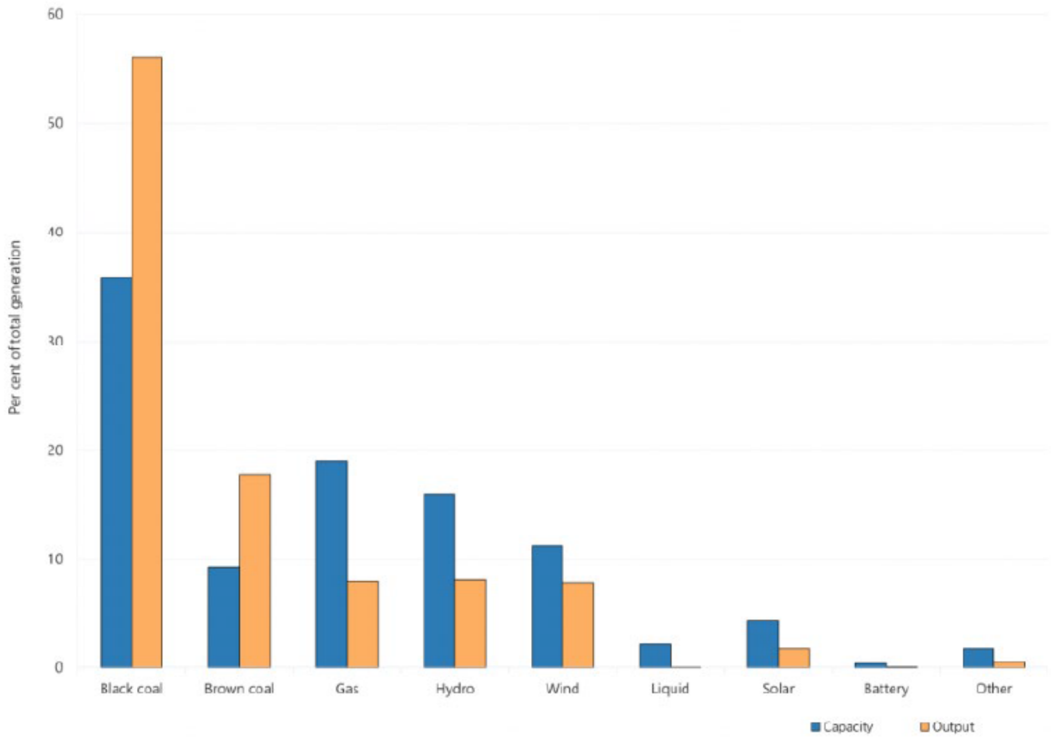

Figure 3: Australian's Fuel Mix in 2019

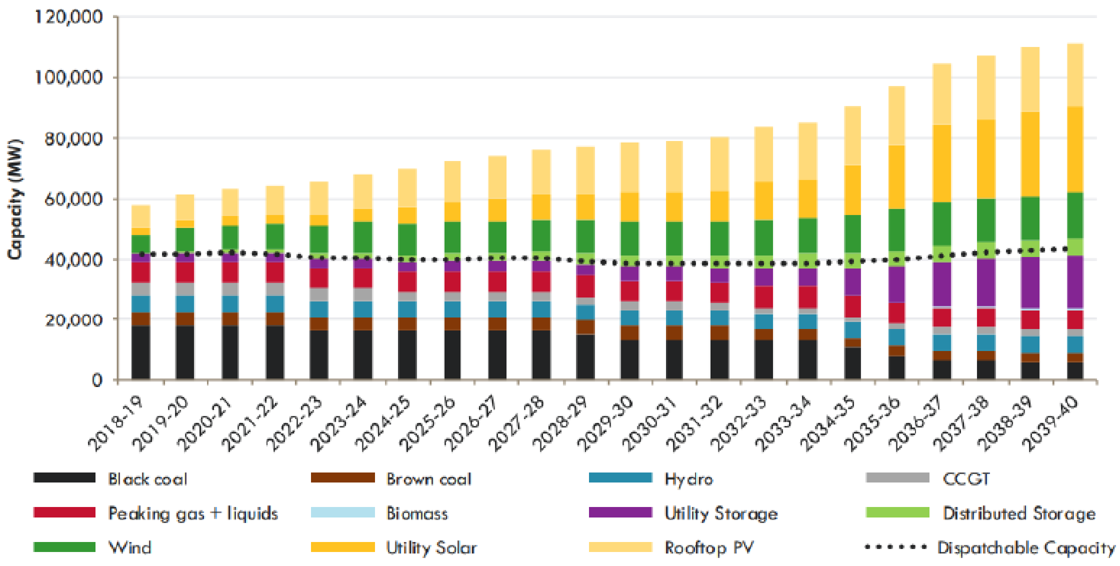

Figure 4: Forecast NEM Generation Capacity

Focusing on the location where the project will be carried out, Queensland has an installed capacity of around 13.5 GW. The fuel mix for this state in 2019 details that the 75% of the energy comes from coal, a 15% from natural gas and only about 8% come from renewable energies. A preliminary study of the spot market in Queensland show that the peak prices apply from 17:00 to 20:00, having off-peak rates from 8:00 to 11:00.

1.4 INTRODUCTION TO BATTERY ENERGY STORAGE SYSTEMS AND CURRENT SITUATION IN AUSTRALIA

In terms of the Battery Energy Storage System (BESS), this technology has been developed in Australia for the last 20 years. Nowadays, the two most important and most used types of battery are the Lithium-Ion Battery (LIB) and the Vanadium Redox Battery (VRB). They are different in the way they store energy: a LIB is a cell design storage unit. Contrarily, VRB store their energy in a tank and is based on fluid transfer. To obtain a higher capacity, as a LIB is small, it will be needed a huge amount of them, but with a VRB it will be only needed to increase the size of the tank. Altogether, battery storage projects show the increasing transition of the grid towards renewable energies.

Currently, there is a lack of detailed regulation in terms of battery storage in energy plants. Projects involving BESS are an example of technology development outpacing the regulatory reforms required to enable them. Despite this fact, Australia has continued to make progress in their development of projects with batteries integrated over the past few years, with the remarkable example of the Tesla battery installed in the Hornsdale Power Reserve in South Australia, finished in 2019. This BESS is the world's largest battery connected to the grid, with a nameplate capacity of 100 MW and a storage capacity of 129MWh. It is nowadays being used for two different purposes: grid services (to provide stability to the grid) and energy arbitration (to store energy when prices are low and sell it when prices are high). These are the two uses which the battery used in the project will provide to the power plant.

1.5 Introduction to the Functioning of Photovoltaic Power Plants

1.5.1 Components of a Photovoltaic Power Plant

In a PV power plant, the energy production starts in the photovoltaic cells: they transform solar radiation into electricity through the photovoltaic effect. The photovoltaic effect is the phenomenon that occurs when light is absorbed by a material and causes the excitation of an electron into a higher energy-state, and depends on the solar radiation, the temperature and on its own area.

The interconnection and aggrupation of a determinate number of photovoltaic cells form the known as photovoltaic modules, or modules. Again, the aggrupation of modules produces areas of bigger sunlight catchment, and when installed in different trackers form the photovoltaic generators, that have a flexible power range and can be adapted to any circumstance.

The resultant voltage obtained is in direct current (DC). To transform it to alternating current (AC), the use of inverters is needed. These inverters not only transform the direct current into alternating current, but also provide a boost transformation from low voltage (800V) to medium voltage (33kV). Consequently, these stations will be called Power Conversion Stations or Inverter Stations from now onwards. Also, depending on the circumstances, another stage of voltage-boost transforming (medium to high voltage) might be needed to satisfy the characteristics of the grid that the plant will be connected to. Figure 5 represents a generalised outline of a standard PV Plant.

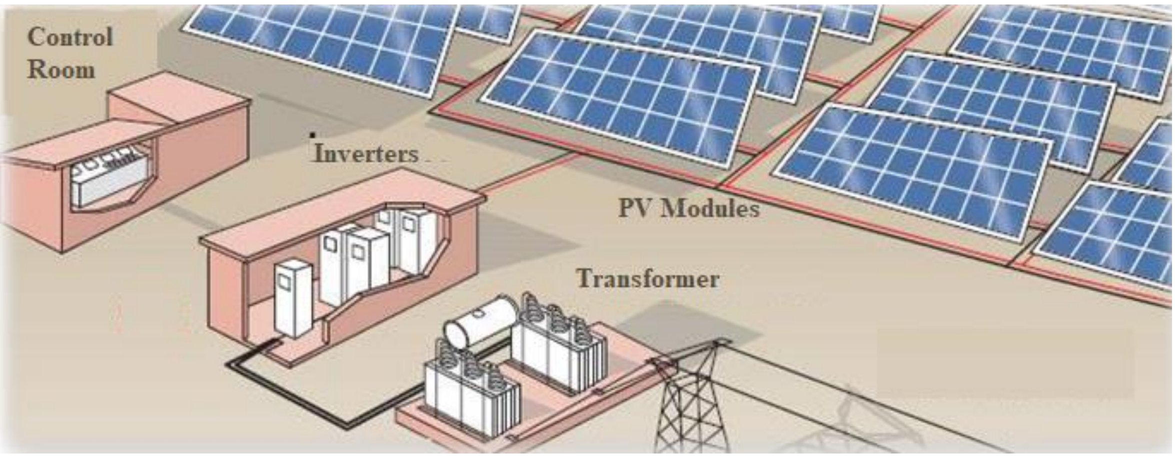

Figure 5: Outline of a PV Plant

1.5.2 MODULES

The PV Modules are the units that offer the support for the electrically connected photovoltaics cells. They capture the photons of the sunlight rays, and the semiconductor materials present in the modules transform them into a direct electron current. Apart from being the support for the cells, the modules protect them through an encapsulant. The most used one is the EVA (Ethylene Vinyl Acetate), which supports the cells and electrically isolates them from the exterior. A thin layer of Tedlar (Polyvinyl fluoride) is normally used in the back cover. Figure 6 represents the transversal section of a PV Module.

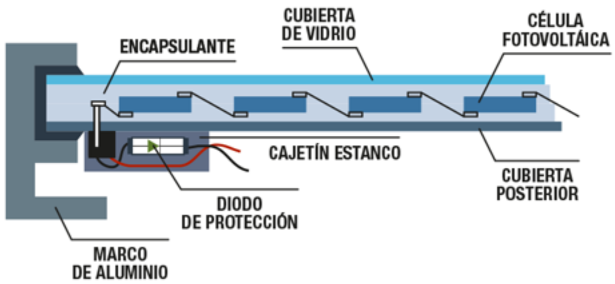

Figure 6: Structure of a PV Module

The translation of the elements in Figure 6 is given below:

Encapsulante: Encapsulant

Marco de Aluminio: Aluminium Batten

Diodo de Proteccion: Protection Diode

Cubierta Posterior: Back Cover

Cajetin Estanco: Watertight box

Cubierta de Vidrio: Glass Cover

Celula Fotovoltaica: Photovoltaic Cell

It is important to remark that nowadays, the efficiency of commercial solar panels is usually very small. Generally, the PV modules used in solar farms do not achieve more than the 20% efficiency in transforming sunlight into electricity. This aspect will be considered in the choice of panels for the solar plant, although further research is slowly developing more efficient modules.

1.5.3 TRACKERS

It must be noted that the trackers that are used in each solar plant depend on two different aspects: First, geographical location. The latitude of the terrain is the main indicator to calculate the inclination of the PV Modules. Second, the weather condition. Aspects that affect the choice of trackers are the average speed of the wind, the number of cloudy days and snow days throughout the year, and humidity.

Depending on the parameters mentioned above, it must be then chosen the appropriate trackers for the plant. The most used ones are the single axis tracker and the dual axis tracker.

When no tracker is added to the plant, the structure that holds the PV Module is called fixed array.

For the fixed arrays, the PV Modules do not trace the sun in any way. It is based on calculating the most efficient position to obtain the maximum solar power over the day and placing the modules adequately. This is usually designed to obtain the most solar radiation in the noon hours, though for the early mornings and late afternoons the misalignment becomes excessive to collect sufficient energy.

To avoid this misalignment, single and dual axis trackers are used. Single axis trackers are structures with one axis in the North direction, allowing the PV Modules rotation around the East-West to follow the complete sun trajectory throughout the day. A backtracking function can be implemented into this type of trackers, which allows to increase the production at early mornings and late afternoons: When the tracker detects a PV Modules row shadowing the immediate posterior row, it corrects their angle in order to avoid the shadowing. A representation of this feature can be seen in Figure 7.

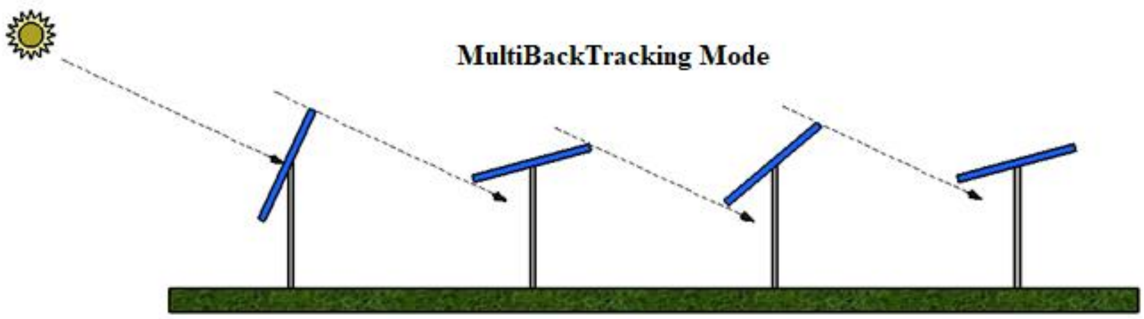

Figure 7: Representation of Backtracking Mode

The dual axis tracker provides another degree of freedom, as allow the PV Modules to rotate around the North-South axis. It must be noted that it will have a better performance than the single axis trackers, but it is as well more expensive, therefore an economic study should be carried out to determine whether these types of trackers are needed.

1.5.4 POWER CONVERSION STATIONS

As stated in 1.5.1, the power conversion stations transform the electricity produced in the PV Modules (direct current) into alternating current that can be then fed into the grid after a boosting voltage stage. These stations include all the general control elements, the wave generation systems based on pulse width modulation (PWM) and some protections. Also, the power conversion stations must be protected from out of range voltages and frequencies, high working temperatures, insufficient generator current and grid failure, among others. They will also have several embedded systems that will provide them a big amount of data describing the situation of the grid and the current.

The power conversion station involves the process of transforming the power obtained by the solar modules to the final grid feeding. Generally, the inverter itself provides a low voltage, that must be then boosted by a boost transformer. As so, the pair of inverter and transformer are part of the power conversion station. It must be noted the existence of blocks called skids, that provide the answer of an inverter and a transformer together. However, these are usually designed for more powerful plants than the one in the project, and they will not be used.

1.6 MOTIVATION

The development of this project gives answer to two different concerns. First, as stated in the introduction and the current situation, the importance of renewable energies in Australia has been increasing in the last 20 years but it is not enough. The independence of coal as the main energy resource is an important objective for Australia and for the collaborating company *Gransolar (GRS)*, and so one of the reasons why this project has been selected. It is important to also point out that Australia is one of the countries with more sun hours per year. It receives approximately 58 million PJ (Petajoules), which is about 10.000 times larger than the country's energy consumption (Geoscience Australia, 2019). However, only 5.2% of the total energy come from solar energy. Hence, it is an energy source highly misused according to its numerous benefits, and an opportunity for the project to take advantage of this situation.

It is also important to remark that due to its nature, the introduction of renewable energies is going to increment even more the price difference between off-peak and peak periods of time. Renewable energies are intermittent sources of generation, as solar energy can only be produced during sun hours and wind energy is mostly produced at night. Therefore, if these generators increase the production, their active hours will lower the spot price as there is a large amount of energy being injected to the grid, but when none of them is generating at the same time that the demand is high, the peak prices will be even higher.

Secondly, higher research in terms of battery storage system is needed in order to optimise and normalise its use. There are several benefits that come from the usage of energy storage systems. Renewable energies are not totally trustworthy as they are non-dispatchable, that is, they cannot produce energy if sun is not shining or wind is not blowing. Batteries are a perfect complement as this energy can be released when needed. Also, batteries can change some of the grid characteristics such as frequency and voltage, giving the grid a better quality. GRS is just starting to make use of this type of storage and one of the aims of this project is to obtain more information about their behaviour and potential upsides in large photovoltaic power plants.

In the long term, the use of this type of battery storage systems will eventually flatten the spot prices, as the energy produced can be stored and released when needed. <u>However, until the electricity market arrives to this point, the installation of PV Plants with BESS integrated is a niche market that the project will take advantage of.</u>

1.7 PROJECT OBJECTIVES

The objective of this project is not to carry out the final implementation of the PV plant and the BESS, but to give complete understanding of what are the factors that contribute to their development, analysing if the project is economically viable and if it could be deployed in an existing or future installation. The project will study all the components needed to build the PV Plant and the battery to make a realistic analysis.

Moreover, as any company-related project, its final objective is to maximise the revenue of the operation. The more realistic the technical and commercial analysis, the more precise the final economic model will be. Therefore, the PV plant study will consider not only the overall capex and revenue given by the plant once installed, but the price breakdown and technical assessment of the main components that compose it (such as PV modules, inverters and trackers). To complete this accurately, a proper understanding on how it works a PV plant with a storage system is needed and will be another objective to pursue in this project.

1.8 CURRENT SITUATION AND PROPOSAL

The proposal for the PV Plant is to be located in a land 7 kilometres away from the town of Jericho, Central Queensland (coordinates specified in Chapter 2). The characteristics of the PV Plant are:

- Nominal Power ≡ Nameplate Capacity = 3,00 MW_{AC}
- Peak Power = 3,155 MW_{DC}

All other characteristics for the power plant, such as PV Modules, trackers, inverters, or batteries are to be chosen based on the profitability and availability, according to Gransolar and its subsidiary E22 stock. Also, for the study of the economic report when the plant is developed, the IRR to compare both PV Plant with and without battery will be done to 25 years, as it is the standard duration of the components warranty.

It is also stated that the case study included in this project does not consider any PPA but rather 100% of electricity will be sold to the spot market. It must be noted that this proposal, including available area and plant power, have been provided by Gransolar.

1.9 PROJECT DEVELOPMENT STAGES

For the development of the project, it will be divided into four different stages, as specified below:

1.9.1 STAGE 1: TECHNICAL DESCRIPTION OF THE PLANT

The proposal for the PV Plant is to be in Central Queensland with characteristics of Nominal Power: 3.00MWAC and Peak Power: 3.155MWDC. In this first stage, according to the characteristics provided, the main equipment of the PV Plant will be chosen: The PV Modules, Inverters and Trackers. The model and the power of the equipment mentioned will be decided.

Once defined the technical scope, it will be assessed the total cost for the engineering, procurement, and construction (EPC) of the PV plant, and a technical proposal will be redacted based on the components used.

1.9.2 STAGE 2: CALCULATION OF THE REVENUE OF THE STUDIED PV PLANT IN THE SPOT MARKET IN QUEENSLAND IN A REFERENCE YEAR

Having defined the characteristics of the photovoltaic plant, the TMY (Typical Meteorological Year) will be obtained for the desired location. The TMY specifies the values of the solar irradiation and temperature for every hour of the year. With these values and the technical configuration obtained in Stage 1, a PVSyst simulation will be developed, obtaining the generation that can be fed into the grid for every hour of the year. The obtained values will be then processed together with the spot prices of the market in Queensland in the reference year (2019), obtaining the revenue of the PV plant itself. Considering the EPC price (capex) obtained in Stage 1 and the revenues obtained in Stage 2, an economic model will be carried out in order to obtain the IRR (Internal Rate of Return) of the project, which will be compared to the one developed for the battery.

Other assumptions will be considered such us degradation of the PV modules, inflation, number of years of operation, etc… A further explanation of the resources used can be seen in 1.10.

1.9.3 STAGE 3: STUDY AND INCLUSION OF THE BESS

The objective of the BESS is to store part of the energy from the off-peak hours in order to feed it into the grid in the peak hours when the prices are higher. An analysis of the peak hours for the state of Queensland will be developed, deciding then which is the optimal battery charge and discharge period. The information of the batteries available will be collected (Maximum power storage (MW), Capacity (MWh) and price), and it will be then studied which battery provides better IRR according to its price, characteristics and the analysis of the spot market (The highest IRR will indicate the optimal sizing of the battery).

1.9.4 STAGE 4: ANALYSIS OF THE FINAL PROPOSAL – PV PLANT AND BESS

The model of the PV plant will be analysed separately with the PV Plant+BESS model to provide conclusions about the total upside generated by the battery. It will be then assessed if the battery is worth it, and it will be presented the final output of the financial model.

1.10 RESOURCES TO BE USED

Stage 1: To obtain the optimal components (PV modules, Inverters, Trackers, BESS) that compose the PV Plant, the datasheets and information of the most used ones will be provided for its study by GRS.

Stage 2:

- The Typical Meteorological Year needed for the location of the plant will be obtained from one of the GRS databases.
- The simulation to obtain the energy that can be fed into the grid according to the characteristics of the PV Plant will be carried out with PVSyst. This program takes all the characteristics of the plant and the information obtained from the TMY and

returns a full report of the energy that can be obtained. It is the most used program for solar energy tracking in the world.

- The price and demand of energy in the state of Queensland will be obtained through the AEMO (Australian Energy Market Operator) website, which has the data of the spot market of the past 20 years for every state of Australia.

Stage 3 and Stage 4: The available batteries, as well as their detailed information and datasheets will be provided by Gransolar and its subsidiary E22 specialised in battery storage solutions.

Chapter 2. TECHNICAL DESCRIPTION OF THE PLANT

2.1 LOCATION CHARACTERISTICS

As stated in Chapter 1, the proposal for the Solar Plant is to be located 7 kilometres away from the town of Jericho, Queensland. A study of the characteristics of the terrain will be developed in this subchapter.

To put the location into context, the following figures show the exact location of the plant and the main towns around.

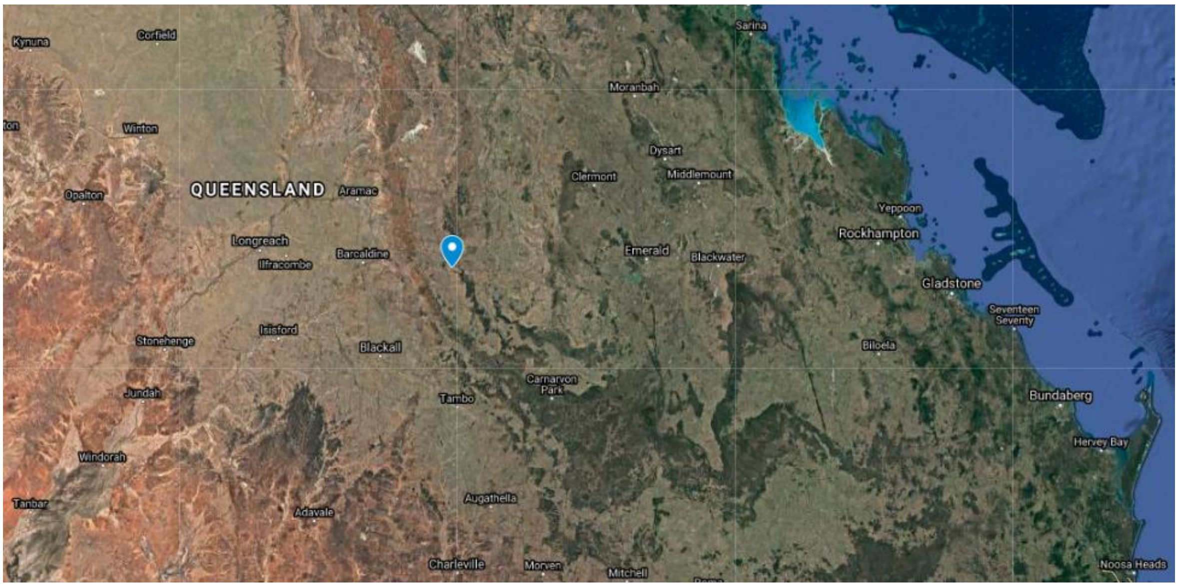

Figure 8: Solar Plant Location

Figure 9: Detailed View of the Location of the Solar Plant

Figure 10 below shows the available terrain to build the solar plant:

Figure 10: Available Terrain

The following table shows the specific characteristics of the chosen location, with coordinates, total land available and elevation:

	Solar Plant Characteristics
Latitude	-23° 36' 3.1"
Longitude	146° 11' 16.55"
Land Occupied	7,5 ha
Elevation	352 m.a.s.l

Table 3: Solar Plant Characteristics

A preliminary study about the suitability of the terrain can be made through the data available from a weather station in Barcaldine, located 80 kilometres west from the location of the plant. It must be noted that for the calculation of the production of the solar farm, a PVSyst simulation will be carried out using the data provided by the SolarGis, that will provide better accuracy and detail. This will be extended in Chapter 2.

The available data shows the mean daily solar exposure, in MJ/m^2. To put the data into context, the equivalent in MWh/m^2 and in MWh/ha is calculated and added to the table below:

	Jan	Feb	Mar	Apr	May	Jun	Jul
MJ/m2	26	24,6	22,8	19,6	16,3	14,7	15,8
MWh/m2	0,00722	0,00683	0,00633	0,00544	0,00453	0,0041	0,00439
MWh/ha	72,2223	68,3334	63,3334	54,4445	45,2778	40,833	43,8889

	Aug	Sep	Oct	Nov	Dec	Annual
MJ/m2	18,8	22,2	25,1	26,4	26,8	21,6
MWh/m2	0,00522	0,00617	0,00697	0,00733	0,00744	0,006
MWh/ha	52,2223	61,6667	69,7223	73,3334	74,4445	60

Table 4:Mean Daily Solar Exposure (Australian Government, 2020)

It is reminded that the desired solar plant has AC installed power of 3MVA, and that the solar exposure hours vary between 10 and 12 hours depending on the weather station. Consequently, given the available terrain (around 7,5 ha), the energy production will be achievable according to this preliminary study.

Topographical information is as well provided, concluding that the available land is mainly composed of regular areas. Earthworks are usually done in some solar plant projects to level the available terrain to make the installation of the solar panels feasible. As the terrain is regular and mostly flat, earthworks related to grading and levelling are not to be considered.

2.2 SELECTION OF THE PRINCIPAL PV PLANT COMPONENTS

2.2.1 PV MODULES

2.2.1.1 Monofacial vs Bifacial

The first choice to make when selecting PV modules is the type. Nowadays, there are two main types used in solar farms: monofacial and bifacial. The difference comes from the total surface that absorbs the sunlight: monofacial solar panels have only one face that absorbs them, while bifacial solar panels can absorb the irradiation through the two different faces. As so, bifacial panels are more expensive than monofacial.

However, for this project, the decision on whether to choose monofacial or bifacial does not come from a profitability point of view. The main disadvantage from bifacial modules is the uncertainty: the supplier provides detailed information of the power that can be obtained from one of the faces, but only provides an estimation of the achievable power from the other face. Consequently, to obtain precise data about the power that will be obtained from the plant, it has been decided to use monofacial solar modules.

2.2.1.2 Aspects to consider

Inside solar farms, PV Modules are the most important component as they are the ones in charge of transforming the solar irradiation into the electricity that will be sold afterwards. Consequently, an efficient choice of the panels will result in a more cost-effective power plant.

As specified in 1.5.2, the conversion efficiency is usually low in terms of PV Modules. According to the Photovoltaic Energy Factsheet paper (University of Michigan, 2019), the average efficiency that is nowadays achieved is around 16%. Consequently, the optimal efficiency for the solar panels of the power plant will be higher than 16%. However, some projects developed by the partnering company Gransolar confirm that PV Modules with around 20% efficiency are cost-effective and useful for the developing of solar plants in Australia. Therefore, the search of solar panels will be limited to the ones that can achieve those efficiency numbers.

In terms of available terrain, it is important that the PV Modules are sufficiently small so that the power desired can be achieved within the limits of the land. The solar farms built by Gransolar confirm that, in terms of available terrain/power ratio, 2 hectares should be available per MW desired. As the area proposed is of 7.5 ha and the power plant should have a nameplate capacity of 3 MW, space will not be an issue if usual solar modules are used.

Some other aspects must be as well considered. As efficiency, degradation is an important characteristic in terms of PV Modules. It has been pointed out that the average power attenuation of a standard PV module is around 0.72% per year. As stated in 1.8, the desired economic model will be developed for 25 years, hence a loss of power of almost 18% is to be expected at the end of this period, with the loses of income that this entails. Consequently, any photovoltaic module that can achieve a smaller power attenuation than the standard would be highly desirable.

Other aspects such as the operational temperature or safety classes are as well important but usually common to all solar modules produced, therefore will not be something that influence the choice of PV Modules. It is important to remark that, once the solar modules have been chosen, the search for inverters will be limited to the characteristics that these modules can provide.

2.2.1.3 Model Selection

Having set all these parameters into the available PV modules for projects in Australia, the results set that there are two suitable models: Canadian HiKu CS3W 420P and Longi Hi-MO LR4-72HPH-435M. Both have similar prices: around 0.21 USD/Wdc considering the capacity of the solar plant, but differ in some characteristics. The aspects discussed in 2.2.1.2 for both solar panels will be compared in Table 5:

	Longi	*Canadian Solar*
Nominal Power (W)	435	420
Max. System Voltage (V)	1500	1500
Area (m^2)	2.17	2.21
Power Degradation (%/Year)	-0.55	Not Specified
Efficiency (%)	20	19

Table 5: Comparison between Solar Modules

As it can be checked in Table 3, Longi PV modules offer higher nominal power for the same price, as well as a smaller area of panel and a power degradation smaller than the average. Contrarily, Canadian Solar PV Modules do not specify the power degradation and have smaller nominal power. Also, the efficiency for the Longi modules is higher than the Canadian Solar ones. Consequently, the modules that will be used for the solar plant will be the **Longi Hi-MO LR4-72HPH-435M**.

Longi is a world leading manufacturer of PV Modules, being Top 1 in the world in module shipment for monofacial types from 2016 to 2018, and they are expected to reach 45GW of production capacity by this year. This does nothing but confirm the good choice in the model selected.

The datasheet for this model can be found in Annex II. A table with the principal characteristics and a figure reflecting the design of the module can be found below.

Maximum Power (W)	*435*
Open Circuit Voltage (V)	48.7
Short Circuit Current (A)	11.39
Max. System Voltage (V)	40.9
Max. System Current (A)	10.64
Module Efficiency (%)	20

Table 6: Principal Characteristics of PV Module Selected at Standard testing conditions

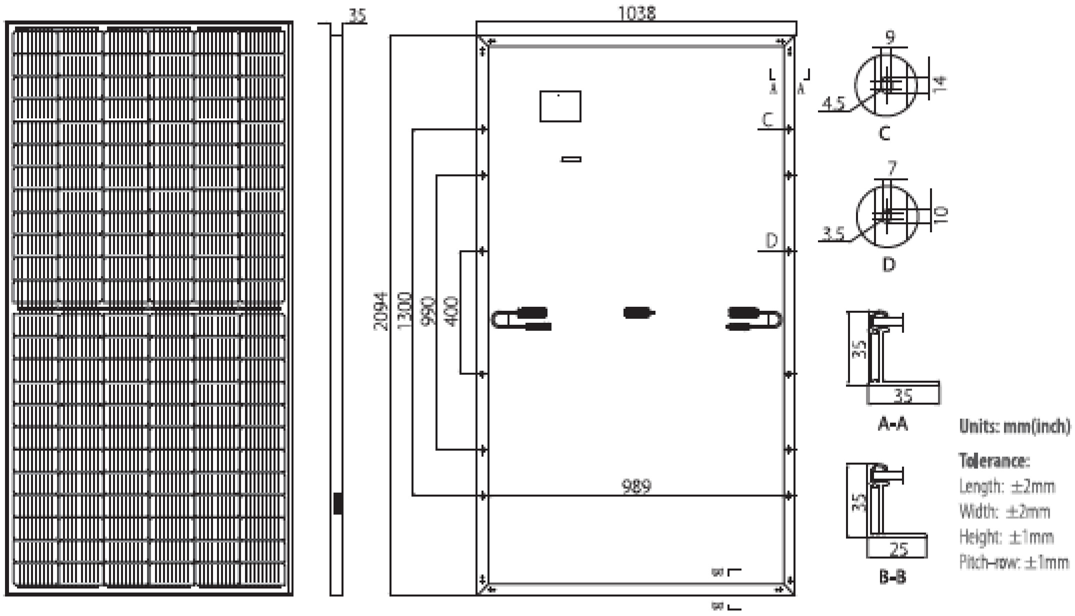

Figure 11: Design for the Solar Module

The number of PV modules used will depend on the characteristics of the tracker and inverter. As so, this number will be calculated later on.

2.2.2 TRACKER

2.2.2.1 Type

As stated on 1.5.3, the three used ways to provide a structure to the solar modules are the fixed arrays, single-axis tracker and dual-axis tracker. This subchapter will analyse the optimal type to use for the project.

In terms of fixed arrays, they are the most basic structure type for solar modules. They are mainly used in household solar installations, as trackers suppose an extra cost for the installation that is not usually profitable for a small installation. However, for bigger installations as the one studied in the project, single and dual axis tracker become more profitable than the fixed arrays. As so, they are discarded for the project and the focus will be put in these two types.

Azimuth plays a key role on choosing the type of solar tracing. The azimuth is the compass angle from which the sunlight comes, between the north direction and the sun position. Figure 12 illustrates this concept.

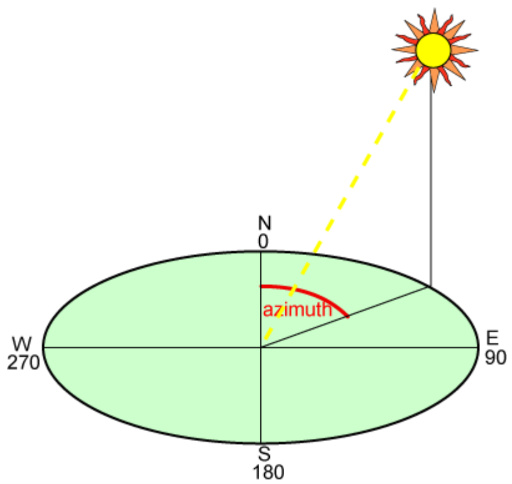

Figure 12: Definition of Azimuth

With respect to tracking, Azimuth is the differential factor that will make worth the use of a single axis or a dual axis tracker.

As explained before, single axis trackers provide only one degree of freedom in solar tracing. This degree of freedom is normally fixed in following the solar trajectory throughout the day, this means, tracing the sun in its West-East trajectory. As so, if there was no variation of Azimuth throughout the year, then single axis tracing would provide the optimal solution, as the sun would follow the same trajectory for all days of the year. However, for this location, it is not the case.

Azimuth varies according to the latitude, and as so, adding another degree of freedom to track the azimuth could be as well something to consider. To study that concept, it is needed to check the azimuth variation through the year in the desired plant location. This angle can be easily calculated through a simulator knowing the coordinates and the time of the year. Suncalc.org simulator will be used. Table 7 shows the azimuth angle for the beginning of each month in 2019 for the sunrise position:

	Jan	Feb	Mar	Apr	May	Jun
Azimuth	115.74°	109.36°	99.05°	85.71°	74.13°	66.36°

Jul	Aug	Sep	Oct	Nov	Dec
65.09°	70.56°	81.15°	93.59°	105.97°	114.27°

Table 7: Azimuth angle for each month

As it can be inferred, the azimuth variation for a whole year varies in a range of 50.66°, which means that if the solar modules are fitted in a 90° azimuth position, the maximum variation will be of approximately 25°, which is not significant enough to make profitable a dual axis tracker. Also, it is important to note that there are other various factors to consider. First, dual axis trackers are not designed to fit large amounts of panels. In fact, they are designed to fit no more than 15 modules per array. If these trackers are separated appropriately to avoid shades between them, the space needed to fit this configuration is considerably higher than the one that is available. Second, dual axis trackers are as well more expensive than single axis trackers. All aspects considered, it can be concluded that installing dual axis solar trackers is not worth the investment, and the structures used will be single axis solar trackers.

2.2.2.2 Aspects to consider

Having set the type of tracker to use, the desired parameters will be set to look for the appropriate tracker. It must be noted that the tracker also involves the program used to track the sun and move the structure accordingly.

The first aspect to consider is if the tracker supports the specific PV module that has been chosen for the project. Secondly, it has been proved in other similar projects that an acceptable rotational range for the West-East rotation is to be from +60° to -60°, as it receives sufficient solar energy in the early mornings and late afternoons, and prevents shadowing between modules. Related to this is the concept of backtracking, explained in 1.5.3 and that will be another feature expected for the tracker. It is also important that the tracker is resistant when facing adverse weather conditions. With respect to wind, it should be at least resistant for 150kph wind speed, and it should have been tested in a wind tunnel. As the other elements of the plant, it must be compatible with SCADA in order to monitor all data.

2.2.2.3 Model selection

In terms of model selection, it must be noted that PVH (PV Hardware) is usually Gransolar's tracker supplier, apart from being the third tracker supplier in the world. Consequently, the adequate model will be searched in the catalogue that this supplier provides.

The single axis tracker models from PVH are called Monoline, and their datasheet can be seen in Annex II. There are three different types of trackers: Monoline 3H, Monoline 2V and Monoline 2V Bifacial. As the solar modules studied for this project are monofacial, the Monoline 2V Bifacial will be discarded and the selection will be made between the other two.

Both two support the modules chosen for the project and have the characteristics listed above. In terms of profitability, both trackers have similar pricing, around 34EUR/PV Module considering the capacity of the plant. However, the main difference between the two is the number of panels that the tracker can hold. In the case of the 3H, it can hold 90 panels per row, while the 2V can only hold 60 panels row. As a matter of space, it would be interesting to choose the one that can fit a higher number of panels. Consequently, the tracker chosen is the **PVH Monoline 3H**.

As stated before, PVH is the third biggest tracker supplier in the world, having provided their structures to more than 140 PV Plants, with a total installed power of more than 8GW. The following table resumes the key features of the model selected:

Characteristic	*Data*
Module Configuration	3 modules in landscape
Rotational Range	+/-60
Wind Load Maximum	193 kph
SCADA compatibility	Yes
Tracking Method	Astronomical algorithm
Modules per string	29
BackTracking	Yes

Table 8: Key Tracker Features

The following figure provides a scheme of how the tracker will look like when the modules have already been installed. The complete datasheet can be checked in Annex II.

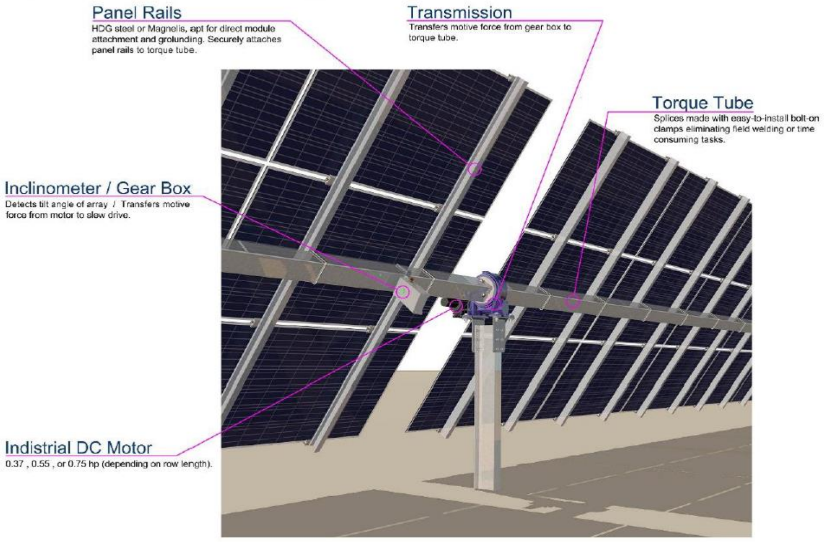

Figure 13: Tracker selected with modules

Having 29 modules per string, now the total amount of solar panels can be calculated. The objective will be to use a whole number of trackers and not leaving any tracker with empty solar module gaps. Given that the maximum power is 435 W, and the desired installed power is 3,155 MW_{DC}:

$$Total\ modules = \frac{Total\ power}{Power\ per\ module} = \frac{3.155.000W}{435W} = 7.252{,}87\ modules$$

Knowing the exact number of modules, a divisor of the approximate number of modules between the 29 modules per string will be searched. Two options are obtained:

- 7250 modules in 250 strings, obtaining an installed power of 3.153.750 W.
- 7279 modules in 251 strings, obtaining an installed power of 3.166.365 W.

Both options are valid: the first one has been chosen. All in all, 250 strings of trackers will be used, holding a total of 7.250 modules and resulting in an installed power of 3.153.750 W.

2.2.3 POWER CONVERSION STATION

2.2.3.1 Electrical specifications

1.5.4 explains that the power conversion stations involve all the process from receiving the energy from the solar panels to the interconnection with the grid. Consequently, it is important to analyse the electrical characteristics of the previous selected components, to choose the optimal power conversion station.

First, the configuration of the tracker structure will provide useful information about the type of inverter to use. As seen in 2.2.2.3, the selected tracker offers a structure of 29 modules per string. A string is considered a group of panels that are wired into a single input of the inverter, and the panels that form a string are connected in series. As so, the first specification needed for the inverter is to be able to handle the voltage of 29 modules connected in series. This will be calculated for the most extreme case, where all the panels are working at full power.

Going back to the datasheet of the solar panels, it can be checked that for standard testing conditions, the voltage at maximum power is:

$$V_{mp} = 40{,}9V$$

Therefore, the minimum voltage that the inverter will need is:

$$V_{inverter} \geq V_{maxstring} = V_{mp} \cdot n_{modules} = 40{,}9 \cdot 29 = 1186{,}1V$$

It will be also important for the inverter to be able to handle the number of strings that the plant will need, however, this will be a matter of modifying the number of inverters needed, so it will not be a limitation.

As the power conversion station is responsible of the final feeding to the grid, the characteristics of the grid near the solar plant are required to provide the same terminating voltage from the station.

With the information provided in the proposal, it has been specified that the closest line to the solar plant is a medium voltage line of 33kV. Consequently, the power conversion station will have to provide this output voltage. There are two possible ways to obtain this voltage: First, directly through the inverter. It has been stated in 1.5.4 that skids provide both inverter and transformer. However, the characteristics of the plant might not be suitable for the use of a skid, as they work with high power values. The second case appears when a skid cannot be used, where an inverter and a transformer, separately, will be used to provide this output voltage. This will be studied in the next subchapter.

2.2.3.2 Configuration

The characteristics of the available skids will be studied, and a decision about the configuration type of the power conversion station will be made.

It must be noted that, for the study of the skids and the inverters, only the components available from SMA Solar Technology will be considered, as they are the leader supplier of power conversion stations in Australia and are the usual provider of the partnering company. The datasheet of the available skids can be found in Annex II.

The three different types of skids (MV Power Station 5000,5500 and 6000) offer a maximum input voltage of 1500 V, so the maximum string voltage will be fulfilled. However, these three skids are designed for power values of 5000 kVA, 5500 kVA and 6000kVA, respectively. These power values differ significantly from the one that the plant is predicted to provide, around 3000kVA according to the specifications. If the skid with the minimum power is installed in the power plant, the overall functioning would be correct. However, it would not be the most profitable solution, as there are 2000kVA of extra power that the plant would not use. As this is the minimum power that the provided skids can offer, the configuration followed by the plant will be an inverter plus a transformer. Also, following this configuration, a switch gear is to be installed. The main purpose of the switch gear is to protect the electrical equipment in case of a malfunctioning of the grid. In the case of having chosen a skid, this component would already be part of the skid. The switch gear will be studied posteriorly.

2.2.3.3 Component selection

The datasheet of the available inverters can be found in Annex II. There are 5 different models available. All these models are compatible with battery energy storage systems. They can be divided in two subgroups depending on the maximum input voltage they can handle: Sunny Central 1000V and Sunny Central 1500V. As calculated in 2.2.3.1, the inverter should be able to provide a minimum input voltage of 1186.1V. Therefore, the subgroup Sunny Central 1000 V is directly discarded.

Inside the subgroup of Sunny Central 1500V, there are three different models, which differentiate themselves according to the power they can handle. Sunny Central 2500-EV provides capacity for 2500kVA, Sunny Central 2750-EV provides capacity for 2750kVA and Sunny Central 3000-EV provides capacity for 3000kVA. According to 1.8, the plant will be designed to grant a nameplate capacity of 3MW. Consequently, the only inverter that can provide sufficient capacity is the **Sunny Central 3000-EV**, which will be the chosen model.

SMA are a leader manufacturer in inverters and power conversion station. Apart from Australia, is the top Europe inverter manufacturer, and has more than 75GW of installed inverter capacity worldwide. The following table resumes the key features of the model selected:

Nominal AC Power (KVA)	*3000*
Max. Input Voltage (V)	1500
Max. Input Current (A)	3200
Nominal AC Current (A)	2646
Nominal AC Voltage (V)	655
Nominal AC Voltage Range (V)	524-721

Table 9: Main characteristics of the inverter

Figure 14 represents the selected inverter.

Figure 14: Sunny Central 3000-EV

It must be noted that, according to the characteristics of the inverter, only one power block will be used which will hold all different entries from the strings of the trackers. This is possible due to the small size of the proposed plant: generally, for a more powerful solar plant, more modules are needed which lead to a bigger number of inverters.

Having selected the inverter, the transformer will be now selected. According to the plant characteristics defined in 1.8, the plant is designed for a nominal power of 3 MW_{AC}. Consequently, the transformer that will be used should have be of at least 3MVA to handle the power coming from the plant.

In terms of transformers, there are not specific characteristics it should accomplish apart from offering high efficiency and providing the exact power needed for the project. Commercial transformers for this type of projects have similar characteristics. As so, the supplier used by Gransolar in the last PV projects will be used. The company Ingecon offers transformers for input voltage of 1500V and a wide range of different powers. The datasheet with the available transformers can be seen in Annex II. It is reminded that the nominal power of the PV plant is 3 MVA, and a transformer of this power should be chosen accordingly. Inside the Dual Ingecon Sun series offered in the datasheet, the transformer that best fits in the solar plant is the DUAL INGECON® SUN 1500TL B578, as it is the one that provides the exact power needed. A table with the main characteristics can be seen below:

Nominal AC Power (KVA)	*3000*
Max. Input Voltage (V)	1500
Max. Input Current (A)	1850
AC Voltage Output (kV)	33
Operating Efficiency	98.9%
THD	<3%

Table 10: Main Characteristics of the transformer

Figure 15 represents the selected transformer:

Figure 15: DUAL INGECON® SUN 1500TL B578

2.2.4 INTERCONNECTION

Once the voltage has been transformed to the adequate voltage of the transmission line in alternating current, the only missing aspect is the final connection to the grid. For photovoltaic plants of bigger size, it is usually needed to build a complete substation in order to correctly connect the plant to the grid. However, the size of the studied plant makes possible a connection without the creation of a substation.

As so, the correct approach to connect the plant to the grid is via a switchgear. A switchgear, apart from connecting the plant to the grid, ensures that, in case of any misfunctioning in the plant that might damage the grid, the plant can be completely cut off from the grid. It is also known as a circuit breaker, and apart from safety reasons, it might be used when maintenance of the plant is needed.

As every plant requires different connections, the switchgear is designed entirely different for each PV Plant. Consequently, no datasheet can be added to the project for the switchgear. However, an estimation of the price according to the characteristics of the project will be proposed. An approximate diagram of the switch gear can be seen below:

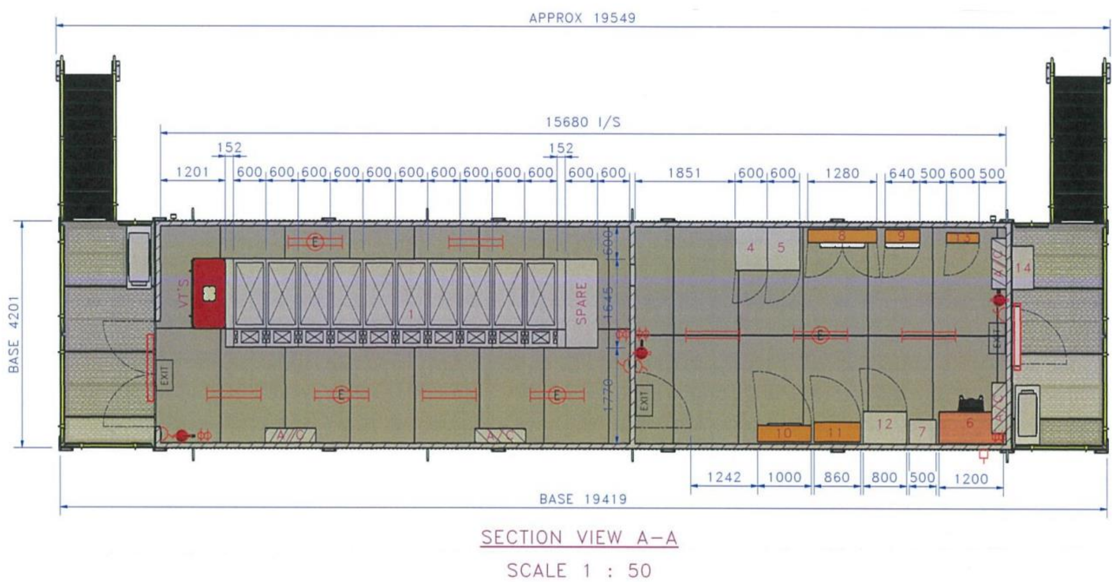

Figure 16: Approximate diagram of a switchgear

Being the interconnection the last component before the plant is connected to the grid, the electricity fed must coincide with the characteristics needed for the grid: apart from having the same voltage than the transmission line, the electricity provided must fulfill several parameters related with reactive power and harmonic distortion. These requirements are summarised in the Electricity Distribution Network Code. This code is different for every country; in the case of Australia, where the NEM is divided into the component states, the code is different for each state.

Queensland's Electricity Distribution Network Code requirements can be found in (Electricity Distribution Network Code made under the Electricity Act 1994, n.d.), and specify the requirements needed for a generator when feeding energy into the grid. As a whole, the grid of Australia is particularly weak due to the long distances that separate generators and consumers. Consequently, the requirements needed are specially demanding, and they are not usually achieved only with the elements proposed before. There is a need of installing a harmonic filter to fulfill all the requirements. It must be noted that the network code in some countries is not as demanding as the Australian code, and does not need a harmonic filter.

There are harmonic filters that are specifically designed to cover the requirements needed in Australia. Consequently, it will only be a matter of finding the one that works in the same voltage as the interconnection and is capable of handling the power provided by the plant. An active harmonic filter has been proposed from the Chinese manufacturer Eaton. The 33kV 4.5MVar 4.5th C type Filter Bank provides the requirements needed for feeding energy into the grid. The datasheet can be found in Annex II. The diagram of the chosen harmonic filter can be seen below:

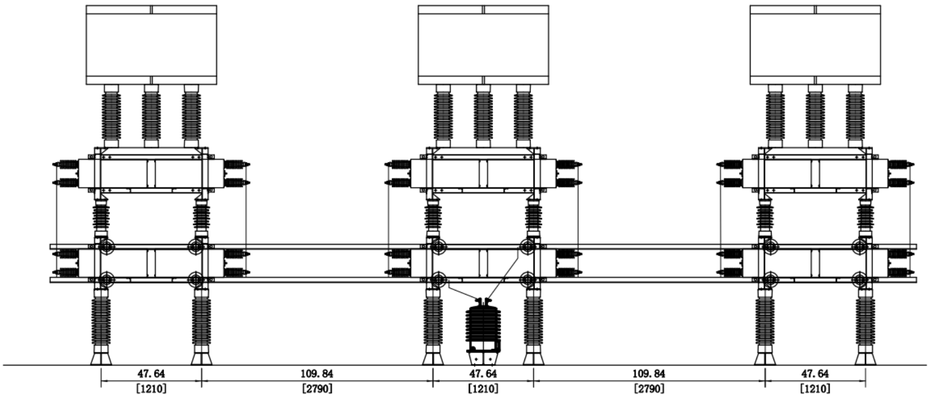

Figure 17: Harmonic Filter diagram

As stated before, the characteristics provided by the harmonic filter are the optimal needed for Australian's electricity and will not be studied in detail. The main aspect to focus is the 33kV voltage rate and the 4.5MVA maximum power, which fit perfectly with the characteristics of the solar plant.

Once the interconnection has been studied, the block diagram that represents the connections between components will be studied below.

2.2.5 PLANT'S BLOCK DIAGRAM

The complete process of obtaining the energy from the solar panels to the grid feeding can be seen in the block diagram below.

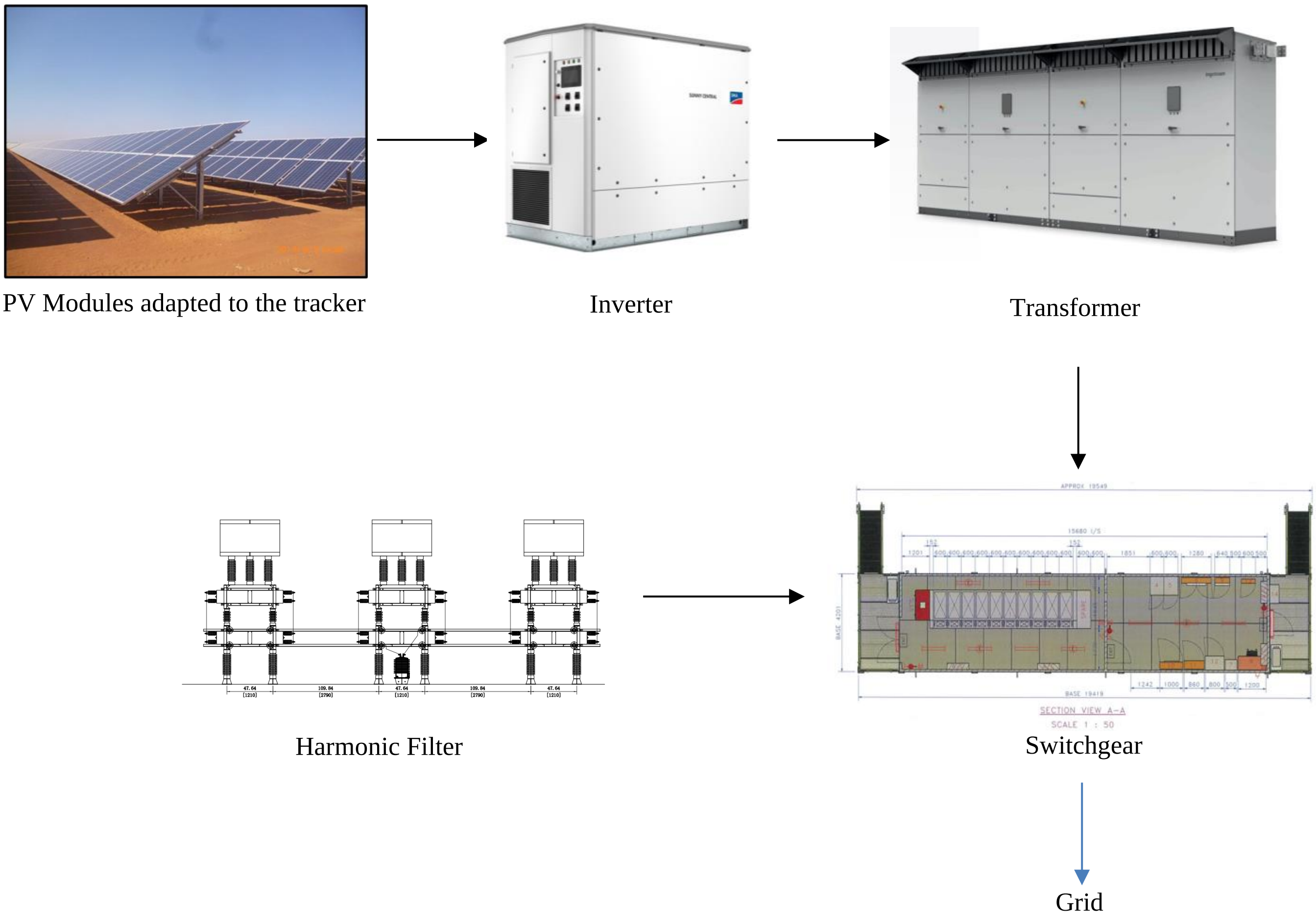

Figure 18: Block Diagram of the Plant

Considering all calculations made for the solar modules and the general configuration of the solar plant, a table which synthesises the technical aspects of the plant can be seen in Table 10:

PV PLANT CONFIGURATION	
AC Installed Power (@35°C)	3 MVA
DC Installed Power	3.153.750 W_{DC}
PV Module Technology	Monofacial PERC (Passivated Emitter and Rear Cell) framed module
Module Manufacturer	Longi
Module Model	Hi-MO LR4-72HPH-435M
Module Power	435 W
Voltage	1.500 V
Modules per String	29 (Refer to tracker characteristics)
Number of modules	7.250
Inverter Manufacturer	SMA
Inverter Model	Sunny Central 3.000-EV
Inverter Nominal Power (@35°C)	3.000 kVA
Inverters Blocks Power	1 power block of 3.000 kVA
Strings per Inverter Block	250
Number of Inverters	1
Transformer Nominal Power (@25°C)	3MVA
Number of Transformers	1
Racking Structure Manufacture	PVH
Racking Structure Model	Monoline 3H
Racking Structure Configuration	Independent-row horizontal single-axis (Three modules in landscape(horizontal))
Pitch	58(29*2) m per large, 29*3 pannels per row

Table 11: Technical Characteristics of the Plamt

Having defined the most important components of the solar plant, now the layout of the plant will be studied. The exact prices of the main equipment will be detailed in the economic study and the posterior commercial offer.

2.3 DESCRIPTION OF THE PLANT LAYOUT

This subchapter will study all the PV plant elements that are not the main equipment but are needed to form it. This includes all previous works needed in the terrain and different non-principal elements such as gates or alarms. The prices of all this layout will be summarized in the Balance of System (BOS), which will appear in 3.3.2. It must be noted that the price of each element or work needed in the layout will not appear individually and an approximate cost of the whole BOS will be provided by Gransolar.

2.3.1 GROUND PREPARATION

The philosophy used by the partnering company when it comes to ground preparation is to respect as much as possible the existing ground conditions, as trackers are usually suited to adapt to the original ground shape. However, there are some basic ground works that must be carried out in order to avoid any shading in the solar array or delay the construction of the plant itself, which include:

- Removal of trees and weeds.
- Clearance of the top soil layer.
- Removal of any undesirable material.
- Archaeological works.

Another aspect to consider when studying the ground preparation is grading. In this case, it has been indicated that the slopes are considerably constant with tiny inclination. Therefore, it should not be considered any bulk levelling works and the earthworks required are only for cleaning purposes as indicated above. It must be noted that choosing a site of these characteristics cheapens highly the conditioning of the ground, as the construction of the plan can be started almost immediately (the ground preparation mentioned above is fairly simple).

2.3.2 ROADS, GATES AND FENCES

The plant requires the construction of roads both internally (for the installation of the elements and their repair) and externally (providing an access from the main road). Returning to the detailed figure of the situation of the plant (Figure 19):

Figure 19: Detailed Plant Situation

The plant is connected to a road parallel to Capricorn Highway, which is accessed 2.5 km west from the location of the plant (Lagoon Park Road, blue-pinned location in Figure 20):

Figure 20: Site Access

The location of the solar plant is pinned in red. It has been indicated that Lagoon Park Road is sufficiently wide and resistant for the construction machines to get through; consequently, the only perimetral road to be built is the black line distance covered in Figure 19.

For the internal roads, it has also been indicated that there will be needed approximately 350 linear meters of internal roads, according to the size of the solar plant.

Both internal and external roads usually built by Gransolar consist of a 4 meters wide road section, made of two layers of granular material (sub-base and base courses), which may not be lower than 20 cm thickness for the sub-base and 10 cm for the base course. It is also important for the roads to have an appropriate drainage and erosion control, and to be rain resistant. The following figure shows an example of the roads to be built, provided by the partnering company:

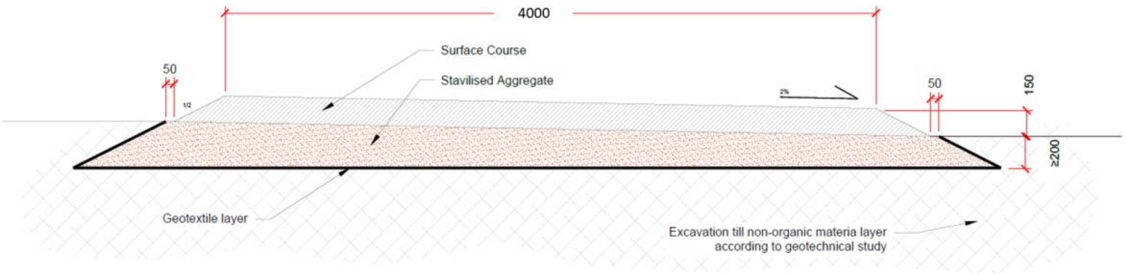

Figure 21: 4 m. Road Diagram

The perimeter of the plant must be fenced both for safety reasons and environmental purposes. Standard fencing for solar installations requires about 2,10 m. of height and two rows of barbed wire of 0,50 cm. above of them. The following figure shows the schematic of the purposed fence, provided by the partnering company. As it can be inferred, the total length of fence needed equals the perimeter of the installation, which as can be seen inFigure 19, is of approximately 1,10 km.

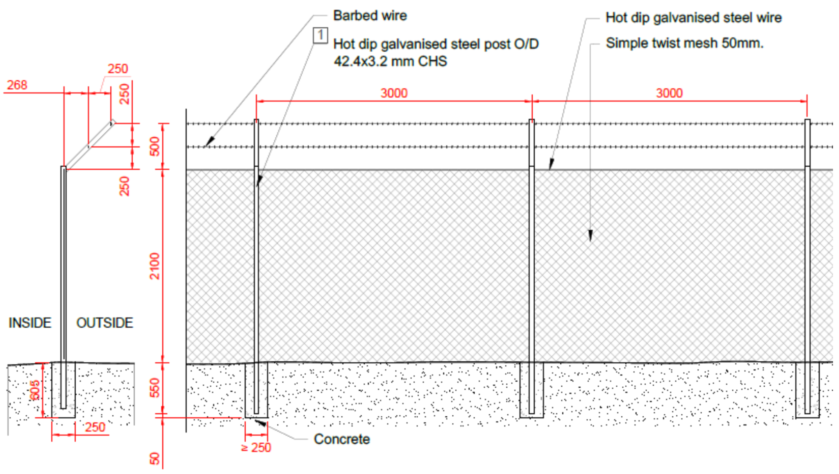

Figure 22: Fencing Details

In terms of gates, there will be two gates needed: one supporting the pedestrian access and one supporting the vehicle access. The pedestrian access gate will be of the same height of the fence mentioned above with 1 m. length, made by steel. The main access gate (vehicle gate) is required to be a sliding gate sufficiently long and wide to support access to the vehicles needed for the construction of the plant. This requires at least 6 m. of length, being the same height as the fence. The standard gates used by Gransolar are automatic sliding gates, operated by an electric motor remotely controlled, with the respective sensors and contacts for a safe operation. The detail of the main access gate can be seen below:

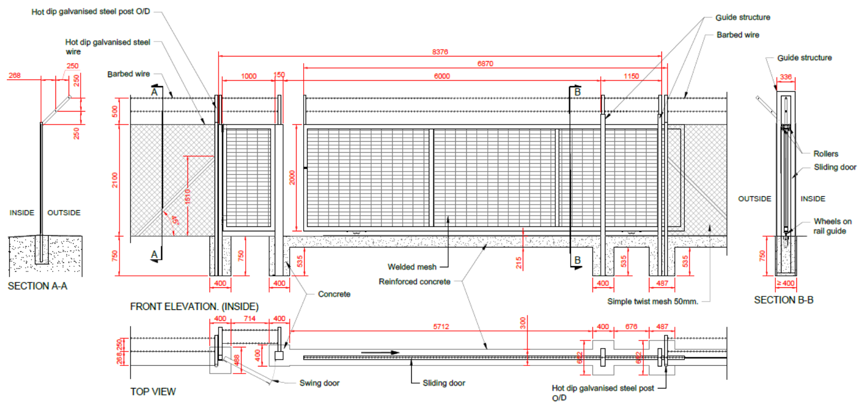

Figure 23: Main Access Gate Detail

2.3.3 OTHER EQUIPMENT

2.3.3.1 Operations and Maintenance Building

As it will be seen in the following chapters, there will be a permanent operations and maintenance (O&M) cost, which will be caused by and O&M contractor that will be permanently in charge of the safe operation of the plant. Consequently, a building will be needed for this purpose. During the construction of the solar plant, this building might be used as a construction site office with administration equipment. Once finished, the O&M building will consist of a control room, an office and a warehouse.

2.3.3.2 Security System

The security system of the PV plant will have the following elements as standard:

- Thermic Cameras.
- Video Recording System.
- Alarm System.

All these elements will react when an alarm is triggered when an intruder is trying to access the plant. The PV Plant will be monitored from a remote place through the communication system. It must be noted that using a high-level security system is sometimes counter-productive because of the wildlife of Australia: it has been indicated that high-security alarms tend to go off easily because of the appearing of kangaroos or other type of wildlife in the solar farm.

2.3.3.3 SCADA

The obtention of all data needed for the correct operation of the solar plant belongs to a SCADA (Supervisory Control and Data Acquisition). SCADA is not a concrete technology but can be any type of application used to monitor the data. The SCADA normally used by Gransolar is the one given by PVH, which is the same provider as the tracker, called PV Performance Control. The purpose of this system is to acquire, store, and display the operating parameters of a PV plant.

This system is based on a server which centralises all devices integrated. The following schematic shows a SCADA architecture:

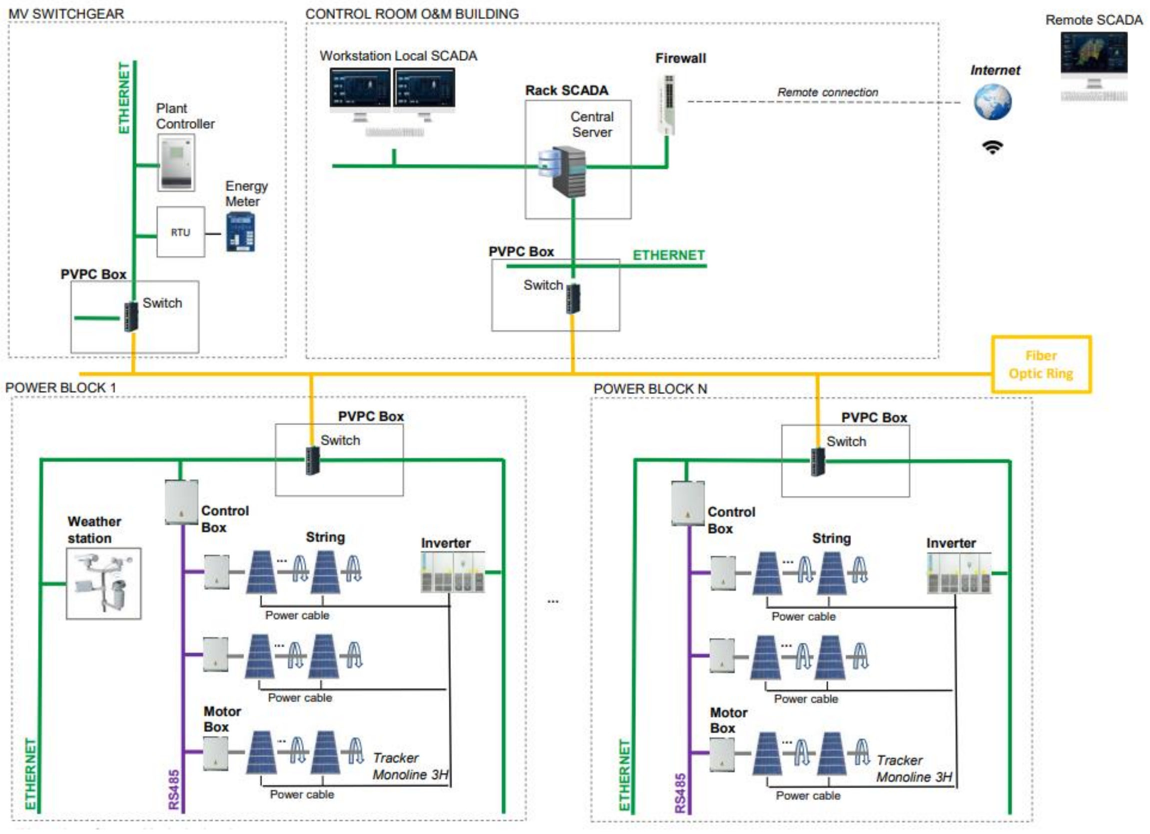

Figure 24: SCADA Architecture

The use of this type of technology is key for the correct functioning of the PV Plant. It can indicate failure of components almost instantly, which otherwise would result in significant losses if not fixed at that very moment.

PV Performance Control provides all the functions required to visualize and operate PV plants, from the modules themselves to the inverters and grid connection. It can also acquire data and store them long term, which is particularly useful for the study of the profitability of similar projects in the long term. The dashboard provided by PV Performance Control provides up to date information of the key aspects of the plant. A figure showing the dashboard appearance is shown below:

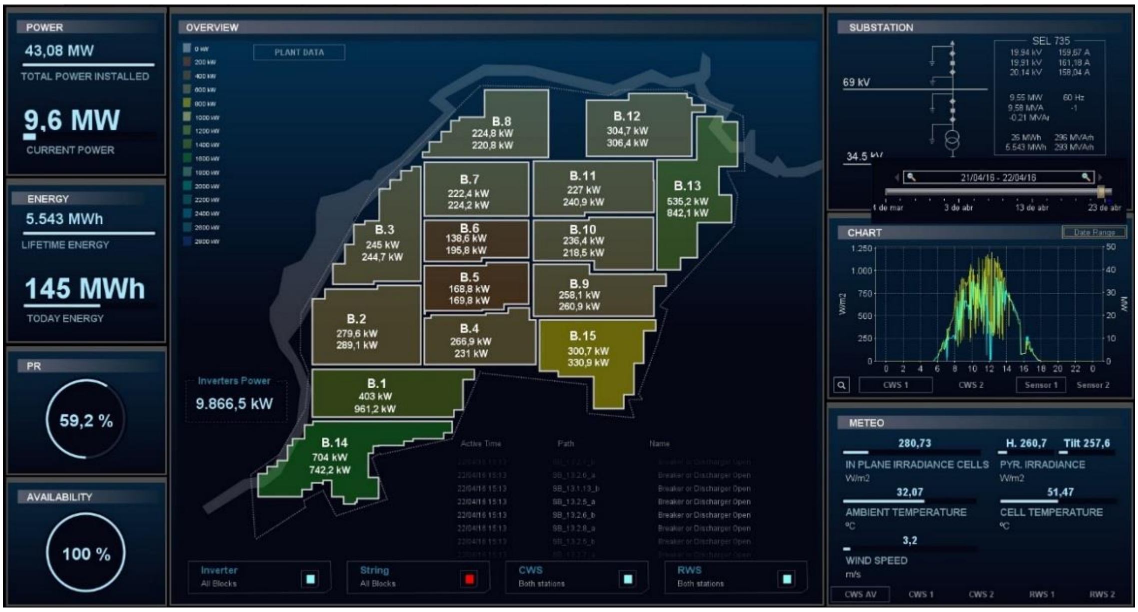

Figure 25: Dashboard Example

Normally, one dashboard is used by the O&M contractor to ensure the correct functioning of the solar plant.

The installation of the SCADA requires as well the installation of a weather station to ensure the veracity of the data collected and to complement it. This weather station is autonomous and measures all different weather characteristics. It will consist on:

- Pyranometer (used to measure solar irradiation). One will be installed in the horizontal plane and the other one in the solar array plane.
- Barometer (used to measure atmospheric pressure).
- Pluviometer (used to measure quantity of precipitation).
- Air Temperature and Humidity Probe.
- Anemometer (used to measure wind's speed).

Chapter 3. CALCULATION OF THE REVENUE OF THE STUDIED PV PLANT IN THE SPOT MARKET OF QUEENSLAND IN A REFERENCE YEAR

3.1 PLANT PRODUCTION ACCORDING TO DEFINED CHARACTERISTICS

Once the plant has been completely designed, the energy production will be simulated to obtain the total revenue that the plant will offer. The program used will be PVSyst, which is a PC Software package used for the study, sizing and data analysis of PV systems (Pvsyst.com, 2019). The program works as follows: Available area, meteorological data, solar array model and inverter model will be provided to PVSyst, which will then propose the most effective orientation of the solar panels according to the characteristics provided. Secondly, more specific parameters are to be defined to the program, such as shading, module quality or thermal behaviour. The program will then provide a simulation of the hypothetical energy that would be fed into the grid, that can be displayed in different time values. With this simulation, the optimal revenue of the PV plant can be then calculated. A detailed explanation of the results will be studied afterwards.

3.1.1 SIMULATION: PROJECT DESIGN

The first step in the simulation is to provide the geographical characteristics of the plant, which include location and weather data. As defined in 2.1, the available terrain is located in the town of Jericho, Queensland. A summary of the data provided to the program can be found on Table 12:

	Location Characteristics
Latitude	-23° 36' 3.1"
Longitude	146° 11' 16.55"
Land Occupied	7.5 ha
Elevation	352 m.a.s.l

Table 12: PVSyst Location Characteristics

Once the location is set, the meteorological data is to be defined. There are several weather databases included in PVSyst, but to obtain a better accuracy of the simulation, the SolarGIS database will be used. This database is external to PVSyst, and is utilised by Gransolar in their project studies. SolarGIS is used in more than 100 countries by approximately 1500 companies (Solargis.com, 2019). It is more expensive than using the internal PVSyst databases, but it provides extremely accurate values of irradiation for the location provided, as well as hourly values for a characteristic year. Consequently, this will be especially useful for the study of the solar plant revenue, as choosing one specific year could lead to inaccuracy of the data. The results of the simulation will then show the energy fed into the grid every hour.

Model characteristics for the solar plant will be then specified to the program. As selected in Parte I2.22.2, the chosen models for the solar arrays and inverter are as shown in Table 13:

	PVSyst specified models
Solar Arrays	Longi Hi-MO LR4-72HPH-435M
Inverter	Sunny Central 3000-EV

Table 13: Selected array and inverter models

Once the basic characteristics are defined, more complex specifications could be indicated to the program. The most important ones are shadowing and incidence angle losses, as are the ones that directly signify a loss in irradiation received by the plant. In terms of shadowing, it must be noted that, for the installation of the solar plant, there are some preliminary works that must be carried out before the installation. These include tearing down all vegetation and objects that could partially shadow parts of the plant. As so, it will be supposed that no shadowing will be present in the plant. Also, in terms of incidence angle loss, it has been indicated by the supervisor that the losses are negligible for the size of the solar plant studied. Consequently, these specific terms will not affect the overall plant production.

3.1.2 SIMULATION: EXPLANATION OF RESULTS

Once the simulation has been carried out, the results offered by PVSyst can be read through an Excel worksheet. As explained in 3.1.2, this simulation will provide the different irradiation data for every hour of the day, for a typical meteorological year at the location provided. The first section of the simulation will be shown in the following page (Table 14), which has been modified to horizontal for clarity sake. The complete simulation can be found in the attached documents. The explanation of all different data obtained will be studied after the simulation.

PVSYST v6.80					
	File	File date	Description		
Project	PR_I19-0061-MO(	22/03/20 13h01	THESIS PROJECT STUDY-AUSTRALIA		
Geographical Site	Jericho_SolarGIS.S	22/03/20 13h01	Jericho	Australia	Australia
Meteo data	Jericho_SolarGIS_!	19/02/20 13h26	Jericho	SolarGIS Mor	Synthetic
Simulation variant	PR_I19-0061-MO(	22/03/20 10h36	MF2V7.2_3_3.15_400x29_HW_LC		
Simulation date		22/03/20 10h43			
Simulation:	Hourly values	from 01/01/90	to 31/12/90		

date	GlobHor	DiffHor	T_Amb	GlobInc	EArray	EOutInv	Aux_Lss	IL_Nigh	E_Grid	TArray
	W/m²	W/m²	°C	W/m²	W	W	W	W	W	°C
01/01/1990 0:00	0	0	29,3	0	0	-75	250	75	-3447,3	0
01/01/1990 1:00	0	0	28,63	0	0	-75	250	75	-3447,3	0
01/01/1990 2:00	0	0	28,26	0	0	-75	250	75	-3447,3	0
01/01/1990 3:00	0	0	27,89	0	0	-75	250	75	-3447,3	0
01/01/1990 4:00	0	0	27,63	0	0	-75	250	75	-3447,3	0
01/01/1990 5:00	19,108	12,497	28,05	11,427	23259	18753	4100	0	11529	28,32
01/01/1990 6:00	263,9	69,899	31,12	138,54	290962	285671	4100	0	277926	33,805
01/01/1990 7:00	390,19	117,9	33,17	311,59	785677	776521	4100	0	765436	40,285
01/01/1990 8:00	531,8	192,8	35,08	476,64	1222958	1209374	4100	0	1192784	46,306
01/01/1990 9:00	795,3	190,8	37,54	743,76	1889143	1867359	4100	0	1837804	55,527
01/01/1990 10:00	759,69	298,4	39,01	730,02	1835665	1814304	4100	0	1786000	56,597
01/01/1990 11:00	454,19	258	38,92	439,75	1115252	1102373	4100	0	1087368	49,352

Table 14: PVSyst Simulation

As it can be seen above, the program provides different data according to the characteristics set before. It must be noted that in the Date section, the year shown is 1990, which is simply a way to indicate that is a typical meteorological weather year and not one in particular. The meaning of the sections obtained will be explained below:

GlobHor: Horizontal Global Irradiation – This parameter is provided by the weather database and is measured in W/m^2.

The horizontal global irradiation measures the total amount of solar radiation received, which is the sum of diffuse irradiation and beam irradiation. Beam irradiation parameter does not appear on the simulation results, but can be calculated as:

$$BeamHor = GlobHor - DiffHor$$

And is the irradiation obtained through direct sun beams.

DiffHor: Horizontal Diffuse Irradiation – This parameter is provided by the weather database and is measured in W/m^2.

The horizontal diffuse irradiation measures the total amount of radiation that does not arrive directly from the sun, but from the different sky elements that can provide radiation, as the blue sky or clouds. (www.3tier.com, n.d.)

T_Amb: Ambient Temperature – This parameter is provided by the weather database and is measured in ºC.

GlobInc: Incident global irradiation in the collector plane. It is directly related to the horizontal global irradiation, but the incident irradiation will always be less than the horizontal irradiation as there are losses in the solar arrays angle with respect to the sun. It is measured in W/m^2.

EArray: Effective energy at the array output. Measures the total energy obtained once the irradiation it has been transformed through the solar panel, and it is measured in Wh.

EOutInv: Effective energy at inverter output. Measures the total energy obtained once the output array energy has gone through the inverter. It will be less than the one at the array output as there are some losses in the process (wiring, inverting, etc…). It is measured in Wh.

Aux_Lss: Auxiliaries consumption. Measures the energy lost in auxiliary components, mainly maintenance elements. It is measured in Wh.

IL_Night: Inverter energy loss during night. Measured in Wh.

E_Grid: Energy injected to the grid. Measured in Wh.

TArray: Array Temperature. Measured in ºC.

It must be noted that the energy at array output, inverter output, auxiliary consumption, inverter loss and injected to the grid appear in the PVSyst as W, which is a power unit. However, as the program provides results for every hour, the energy in Wh will be the same as the power provided by the simulation. This is a key factor to consider.

Definition of the different data come from the simulation variables information on PVSyst.

Once studied all different results obtained in the simulation, it is important to remark the way which the PV Plant revenue will be studied. As specified in 1.8, all energy output of the solar plant will be considered to be sold entirely to the spot market. As so, the main factor which will be used to obtain the revenue will be the energy injected to the grid.

Analysing the results of the simulation, it can be noted that when the production of the solar plant is null, this means, when at night or when there is not irradiation, the value of the energy injected to the grid takes a negative value of -3447,3 Wh. This value would difficult the correct study of the revenue and has been pointed out by the supervisor as invalid. The correct way to develop the study of the revenue would be to suppose the energy injected to the grid as 0 when no irradiation is present. Consequently, for the posterior study of the revenue, another column has been added in the PVSyst simulation, named

'E_Grid_Corrected', which transforms all these negative values to 0. Once the simulation has been completely explained, the data obtained will be analysed.

3.1.3 Simulation: Study of the Obtained Results

The simulation has provided the energy injected to the grid at each hour of the day for the different months of the year, for a PV plant of the above-cited characteristics. Studying this information will provide a detailed idea of how the energy production behaves depending on the different time of the day or the year,

As it has been explained in 1.5, the functioning of a photovoltaic plant is simple: the energy production will be directly proportional to the irradiation obtained by the solar modules. Consequently, the higher the irradiation, the higher the energy fed into the grid. As so, it can be inferred that the plant will produce the highest amount of energy at the central hours of the day, and the production will be lower at hours close to dusk and dawn. The resultant figure could be compared to a normal distribution, where the peak is at the middle of the day, and it approximates to zero at the beginning and at the end.

To test this functioning, the production of the plant in a sunny day and in a partially sunny day will be studied as follows.

3.1.3.1 Behaviour of the plant in a sunny day

Examining the irradiation values provided, a complete plot of the energy production of the plant can be obtained. A complete sunny day can be considered as one where the irradiation levels are close to the normal distribution explained before. The resultant graph can be seen in Figure 26, which is the total energy fed into the grid in the 6^{th} of January of the characteristic year.

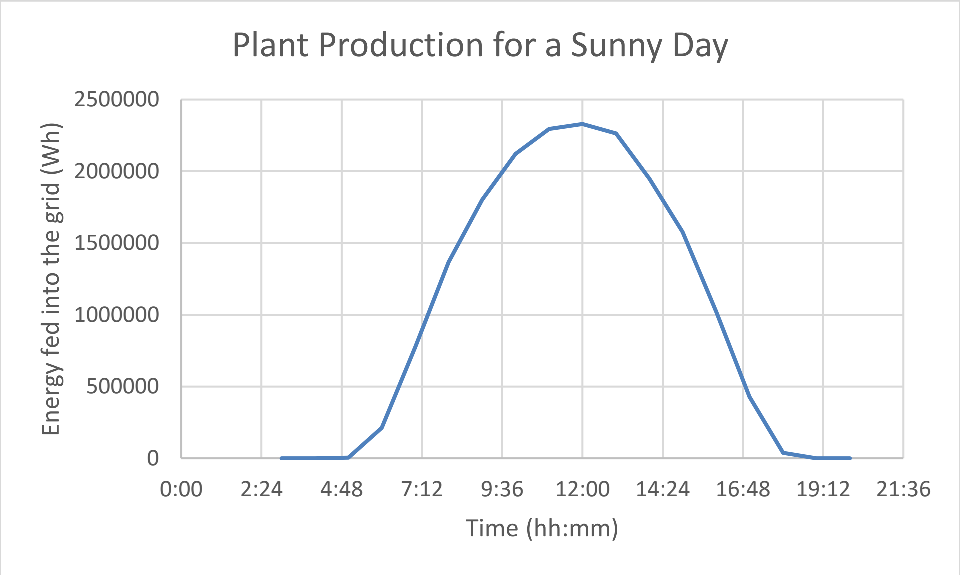

Figure 26: Plant Production for a Sunny Day

It is reminded to the reader that Australia's sunrise and sunset hours differ highly from the Spanish ones, being the 6th of January sunrise hour at 4:59 and the sunset hour at 18:47 for 2020 (www.timeanddate.com, n.d.). As it can be observed in Figure 26, the form of the plot represents accurately the amount of irradiation obtained at each time of the sunny day, obtaining the highest energy production at around 12:00, which is the central hour of the day.

3.1.3.2 Behaviour of the plant in a partially sunny day

It is as well interesting to observe the how the energy production behaves in a partially sunny day, when the production of some hours of the day is affected by clouds. The following figure shows the energy production obtained for the 1st of January of the characteristic year provided, where the irradiation levels are not uniform.

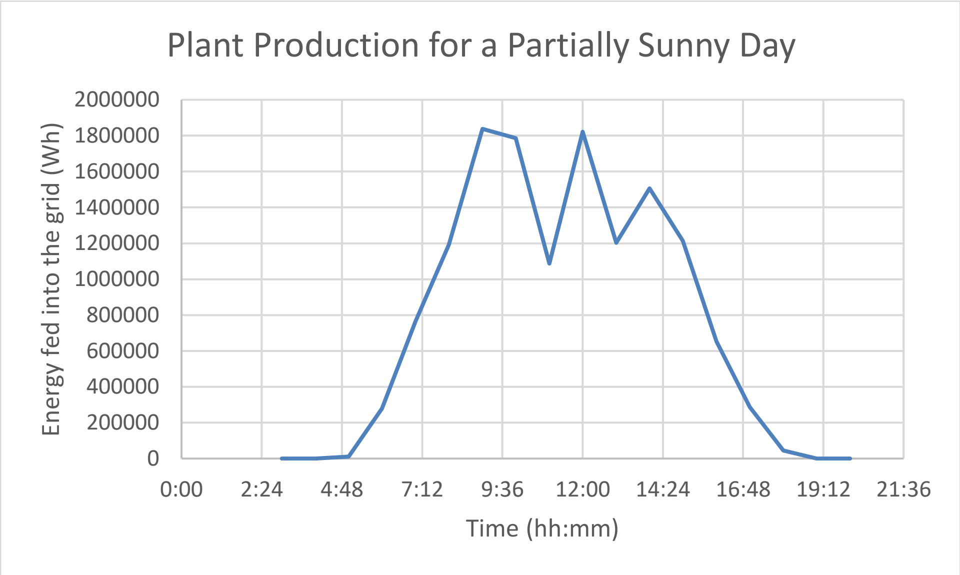

Figure 27:Plant Production for a Partially Sunny Day

The graph shape obtained in this case differs highly with the one obtained previously, as the production is not uniform anymore, and several peaks are obtained depending on the clouds at every hour of the day.

Both behaviours do nothing but confirm the fact that the plant production is directly proportional to the irradiation obtained. As a whole, if the average of every hour of the year is calculated, the resulting graph would be similar to the sunny day one. This overall graph can be seen below:

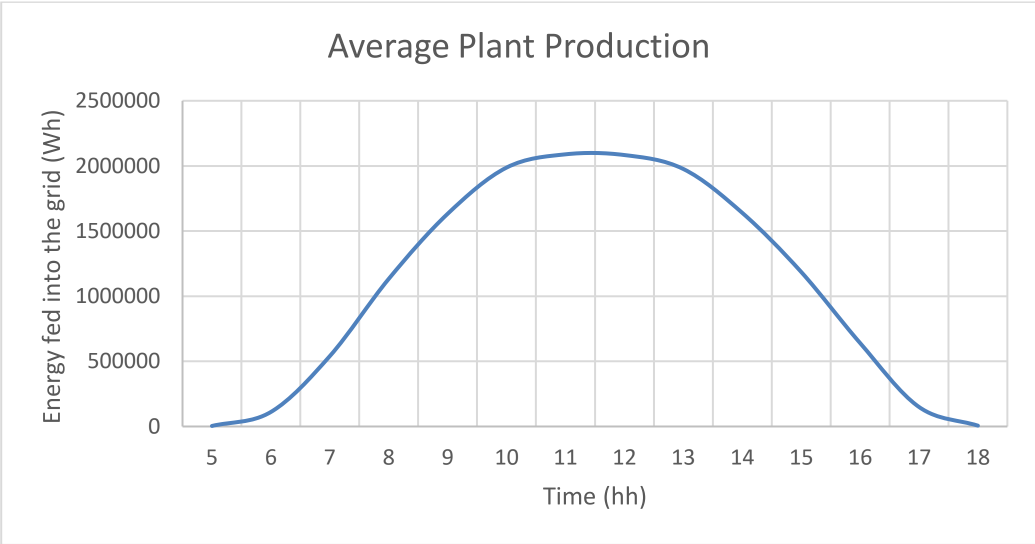

Figure 28: Average Plant Production

3.1.3.3 Comparison of the plant production between summer and winter

To check the accuracy of the data, it is interesting to compare the different production levels between a typical summer month and a winter month. It would be as well logical to deduct that the production will be lower in winter than in summer. As Australia is on the southern hemisphere, the summer months are between December and February, being from June to September the winter months. The following graph plots the total production for each month in a characteristic year.

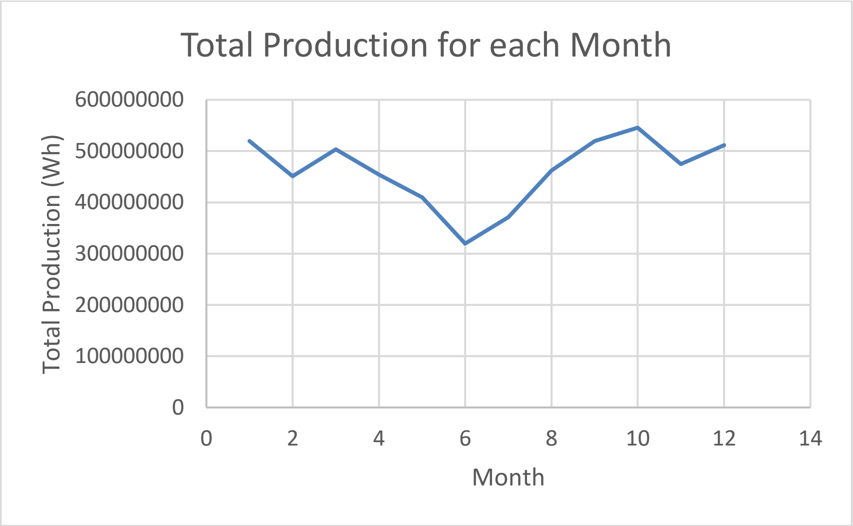

Figure 29: Total Production per month

The figure shows that winter months produce considerably less energy that summer months, which was expected from the beginning and confirms the accuracy of the simulation.

As a summary of the subchapter, the simulation of the energy production according to the location characteristics has been carried out, and the data obtained has been tested to check their reliability, comparing the production between different parts of the year. Once completed, the next step to obtain the total revenue and IRR of the whole project is to obtain the spot market prices for a year, and compare it with the production levels.

3.2 ELECTRICITY MARKET INTRODUCTION AND PV PLANT REVENUE

As detailed in 1.2, Australia's spot market is divided between the different states that compose the NEM, which are interconnected between each other so that when one state lacks in energy production, it can be provided by other states and vice versa. The prices are set each 30 minutes for every state, which would make interesting an analysis of the fluctuation of the prices for each hour of the day depending on the state. However, this is out of the scope of the project and will be referred as a possible future continuation of the project.

3.2.1 QUEENSLAND'S SPOT MARKET AND TRANSMISSION NETWORK

The AEMO website offers the historical data of the demand and the spot prices for all states in its website (www.aemo.com). This website will be used to obtain the different information needed to study the spot market.

The functioning of Queensland's spot market is the usual electricity-trading procedure: there is an exchange of energy between the consumers and the producers which is instantaneously scheduled to meet the whole demand. The price in which energy is sold is set every five minutes. Posteriorly, these prices are averaged to calculate the spot price for each interval (this means, six five-minute prices are averaged to obtain the price of the 30-minute interval). This process occurs for every state that compose the NEM. A further analysis of the shape of the price and demand curve will be carried out in the study of the battery.

Currently, Queensland is the largest former state of the NEM. As so, the transmission network inside the state is the longest of all, covering the distance between Cooktown (Queensland's network further northern point) and Coolangatta (Queensland´s further network southern point), approximately 1550 km. The total transmission line is also the largest, with almost 14000 km. (AEMC, n.d.). Figure 30 shows Queensland's transmission network. The approximate location of the PV Plant studied in this project is marked in the map with a red cross.

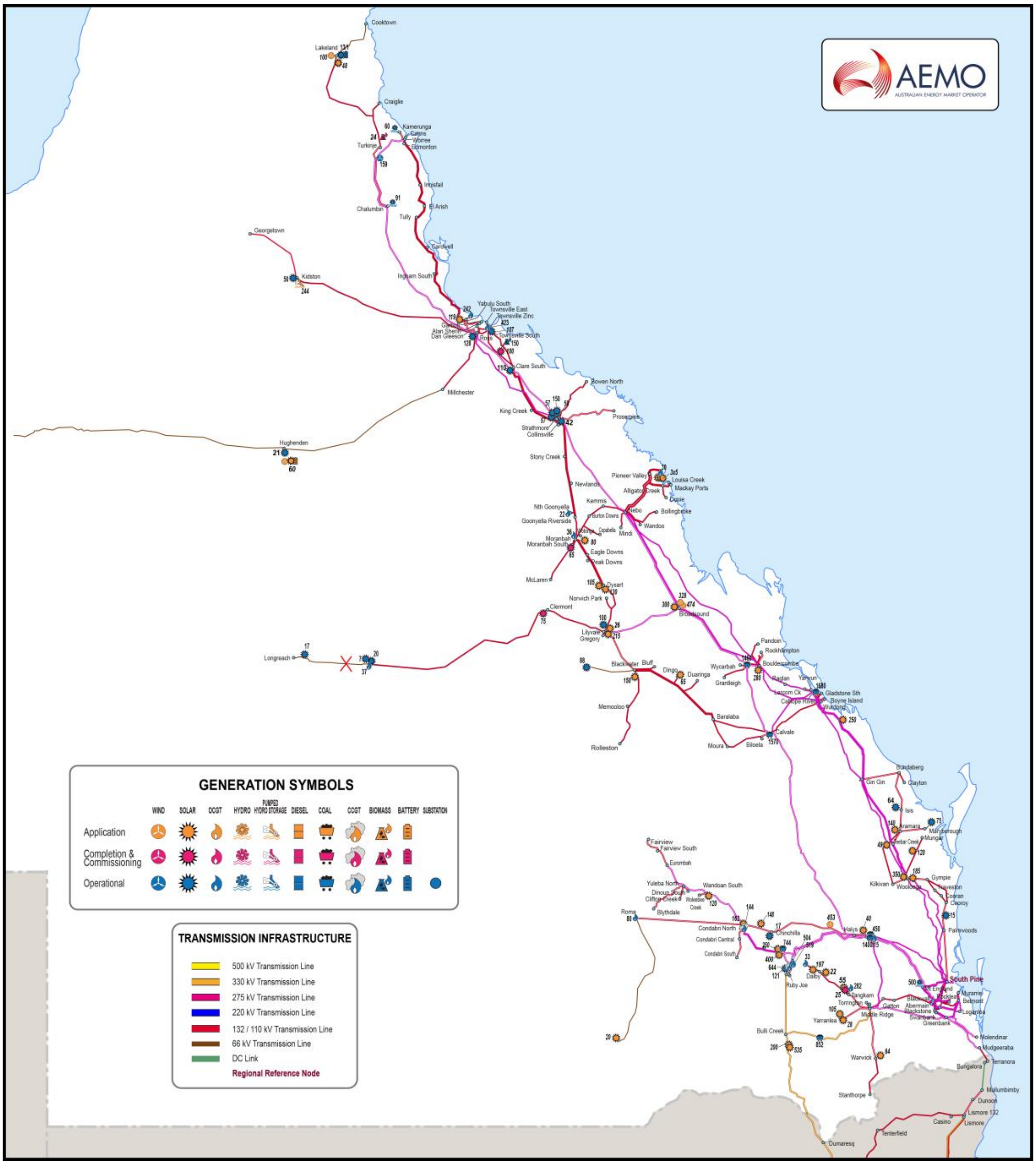

Figure 30: Queensland Transmission Network

The reference shows that the transmission line that goes through the location of the plant is of 33kV, which agrees with the nominal output voltage of the transformer.

The longitude of the transmission network makes distances between costumers and producers often very long, which means significant transmission energy losses. In addition, in the past years, an increasing number of generators have connected to the periphery of the network, which means further distance and lower operating voltages, proportionally increasing the transmission losses (AEMC, n.d.). This is the main reason why Queensland network is said to be considerably weak. However, this is not an issue that should be faced by the EPC company and does not influence in the development of the PV plant or in the revenue calculation, apart from the previously explained installation of the harmonic filter.

Once the electricity market and network has been described and analysed (pending a further price-demand study of the Queensland's market), now the spot market data will be compared to the simulated production levels of the plant, to obtain the gross profit of the plant.

3.2.2 PV PLANT GROSS PROFIT

As explained above, all revenue of the plant will be considered to be sold to the spot market. However, it is impossible to predict future prices of the electricity, hence an approximation must be made when it comes to obtaining the future prices. To do so, the wholesale market of the past years must be studied.

The following graph shows the quarterly volume weighted average price by contribution of price bands for Queensland in the past five years (Australian Energy Regulator, 2019). It must be considered that energy prices from the second quarter of 2020 have been directly impacted by COVID-19 pandemic, which will result in cheaper energy prices due to the lockdown imposed in the majority of states in Australia.

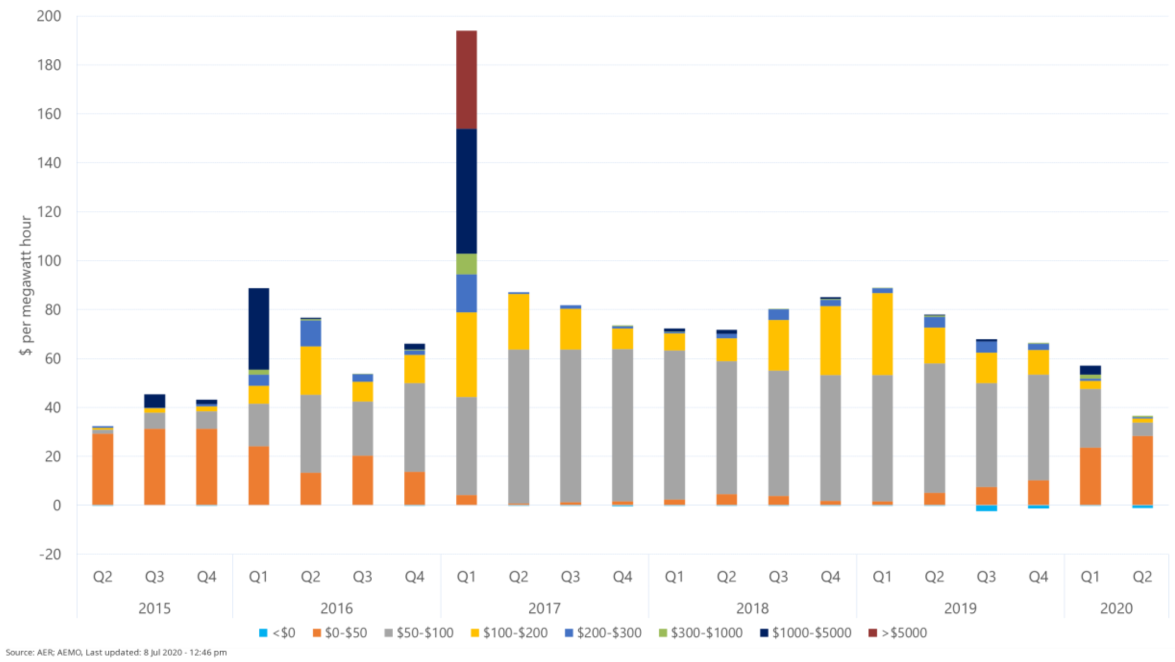

Figure 31: Quarterly volume weighted average price by contribution of price bands

The evolution of the prices during the past 5 years is clear. The first quarter of 2017 marks the beginning of an almost constant evolution of the prices, with the majority being from $50 to $100, having some sparks of prices from $100 to $200, which as will be seen afterwards, will be caused from the morning and evening price peaks. Consequently, it is fair to conclude that using the prices of 2018 or 2019 will provide an efficient approximation of the spot market in the future years. Further estimations could be made to detect the tendency of the prices, which could be then added to the cash flow report and therefore obtaining a more precise IRR. However, the resources needed to carry out this study are expensive and do not provide a significant difference in the final result. As so, <u>the estimation for the gross profit will be developed with the spot market prices from 2019.</u>

The historic data of the energy price for 2019 is obtained through AEMO website. An example of how the data is provided can be seen in Table 15:

REGION	SETTLEMENTDATE	TOTALDEMAND	RRP	PERIODTYPE
QLD1	01/04/2020 0:30	5710.84	48.67	TRADE
QLD1	01/04/2020 1:00	5604.44	51.5	TRADE
QLD1	01/04/2020 1:30	5511.97	49.06	TRADE
QLD1	01/04/2020 2:00	5419.03	46.53	TRADE
QLD1	01/04/2020 2:30	5406.11	38.32	TRADE
QLD1	01/04/2020 3:00	5374.89	38.04	TRADE
QLD1	01/04/2020 3:30	5370.63	36.32	TRADE
QLD1	01/04/2020 4:00	5352.18	34.79	TRADE
QLD1	01/04/2020 4:30	5405.77	39.16	TRADE
QLD1	01/04/2020 5:00	5457.24	42.64	TRADE

Table 15: Demand and Spot Prices

The different sections are explained below:

Region: State from the spot market studied

Settlement Date: Date when the price is fixed (refer to 3.2.1)

Total Demand: Demand in MW

RRP: Spot price in $/MWh

Period Type: Type of settlement (generally trade)

For the study of the gross revenue of the PV plant, the only information required is the settlement date and the spot price.

Obtaining the revenue having the price in which energy is sold and the estimated production is fairly simple: the gross revenue in a year will be the multiplication of the energy production times the spot price fixed. However, there is an inconvenience in the data obtained: the spot prices are set every 30 minutes, but the simulation emitted by PVSyst show the energy production simulation each hour. As so, it is not possible to make this multiplication directly.

Two ways have been presented to solve this issue:

- The average between the two prices given by the spot market could be calculated in order to obtain an hourly price of energy. Once calculated, this price could be multiplicated by the simulated production and an overall revenue obtained.
- The production obtained by the solar plant could be divided between the two 30-minutes period, then multiplicated by the spot price and obtaining an overall revenue. There is some understanding needed in this process. As explained in 3.1.2, PVSyst provides the results of energy fed into the grid in W. However, as it has calculated this power in periods of an hour, the total energy fed into the grid is the same result in Wh. Consequently, if the energy is divided into two time periods, the sum of this division must equal the total energy obtained in the simulation, in Wh. Now the issue comes in how to divide the energy production. It would be fair to deduct that, if all days were completely sunny, there would be a significant difference between half hours. However, this is not the case and there is no exact proportion that could fit all days rather than assuming that the same amount of energy is produced in the first half and in the second half of the hour.

After discussing both possibilities with the supervisor of the project, it has been decided that the second option offer a better grade of precision when it comes to calculating an overall revenue. Choosing the first option would mean a significant loss of information when the peak prices appear as they are very volatile and change highly between two time periods, as it will be seen in the future curve study. Consequently, the energy production will be divided by two to fulfil the two time periods, and multiplicated to obtain the gross revenue. It is important to remark that the energy produced by this method is exactly the same as the one obtained in the simulation and offers better precision.

An example of how the revenue is calculated can be seen below in Table 16. In this table appear both the obtained market data and the simulated plant production transformed.

Date	E_Grid_Corrected	E_Grid_Corrected	RRP QLD 2019	Revenue (1/2 h)
	Wh	MWh	$/MWh	$
01/01/1990 4:30	5764,5	0,0057645	50,93	0,293585985
01/01/1990 5:00	5764,5	0,0057645	47,49	0,273756105
01/01/1990 5:30	138963	0,138963	45,13	6,27140019
01/01/1990 6:00	138963	0,138963	45,53	6,32698539
01/01/1990 6:30	382718	0,382718	50,04	19,15120872
01/01/1990 7:00	382718	0,382718	41,89	16,03205702
01/01/1990 7:30	596392	0,596392	44,01	26,24721192
01/01/1990 8:00	596392	0,596392	46,28	27,60102176
01/01/1990 8:30	918902	0,918902	41,7	38,3182134
01/01/1990 9:00	918902	0,918902	46,43	42,66461986
01/01/1990 9:30	893000	0,893	52,49	46,87357

Table 16: Revenue Calculation

It must be noted that in the Date section, the year shown is 1990, which is simply a way to indicate that is a typical meteorological weather year and not one in particular. All columns have already been explained except the Revenue, which is the multiplication of the energy production times the sell trade price.

Once this has been calculated, several analyses can be obtained from it. First of all, the main objective was to calculate the total revenue. Table 17 shows the total energy produced each month by the plant and the revenue that it supposed, with the total values in the last row.

Month	Energy Output	Revenue
	MWh	$
1	519,334	50081,31
2	450,788	38237,37
3	503,257	39945,85
4	454,241	27401,56
5	409,753	25590,91
6	319,555	23556,85
7	371,076	18460,49
8	461,948	15010,75
9	519,825	10733,23
10	545,606	29168,36
11	474,697	21261,55
12	511,210	24084,82
Total	5541,291	323533,04

Table 17: Monthly revenue

The gross revenue obtained by selling all energy produced to the spot market is 323.533,04 AUD$. It is interesting to analyse the data and compare it with the production levels: it would be logical to infer that the higher the production, the higher the revenue. There are several factors that will affect this statement. The following figure shows the evolution of both production and revenue for every month.

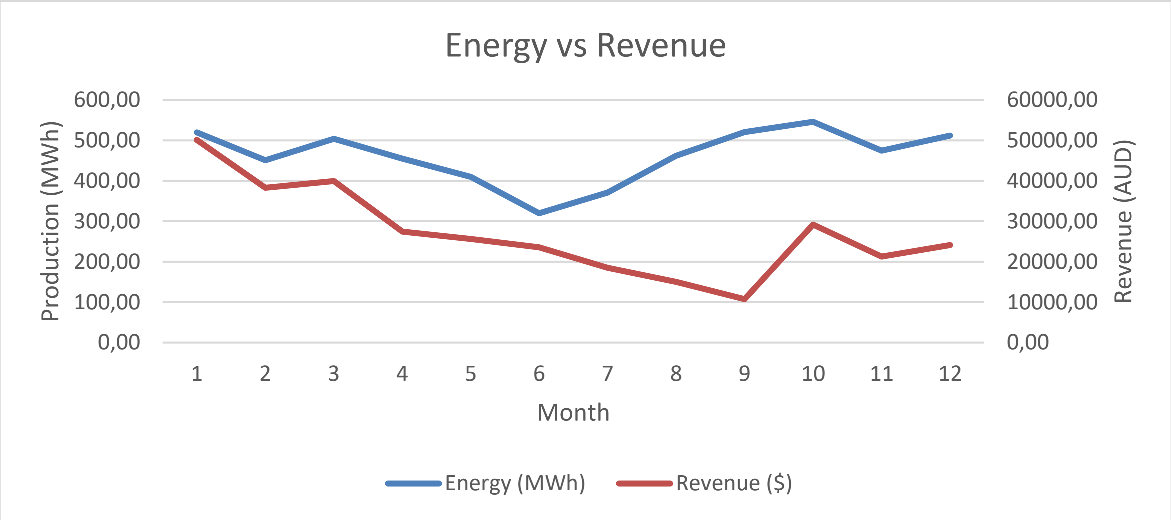

Figure 32: Production of energy against revenue

As it can be observed in the previous graph, the revenue curve behaves significantly similar to the energy produced one for the first six months of the year; nevertheless, from June to September, the revenue curve shows an atypical behaviour. While the production curve is growing, the revenue one is descending.

Figure 31 showed the evolution of prices for the last five years. It can be seen that for the third quarter of 2019, there is an increase in the amount of energy sold in the range of 0 to 50$, which differs from the previous months as the price evolution was almost constant. This would partly explain the difference in the curve, and is an indicator of what could happen in future years: there will be some months when energy is cheaper and some when energy becomes more expensive. Having chosen one whole year as an estimator provides an efficient answer to this volatility of prices and makes the final revenue a trustworthy number.

There are several factors that could explain the diminution of the price such as the opening of a new energy producer or the installation of a battery storage that would cheapen the wholesale market prices.

3.2.2.1 Other Considerations

As stated in 1.2, this project does not consider any PPA agreement to sell energy. The PPA is the most-used contract when it comes to energy trading, where the trading company pays a fixed amount to the energy producer and then resells the energy in the wholesale market. These contracts ensure a revenue to the energy producer when all of the terms of the contract are accomplished, which protects them from different events that could occur in the wholesale market, but limit their profit when the energy is expensive.

The idea of not simulating any PPA is to analyse the complete cost-effectiveness of the project: it provides the most accurate prediction of benefits that the plant itself can provide. In the battery study, it will also be analysed the possibility of signing cap contracts and participating in the contingency market.

Once the gross revenue has been calculated, the costs of all different parts of the PV Plant will be considered and the IRR of this first project (without battery) will be calculated.

3.3 CALCULATION OF THE CAPEX

CAPEX stands for capital expenditure, and refers to the money spent to acquire or upgrade productive assets in order to increase the capacity or efficiency of the company for an accounting period (BusinessDictionary.com, 2020). Taking the definition into our project, the CAPEX can be considered all the costs included in process of building the solar plant.

3.3.1 NOMENCLATURE

A subchapter is needed to present the way how prices are presented when describing solar plant elements. There are two ways to refer to the cost of a product, and depend on the element being described:

1. Price per element: The cost of the element is presented on its own (e.g.: 250.000 AUD$)
2. Price per nominal power: The cost of the element depends on the nominal power of the whole plant (e.g.: 0,1AUD$/$W_{DC}$).

The way the price of an element is presented depends on the quantity being ordered. For example, the number of solar modules is considerably high and will be presented in price per nominal power. However, the number of inverters used is smaller, and as so, it will be presented as price per element. As a whole, it is interesting to obtain the price per nominal power of the whole solar pant for analysis purposes. Therefore, the price per element will be transformed to price per nominal power in the commercial proposal and vice versa.

3.3.2 BALANCE OF SYSTEM (BOS)

The balance of system (BOS) includes the prices of all elements and processes that do not belong to the main equipment of the solar plant, this means, all the costs incurred apart from the ones related to the PV modules, the power conversion station, the tracker and the interconnection to the grid (switch gear). These costs include:

- Design and preliminary studies.

- Plant layout (refer to 2.3), which includes:
    - Mechanical works and ground conditioning.
    - Meteorological stations.
    - Security systems.
- Electrical package.
- Logistics.
- Project and financial management costs, which include all permits needed to build the PV Plant.

It must be noted that the operation and management cost is not included in the balance of system as it is a cost that will be continuous during the operation of the solar plant. Consequently, it is a cost that belongs to the OPEX, that will be explained in 3.4.

As explained in 2.3, the exact price of each specific element is out of the scope of the project. Consequently, an average value of 0,5 AUD$/$W_{DC}$ has been provided by the supervisor to define all costs incurred in the Balance of System.

3.3.3 CONSIDERATIONS AND EXCHANGE RATES

- The original solar plant was designed to have peak power of 3,155MW. However, it has been checked in 2.2.2 that according to the tracker's characteristics, the number of solar modules should be fixed to have a whole number of trackers. Consequently, the corrected peak power of the solar plant is of 3153750W_{DC}, which equivalates to 7250 solar panels.
- The prices of the elements might be indicated in different currencies. More concretely, the prices of the main elements will be presented in Australian Dollars (AUD$), United States Dollars (USD$) and Euros (€). As the exchange rate depends on the day, a standard value for both exchange rates to AUD$ will be used. The exchange rates are:
    - 1 € = 0,61 AUD$
    - 1 USD = 0,68 AUD$

3.3.4 BREAKDOWN OF PRICES

The prices of the main elements and BOS, as referred in 2.3 and in 3.3.2, will be shown below in Table 18. All prices will be directly converted to AUD$ and their equivalent in price per nominal power.

- PV Modules: 0,21 USD$/Wp.
- Power Converter Station (includes inverter and transformer): 275.000 AUD$.
- Tracker (Structure): 34 €/PV Module.
- Interconnection (includes switchgear and harmonic filter): 200.000 AUD$.

CAPEX							
Main Equipment Price	Data	Units	EUR	USD	AUD	Total AUD Equivalent	AUDeq/Wdc
PV Modules	0,21	USD/Wp	-	662.287,5	-	973.952,21	0,3088
Inverter	275.000	AUD	-	-	27.5000	275.000,00	0,0872
Structure (Tracker)	34	EUR/Mod	246.500	-	-	404.098,36	0,1281
BOS	0,5	AUD/Wp	-	-	1.576.875	1.576.875,00	0,5000
Interconnection	200.000	AUD	-	-	200.000	200.000,00	0,0634
TOTAL	-	-	246.500	662.287,5	2.051.875	3.429.925,57	1,0876

Table 18: CAPEX Calculation

The total CAPEX equivalent is 3.429.925,57 AUD$, which equivalates to 1,0876AUD$/$W_{DC}$.

A complete commercial offer will be developed when the optimal project is chosen in Annex III.

3.4 CALCULATION OF THE OPEX

OPEX stands for operating expenditure, and refers to an ongoing cost for running a product or business (Maguire, Smith and Kouyoumjian, 2008). In the case of the solar plant, the only predicted OPEX is the operations and maintenance cost (O&M), which has been defined in 2.3.3.1.

The OPEX cost will be provided for a year and supposed equal for the rest of the years studied (excepting inflation variations). Considering the size of the solar plant, all the O&M cost is the one produced by contracting one plant manager who operates and takes charge of the whole plant. This also includes vigilance costs, and all different repairs needed in the plant. The simulated OPEX will be accurate enough to support all of these costs. The cost of the plant manager has been indicated by the supervisor and is broken down in the following table:

OPEX							
Analysis	Data	Units	EUR	USD	AUD	Total AUD Equivalent	AUDeq/Wdc
Plant Manager-Total Price	140.000	AUD	-	-	140.000	140.000	0,0444

Table 19: OPEX Calculation

The total OPEX equivalent is 140.000 AUD$, which equivalates to 0,0444AUD$/$W_{DC}$.

3.5 ECONOMIC STUDY: CASH FLOW AND IRR CALCULATION

The main aspect from which the project will be evaluated is the comparison of the IRR between the project with and without the battery. The Internal Rate of Return (IRR) is a calculation used to estimate the profitability of potential investments (Hayes, 2019). Several considerations must be considered when studying the IRR:

- The Internal Rate of Return measures the annual rate of growth that an investment is expected to generate. Therefore, it does not provide an exact decision over if the project should be carried out or not. This is usually decided with various parameters that affect directly to the company such as the company's weighted average cost of capital (WACC), which is critical information. As so, the economic study will not decide on whether the project should be carried out or not, but will study its viability and comparison with the battery-added project.
- The IRR formula is:

$$NPV = 0 = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_o$$

Equation 1

Where:

- NPV is the Net Present Value, which is equalled to 0 in a cash flow analysis
- C_t is the net cash flow during period t
- C_o is the initial investment
- IRR is the Internal Rate of Return

As so, the IRR is dependant of the number of years. One new question now appears: what is the usual time used to calculate IRR in this type of projects?

It has been indicated that, for PV plants of all types, the usual time used to calculate IRR is 25 years. This number has got its reasoning. As it can be checked in the datasheets, the warranty offered by some of the elements is of 25 years. Even though it does not mean that the plant will be only functional for those years, it is the amount of time from when degradation of the components might be a significant issue, therefore the plant production might be reduced in the same way.

- There will be two different aspects that will make the cost and benefit to change from one year to another:
  - First, degradation of the components must be considered to make an accurate estimation. There are some of the elements that provide the estimated degradation (as the solar arrays), but the majority of them do not provide this information. After discussing this question with my supervisor, a degradation of -0.4% has been pointed out as a reasonable and precise estimation. This will directly affect the PV plant's yearly production.
  - Second, inflation is a reality in Australia and makes a significant difference in the results from one year to another. It must be noted that it is quite volatile, having reached levels of 9.05% in 1986 to as little as 0.23% in 1998 (Statista, 2018). In the past 20 years, the curve has an oscillating value with a mean value of around 3% inflation rate per year. It is impossible to make an exact prediction about this topic, but it will be considered a 3% increase of benefits associated to the inflation. This will also influence the OPEX cost, that will be modified because of the inflation for every year.
  - It has been decided to keep the benefits obtained from energy selling to the spot market the same, as the variations of the prices of energy inside the year usually level it to similar values as the previous years (as seen in Figure 26).

All aspects considered, it is now possible to obtain an estimation of the final revenue and IRR of the project. Table 16 shows the final cash flow for the first years, and Table 20 shows the data resumed before, having the whole spreadsheet in the Annexed documents:

Table 20: Cash Flow

CASH FLOW	Yr 0	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5
CAPEX	**-3.429.926**					
Production		5.541	5.519	5.497	5.475	5.453
Ingresos		**323.533**	**331.906**	**340.496**	**349.308**	**358.348**
OPEX		140.000	144.200	148.526	152.982	157.571
Operative CF		**183.533**	**187.706**	**191.970**	**196.326**	**200.777**
	-3.429.926	183.533	187.706	191.970	196.326	200.777

Project's IRR - 25 Years	**4,49%**

PV PLANT	Data	Units
Peak Power (MWdc)	**3,154**	MWdc
Total CAPEX (1,08 $/Wp)	**3.429.926**	$
OPEX Year 1	**140.000**	$
Production Year 1	**5.541**	MWh
Degradation	**-0,40%**	
Income Year 1	**323.533**	$
Inflation	**3,0%**	

Table 21: Data used for Calculating IRR

As it can be seen, the benefits obtained from the energy selling have been influenced by the degradation of the components and for the inflation of the currency. Also, the OPEX has been influenced by this same inflation. The project's IRR for a 25-year period is of 4,49%. As stated above, the main purpose of this IRR calculation is not to decide if this exact project should be carried out, but to compare it with the project with the battery added and study if the battery energy storage system is worth the investment. However, even though it is not the main purpose, it is interesting to analyse the results obtained.

It is normally studied when the initial CAPEX has been completely repaid. In the case of the solar plant studied, the PV Plant is totally repaid on Year 16. Generally, the repayment of a solar plant depends on its size, varying between 10 to 20 years according to (publications.industry.gov.au, 2018). As so, taking into account the obtained IRR, it is between the standards of usual PV Plants built in Australia.

The project economic study is limited by two important facts:

- As no PPA agreement has been proposed, it is impossible to compare between the revenue obtained through this method and the PPA revenue. If a PPA offer had been proposed, both economic reports would have been studied and the optimal one would have been chosen.

- The project does not consider any government subsidy for installing a renewable-energy plant. The Australian's Clean Energy Council offers several incentives to green energy plants. Normally, solar plants like the one studied are eligible for renewable energy certificates under the Australian Government's Renewable Energy Target (RET). The benefit obtained from this subsidy is set by various parameters such as the capacity of the plant and the demand of the spot market. It must be noted that the plant is already economically-viable, but obtaining a subsidy from the government would have increased considerably the final project's IRR.

With this analysis concludes the second stage of the project, when all costs are considered and the final revenue of the plant itself is calculated. Next, battery energy storage systems will be studied, and the different batteries the project could handle will be analysed. Once chosen, the same economic study will be carried out and compared with the one recently studied.

Chapter 4. STUDY AND INCLUSION OF THE BESS

4.1 BATTERY ENERGY STORAGE SYSTEM: DEFINITION, TYPES AND FUNCTIONING

Energy storage systems are developed to store any type of energy for a later use. There is a vast variety of ways of how energy can be stored, such as mechanically (springs), thermally (air conditioning based on ice storage) or electrically (capacitors). However, battery energy storage systems are a combination of electrical and chemical storage, as they use electrochemical cells to store the energy: electrical energy is created by chemical reactions or vice versa. There are various types of electrochemical storage systems, but this project will put the focus into two: Lithium-ion batteries (rechargeable battery) and Vanadium batteries (flow battery).

4.1.1 RECHARGEABLE BATTERY: LITHIUM-ION (LIB)

Lithium batteries were first proposed by M.S. Whittingham in 1976. He explains in his paper that the basis of this new storage system is the reaction between layered titanium disulphide with lithium, obtaining lithium titanium disulphide. This reaction is said to be extremely fast and reversable, which makes it a possible storage system (Whittingham, 1976). However, this reaction could never be built in a big-scale because of the expensiveness of the chemicals used.

From 1977, this basic idea has continued to develop into what these batteries are today. Nowadays, the functioning of this type of battery is as follows: The battery is surrounded by a metal case, which is particularly important due to the pressurisation of the battery; if the temperature of the battery ever presents risky levels, the battery has a sensitive vent-hole which will release some of the extra pressure, avoiding the explosion risk (Brain, 2006).

Inside of the case, it can be found a positive electrode (Lithium cobalt oxide, $LiCoO2$), a negative electrode (carbon) and a separator, which are submerged in an organic solvent that acts as an electrolyte. In the process of charging, the ions of lithium move through the electrolyte from the positive to the negative electrode. During the discharging, these ions move back to the positive electrode (Brain, 2006). Figure 33 shows the charging and discharging cycles of these batteries.

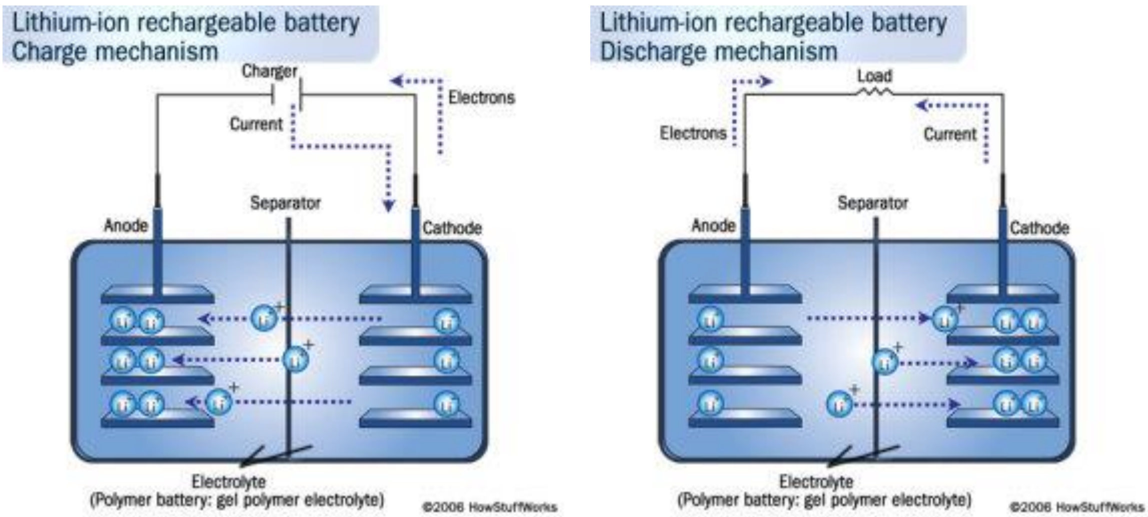

Figure 33: Charging and Discharging of a LIB Battery (Brain, 2006)

Each of these cells produce approximately 3.7 volts, which can be said to be a fairly high voltage for one single reaction. However, as it will be seen posteriorly, there will be a vast number of cells needed to store the energy produced at a PV Plant of such capacity as the project. The main advantages of these batteries are:

- The self-discharge rate of lithium ion batteries is relatively low. The typically stated rate of several manufacturers is of 0.2% per month (Sanyo lionT E, 2016).
- Memory effect does not appear in these batteries. Memory effect is the process occurred when a battery is charged without completely discharging them and the total capacity of the battery is reduced to the remaining capacity. However, if one LIB battery is completely discharged, it will not function again.

- They provide an electrochemical efficiency of around 92%, which is a normal value for commercial batteries.
- It provides quick response time.
- They provide good performance for batteries with short charge/discharge periods (from 30 minutes to 1 hour).

The main disadvantages of Lithium-Ion batteries are:

- They suffer from degradation. The degradation rate varies depending on the type of battery.
- There is a chance of battery explosion, which would result in a fire or arc flash. As stated before, there is a mechanism that releases pressure when temperature gets too high, but if this heating remains in time, it will cause an explosion. This is normally caused by an internal short-circuit, made by the touching of the different electrodes. Toxicity is present in these batteries.
- Significant amount of batteries is needed to give answer to a large project.

Commercial Lithium-Ion batteries come in all shapes, as are used in a huge variety of applications. They can be as little as a phone battery size (seen in Figure 34):

Figure 34: LG's Phone Battery (Amazon.com, 2020)

To as big as the one seen below in Figure 35. The battery shown in this figure is a Tesla LIB installed in the University of Queensland (UQ) in 2019. This battery will be used posteriorly in different reasonings for the battery of the project:

Figure 35: UQ's Tesla LIB (The University of Queensland, 2019)

4.1.2 REDOX FLOW BATTERIES: VANADIUM (VRFB)

The development of redox flow batteries started in Germany in 1954. Scientists patented a procedure for storing energy in liquid, with the main materials used being titanium-chloride (TiCl3) and hydrochloric acid (HCl). It was first designed to provide energy to a future NASA moon base. However, neither the moon base or the battery were designed. In the case of the battery, the additional materials needed were extremely hazardous for the normal development (UPS Battery Centre, 2017).

In 1985, the University of New South Wales (UNSW) in Sidney, Australia, designed the first prototype of a vanadium redox flow battery. Professor Maria Skyllas-Kazacos and coworkers provided a model based on two liquid tanks, that contain the catholyte and the anolyte, that provide the chemicals needed for the reaction, explained below.

These two tanks contain chemical components dissolved in liquids and are separated by a membrane. The process in which energy is exchanged is called Redox, where electrolytes are pumped through a stack of power cells, known as the membrane, and the electrochemical reaction takes place from this flow of electrolytes.

The two tanks stated above behave as a conventional battery, being the cathode and the anode, providing the adequate movement of electrolytes (Linden, 2002). These electrolytes are vanadium based, reason why these batteries take the name. The chemical reaction present in the cathode transforms ions of Vanadium Dioxide (VO2) into VO^{2+}, whether in the anode ions of V^{3+} are converted into ions of V^{2+}. A diagram of these process is shown in Figure 36:

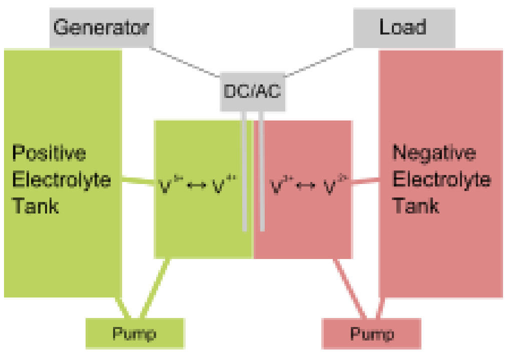

Figure 36: Diagram of a VRFB (Wikipedia, 2020)

As all this process is developed through liquid, increasing the capacity of the battery will be managed through augmenting the quantity of liquid present in the tank. The main advantages of these batteries are:

- Long life cycle. Compared to the LI batteries studied before, the vanadium redox flow battery experience tiny degradation. It is expected to endure over 20.000 charge/discharge cycles, which for the rate of operation is more than 20 years.
- The capacity of the battery is increased by adding more liquid to the tank.

- The operating expenses are small compared to other batteries.
- They are safer than Lithium Ion batteries in terms of flammability.

The main disadvantages of the Vanadium flow batteries are:

- The toxicity of the products used. In the unlikely event of a leak, the environmental damage that could be produced is significant. However, if these products are recycled correctly after their life cycle, it means no harm to the environment.
- The efficiency of these batteries is lower than the Lithium-Ion's.
- They are not practical for small uses such as home devices.
- They are not as efficient as Lithium-ion batteries for short charge/discharge periods as they are normally used for extended periods.

Vanadium redox batteries are usually provided containerised, and according to the characteristics, they are particularly useful for grid services (defined above, meaning providing resources to the grid to maintain a stable frequency). Figure 37 shows a standard VRFB created by Gransolar's subsidiary, E22:

Figure 37: VRF Battery

4.2 BATTERY TYPOLOGY SELECTION

Once both battery types have been studied, a decision about which battery to install in the solar plant should be made. It is now important to define the different functions the battery will provide, and find the one that best fits those needs.

4.2.1 BATTERIES IN PV PLANTS

There is a huge variety of possible uses a battery can offer when installed in a solar plant. It must be noted that these functions are not limited to solar plant, but to any type of renewable energy that allows a storage use (such as eolic energy). However, only the most used ones will be studied, which develop as follows:

1. To provide frequency-response reserve: The frequency-response reserve or operating reserve is the amount of energy generation needed at every moment to meet the assigned demand in case of a misfunctioning or total failure of the generation, which leads to a reduction of the frequency below the allowed limit. Usually, generation plants have an assigned operating reserve which is the capacity of the largest supplier, added a fraction of the peak load (Wang, Wang and Wu, 2005).
   In this case, the battery will offer its amount of energy available in order to provide it as an operating reserve (acting as energy backup). In Australia, this is called Frequency Control Ancillary Services (FCAS), providing answer to the contingencies that may occur in the market. The use of the energy stored in these contingency situations provides an income to the battery in a similar way how the spot market works. Figure 38 shows an example of this methodology given by the UQ's battery: at 16:26, frequency drops to below 49.85 Hz. The battery, which was charging until that moment, starts to discharge in order to stabilise the frequency back to the normal range.

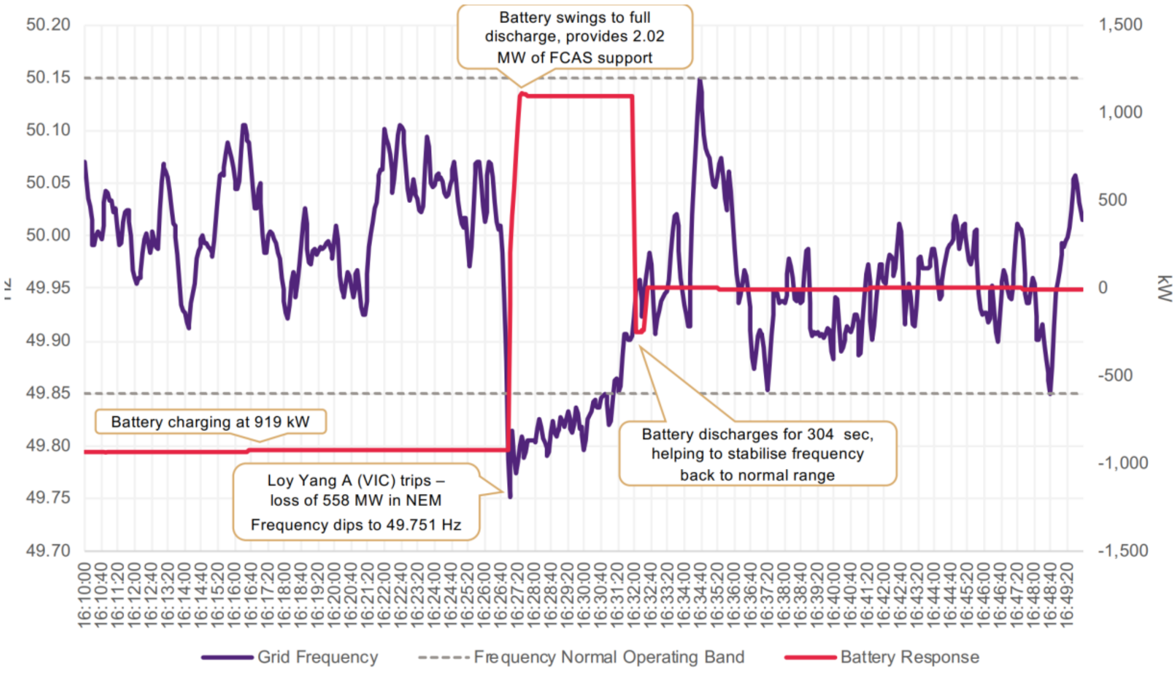

Figure 38: Functioning of a battery acting against contingencies (Wilson, Esterhuysen and Hains, 2020)

2. Used for load levelling: As stated in 1.5 and 3.1.3, the nature of renewable energies makes them a dependant source of energy. In the case of solar plants, clouds or storms could result in a varying energy production throughout the day. Battery storage systems can help solving this issue through load levelling, this means, providing the energy that is not being produced because of the weather, in order to obtain the standard production levels. Using the battery for load levelling helps increasing the renewable penetration, but offers no grid feeding after the sunset. It normally needs about 10 to 25% of the plant's power. Figure 39 shows the functioning of a battery load-levelling, in green:

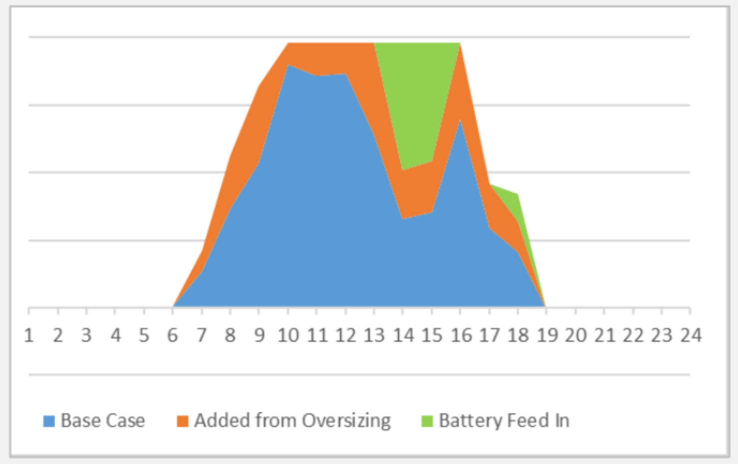

Figure 39: Load Levelling Diagram

3. Used for load shifting: As explained above, solar plants are sun dependant. This means, they can only produce energy when the sun transmits irradiation. However, a battery can be used in order to offer a stable energy output for longer than the daylight. This is called load shifting: storing part of the energy produced in the day to maintain a stable production for longer than the usual 12-hour production. As for the load levelling, this function helps to increase the renewable energy penetration and extend the hour production. It normally takes up to 25-40% of the plant's total power, providing energy response for 4 to 6 hours. Figure 40 shows the normal functioning of a solar plant with a battery functioning as load shifting:

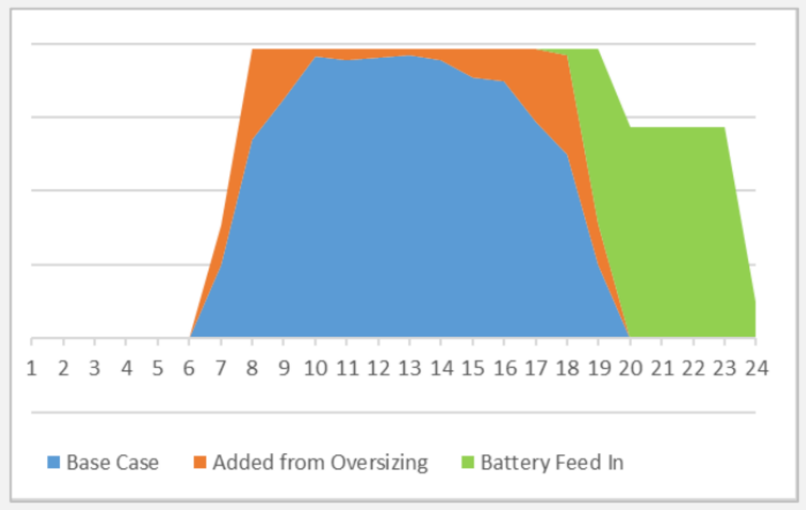

Figure 40: Load Shifting Diagram

4. Used as a peak-hours battery (Arbitrage): The use of a BESS as peak-hour battery takes advantage of the price-demand curve of the country studied. The main purpose of the battery is to store the energy produced when the energy is cheap (as will be studied posteriorly, the central hours of the day) and sell that energy when it is more expensive (normally after dawn). This results in a daily actuation of the battery and ensures certain profitability, but a study of the price and demand curve is required, as well as an algorithm that defines the functioning of the battery. Figure 41 shows the plant production when a peak-hours battery is used. It compares the production of the plant itself without battery (same as studied above) and with battery (keeping some of the energy produced to charge the battery and selling it afterwards).

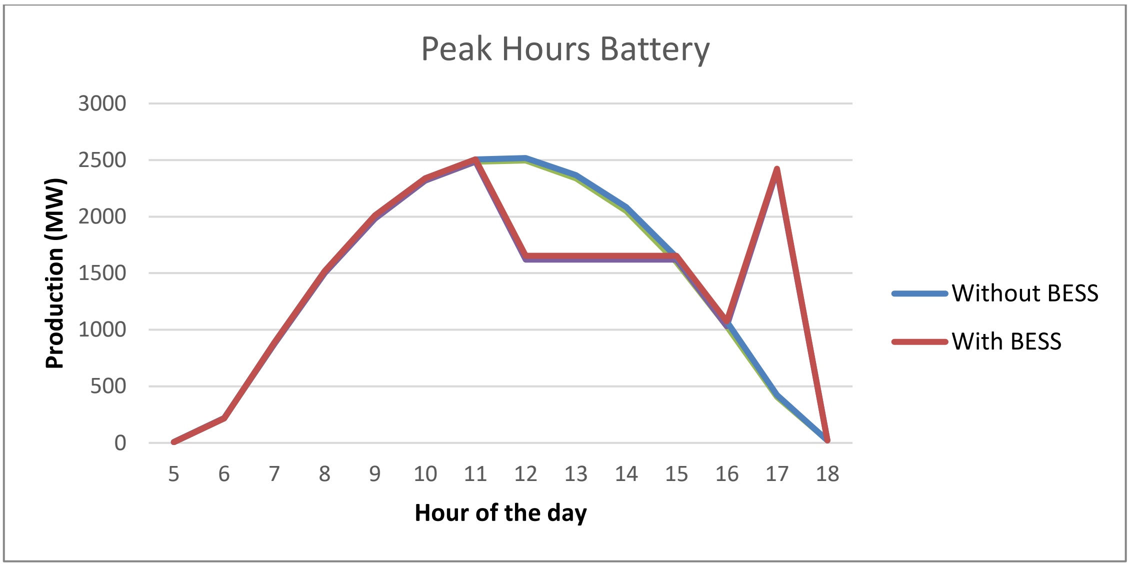

Figure 41: Peak-Hours battery

Once having studied the most-used battery applications when using it in a solar plant, the most cost-effective one will be chosen. It must be noted that, when it comes to battery functioning, there also exists PPA's which ensure a constant input given by the use of the BESS. However, as in the solar plant, no PPA will be proposed for the battery. Consequently, it has been pointed out by the supervisor that, in the long term and without the signature of a PPA, the most profitable mode for the battery to work on is as a peak-hours battery. Nonetheless, it will be seen below that the properties of the battery acting as a peak-hours battery allow to take part into the contingency market.

4.2.2 PROPERTIES OF THE BATTERY AND SELECTION

There are several aspects to consider when a battery is working as a peak-hour battery:

- The most important property is the response time. As the periods when energy is cheapest or more expensive can last for only half an hour, it is important for the battery to start pumping or receiving energy just when it has been indicated. If not, the price might not be most suitable and will result in a loss of money for the project. Consequently, a battery with efficient response time is needed.

- The optimal battery has to be efficient for short charge/discharge periods. A peak-hours battery will only operate for small periods of time; hence it needs to have reliable performance for those cycles.
- Efficiency should be high enough to provide the maximum amount of energy possible for each operating period.
- The operating and management cost should be the lowest possible to ensure the profitability of the solar plant in the long term.
- As it will be seen in 4.4.2.1, the battery should be able to store energy for 8 hours.
- The safest battery should be chosen.

Comparing the two batteries studied in 4.1, it can be checked that:

- Both batteries produce an efficient response time
- Efficiency of the Li-ion battery is considerably greater than Vanadium's.
- The nature of the flow batteries results in a small O&M cost, contrarily to the Lithium ones, that will require fixing and a replacement in the long term.
- For the purpose given by the battery (peak-hours), Li-ion batteries function better than Vanadium's in terms of small charging cycles.
- The cost of a vanadium-based battery is higher than a lithium-based battery.

All aspects considered, it has been proved that for the function needed for the battery, the Lithium-ion rechargeable battery will result in a higher profitability. <u>Consequently, the battery energy storage system will be a Lithium-ion rechargeable battery</u>.

Once the type of the battery has been chosen, as well as its functioning mode, the programmed algorithm for the battery will be studied.

4.3 FUNCTIONING OF THE BATTERY

As it has been studied above, the battery will store part of the energy produced by the solar plant and sell it afterwards, when energy is more expensive. However, it must be noted by the reader that the cost of the energy varies due to several factors, and results in different prices for each day. Accordingly, a study of the price-demand curve for the spot market in Queensland will be carried out, to correctly check the periods when the battery should charge or discharge.

4.3.1 TECHNICAL SPECIFICATIONS AND NOMENCLATURE

The nature of the battery used in the solar plant has already been chosen. However, an energy storage system is completely defined when capacity and power parameters are selected.

The capacity of the battery limits the total amount of energy the battery can store. It is usually measured in Wh, but for smaller devices where voltage is fixed, it is measured in Ah (Amperes per hour). The power defines the maximum power that can be fed into the grid by the battery. It is measured in W, nonetheless kW and MW will be used as well for plants of bigger size. Same occurs with capacity: kWh and MWh are usual units of measure for bigger plants. The understanding of these parameters is key to correctly understand the functioning of a battery. The following example explains this topic:

Let's suppose a battery of 2 MWh of capacity and 1 MW of power. As defined, the power of the battery specifies the maximum amount of power that can be fed into the grid. The amount of time that this power can be pumped into the grid is given by the capacity. As

$$E = P \cdot t \rightarrow t = \frac{E}{P} = \frac{2MWh}{1MW} = 2\ h.$$

Equation 2

Consequently, a 1MW of power and 2MWh of capacity can feed 1 MW to the grid during 2 hours. However, it can occur the case where providing the maximum power is not needed.

Using the same equation, if 0.5MW of power is required, then it can provide this energy for 4 hours. If the results obtained are plotted:

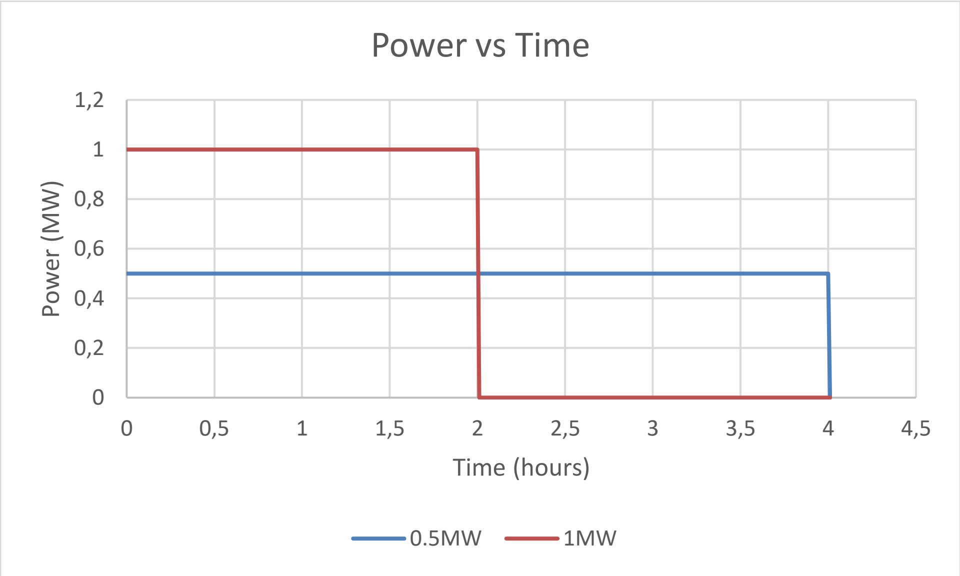

Figure 42: Power vs Time of the two batteries

Then it can be inferred that the capacity of the battery is the area formed by plotting the power provided and the time it can be supplied, with the power limit given by the power of the battery.

This results in the usual battery designation: when describing a battery, the power comes first and the capacity comes second, separated by a forward slash. As so, the previously studied battery is a 2MW/1MWh battery.

4.3.2 STUDY OF THE PRICE-DEMAND CURVE IN QUEENSLAND: CHARGING AND DISCHARGING TIMES

The scope of the battery determines that the battery is only connected to the solar plant. This means that it can only store energy that has been produced in the solar plant studied above. However, this is not the only way a battery could be designed: The University of Queensland's 1.1MW/2.2MWh is only connected to the grid, which means that the energy that is stored is directly bought from the spot market, and sold again to this same market when the energy prices are expensive.

Coming back to the studied solar plant, if the energy that can be stored is only to be obtained from this plant, then the charge and discharge periods should be studied to obtain the best profit from the battery. To accomplish that study, then Queensland's spot market must be analysed.

The procedure used to carry out this analysis has been to study the available data of the market from the past years, comparing it with some papers provided about this same topic. As noted above, the prices of the energy in Queensland's spot market can be obtained through AEMO website. Once all information has been processed, then an algorithm will be proposed, and its development will be detailed.

First, checking if the shape of the curve varies significantly from one weather station to another will denote if the battery requires different functioning depending on the station. It is reminded that the weather stations in Australia comprehend the following months: Spring goes from September to November, summer from December to February, autumn from March to May and winter from June to August. The following graphs show the different mean electricity prices for each hour of the day, for each station in the past year:

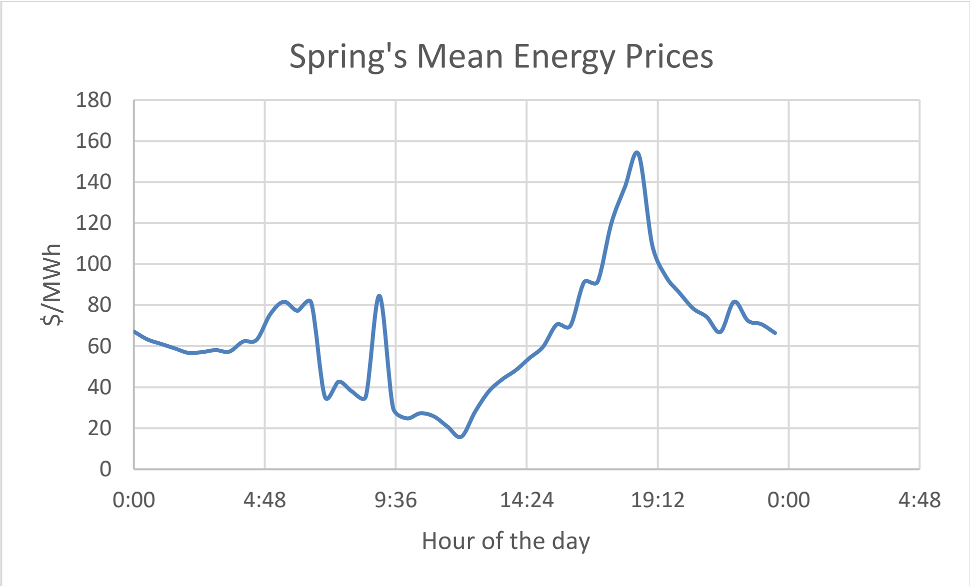

Figure 43: Spring's Mean Energy Prices

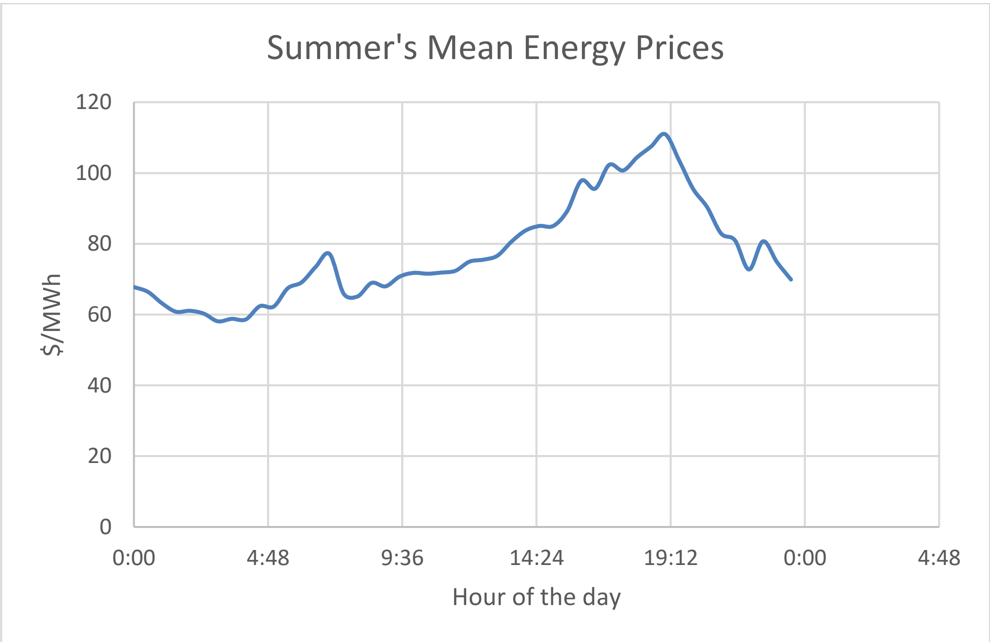

Figure 44: Summer's Mean Energy Prices

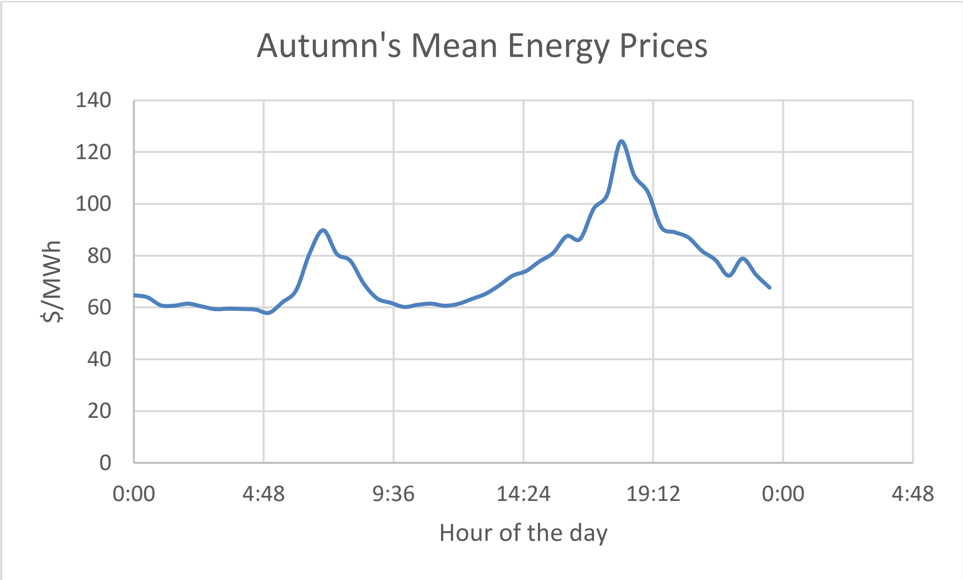

Figure 45: Autumn's Mean Enegy Prices

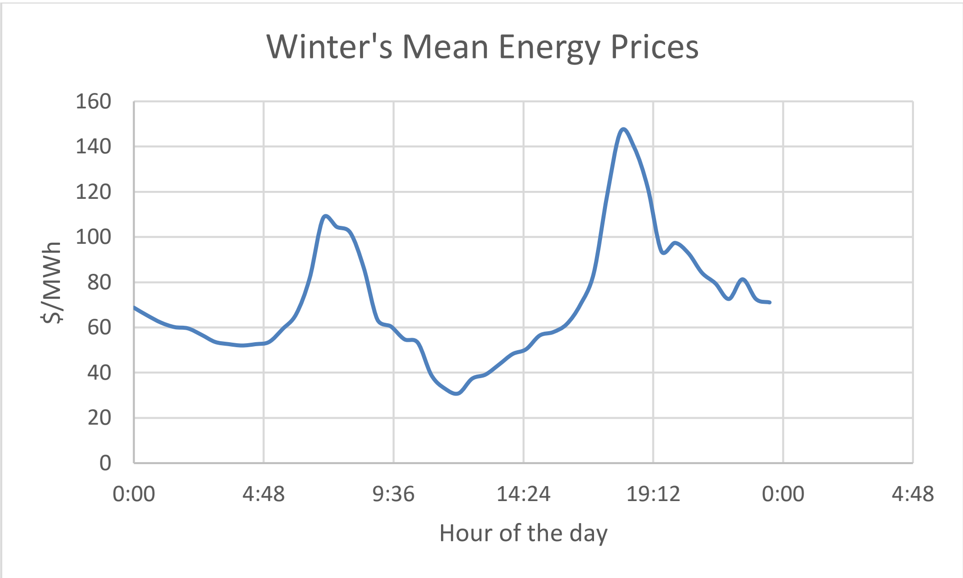

Figure 46: Winter's Mean Energy Prices

In order to compare these curves, a graph showing all different curves with the same scale can be seen below:

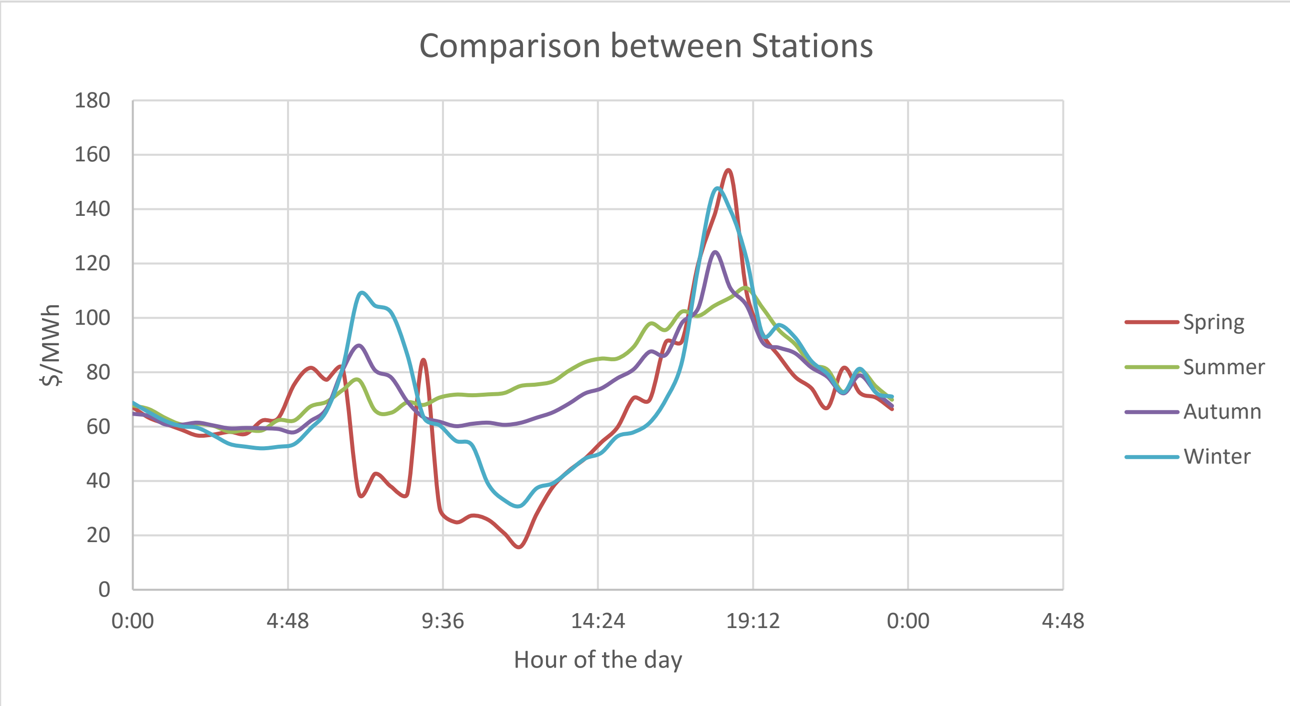

Figure 47: Comparison between Stations

There are different conclusions that can be drawn by observing this graph:

- There exists a peak of electricity price from around 17:00 to 20:00. This agrees with the behaviour predicted in 1.2, and is caused by two different events. First, this period of time is when solar production starts to drop, but most importantly, it is the time when it gets dark. As there is a majority of people awake, electricity demand grows, and so does the energy price. As it can be seen, price rates at this peak oscillate between 120 to 155 $/MWh.
- There exists another, more unstable peak at dawn. As it has been explained in 3.1.3.1 that the usual dawn time in Australia is 5 a.m. Consequently, electricity demand grows as people start to wake up, and so does the energy rate. This peak can be considered to be lower than the evening peak, with prices going from around 60 to 110 $/MWh. It can be seen another peak in spring with same prices as dawn's one.

However, this can be considered to be an oscillation from the first one as it is in the same time range.

- The price rate between peaks, which are called valley or off-peak rates, appear between the end of the first peak (around 9 a.m.) and the beginning of the second one (around 17 p.m.). Prices are not high at this time as production is at its higher rates and energy consumption is not as large as found in the morning or evening. Logically, the prices are considerably lower than in the peak hours.
- It can be observed that summer's price curve is significantly different than the rest. The curve presents a smoother behaviour, as the morning and evening peaks are not as pronounced as in the other stations. This is a direct consequence of the renewable energy penetration, and more concretely, solar energy production: dawn is earlier and dusk is later than in the other stations, and the good weather given in summer allows solar plants to present a high energy production even in these periods of time. As so, solar production can handle part of this demand and the energy rate will not be as high as in the other stations. The energy rate peaks will still exist, but they will not be as noticeable.

All in all, even with the behaviour given in summer, it can be concluded that energy rates throughout the year will experience two different peaks: one in the early morning and one in the evening, presenting off-peak rates between these two peaks and at night. As a result, the mean energy rate curve of the whole year provides a representative shape of how the prices will evolve through the day. This graph can be observed in Figure 48:

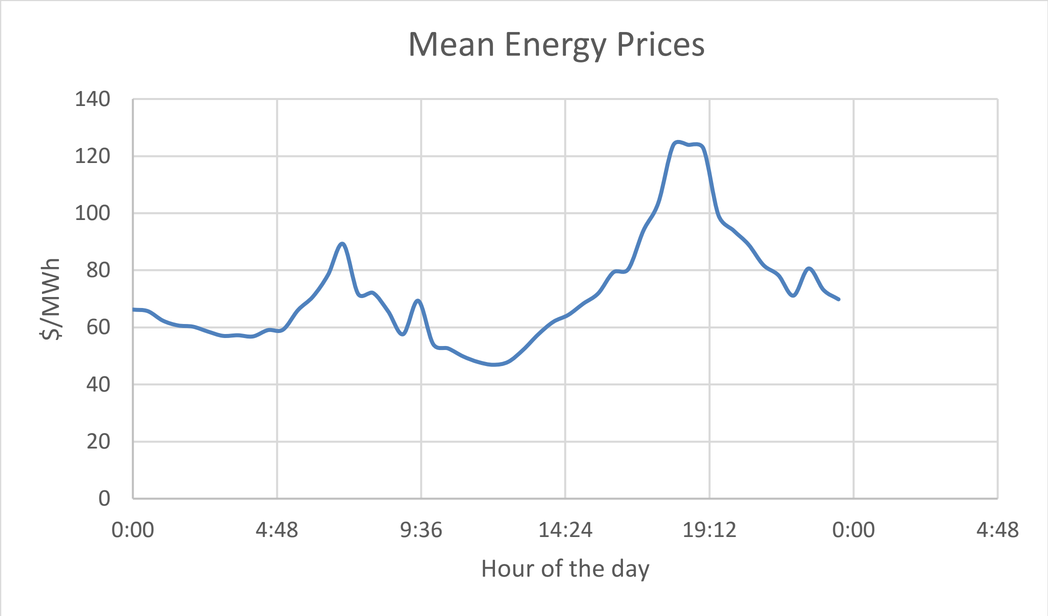

Figure 48: Mean Energy Prices throughout the Year

It must be reminded that, according to Figure 31, the shape of the curve for the year 2019 is representative. Figure 49 shows the mean data for 2018 and 2019 in order to check this affirmation:

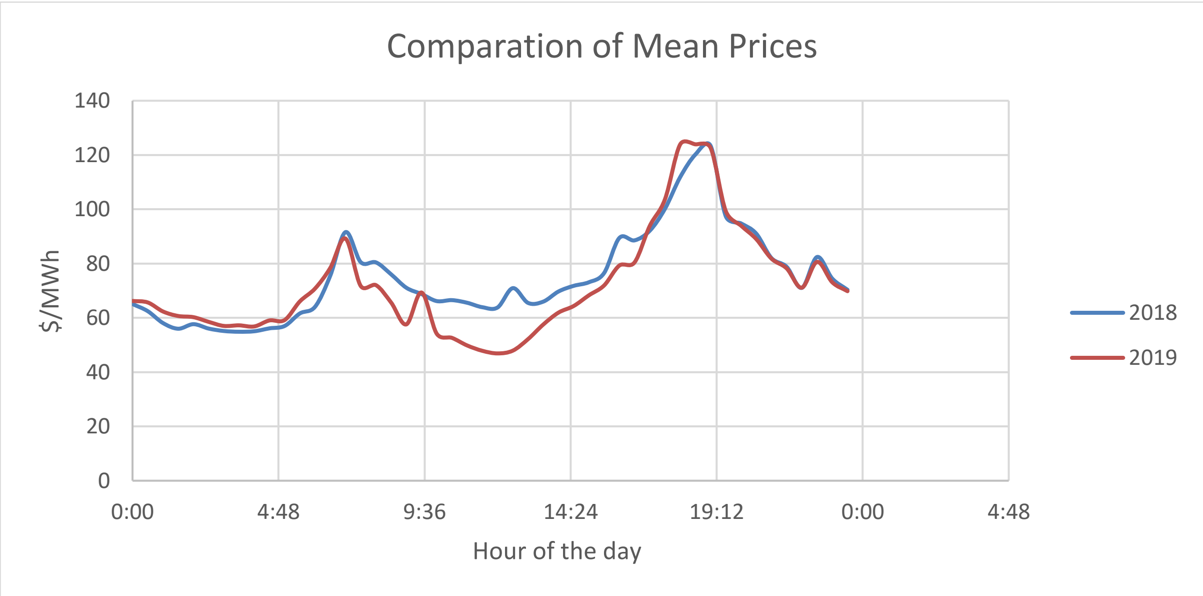

Figure 49: Comparation of mean prices 2018 vs. 2019

It can be inferred that the shape of both curves is precisely similar. It will be studied below that for the study of battery, the importance resides more on the shape that on the overall prices of the curve. Once the study of the energy rates has been accomplished, it is now interesting to compare it with the solar plant's energy production, in order to draw conclusions about the functioning of the battery.

Joining Figure 48 with the mean energy production throughout the year of the solar plant studied, results in Figure 50:

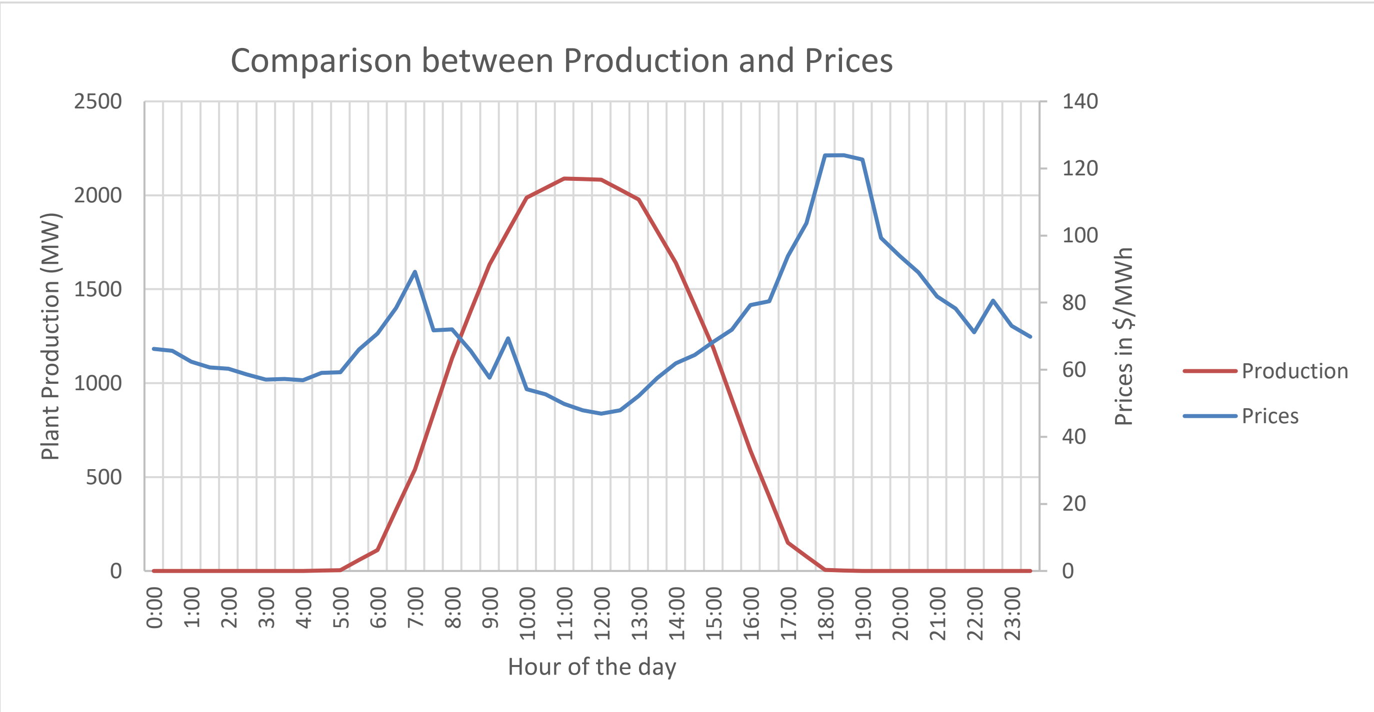

Figure 50: Comparison between Production and Prices

This graph is particularly descriptive due to one fact: the period of time when the plant produces most of the energy coincides with the off-peak rates. The main question now is how to extrapolate this fact to the functioning of the battery.

As explained several times above, the objective of the battery is to store energy from the solar plant and sell it when the rates are more expensive. Figure 51 illustrates this idea:

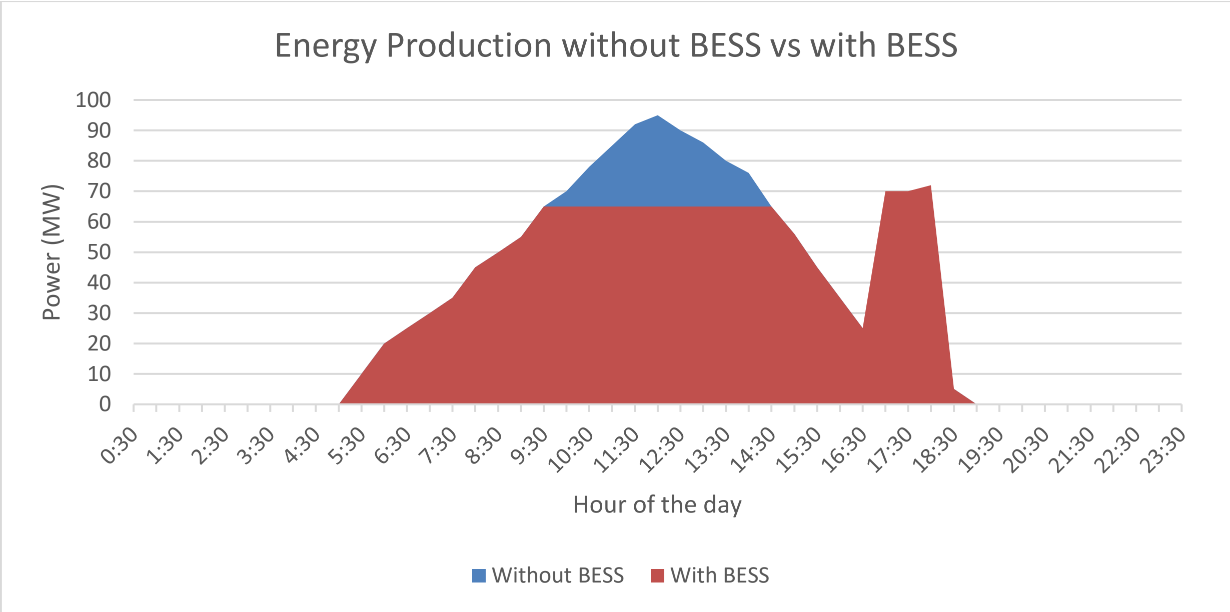

Figure 51: Production with BESS vs without BESS

The blue area shows the energy sold to the spot market without an energy storage system. The difference with the red area is given by the charging and discharging of the battery: when prices are low and the plant is producing, part of the energy produced by the plant is stored in the battery. When prices are more expensive (evening hours), the energy stored is sold into the spot market. This profit could not have been made with the solar plant alone as there would be small energy production at that time of the day.

Consequently, when programming the battery, it would be reasonable enough to infer that the battery should be charged in the production hours of the solar plant and to be discharged when prices are highest. Nonetheless, as seen in Figures 48 and 49, there is a significant peak in the morning. It would be optimal to charge the battery before this peak to obtain another charge/discharge cycle, but as observed in Figure 50, the peak occurs before the energy production becomes significant.

The optimal functioning method has been developed from an idea shown in (Simshauser, 2020). The paper studies if there is a relation between the penetration of renewable energies and the evolution of the curve.

Figure 52 shows the evolution of the spot price in Queensland for August, 2019 and the standard PV energy output:

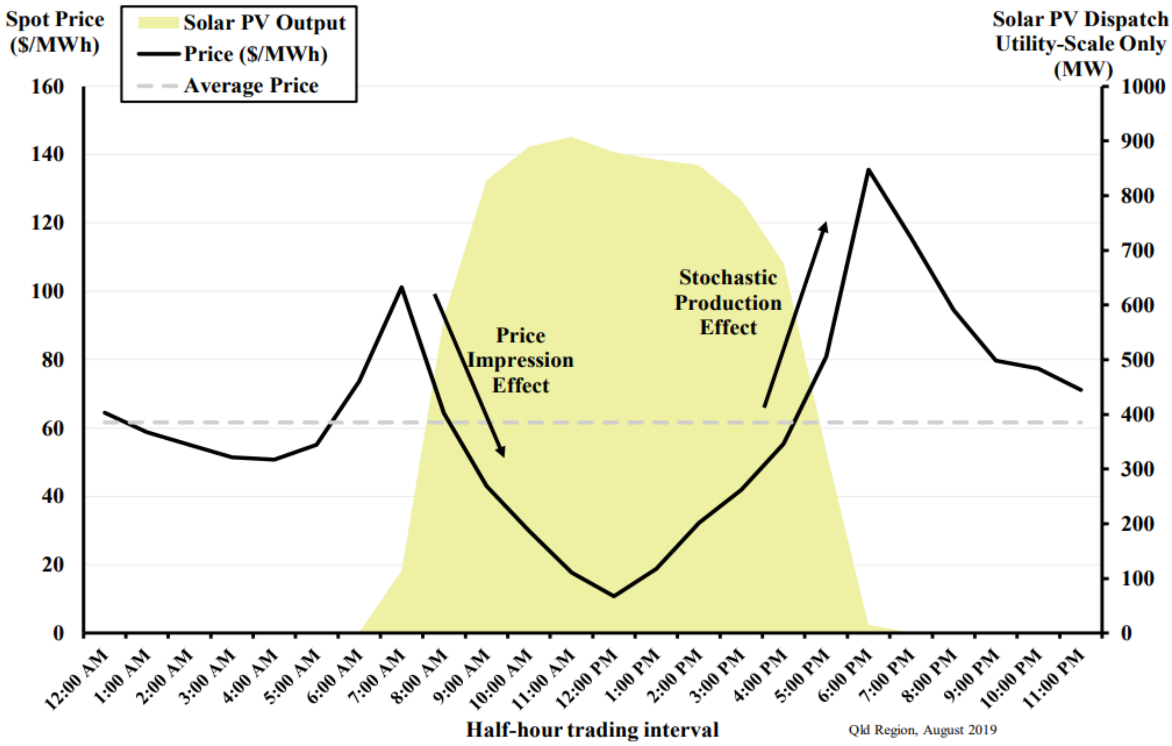

Figure 52: Energy Output vs Price Evolution for Queensland, August 2019 (Simshauser, 2020)

As it can be seen, it mirrors the one obtained in Figure 50. The results obtained explain that the higher the penetration of renewable energies, the further away are the morning and evening peaks from the production hours. This benefits highly the use of a storage system as prices will eventually lower during production hours and will get higher further away from this period of time.

Consequently, the following battery algorithm has been proposed: based on this conclusion, the battery will always charge during the production hours of the solar plant when prices are lower, and will always discharge after the production cycle and just before the following production cycle begins. Making the battery to function this way will take advantage of the evening peak and the morning peak (it is reminded that both peaks are observed away from the production cycle). Figure 53 illustrates this idea:

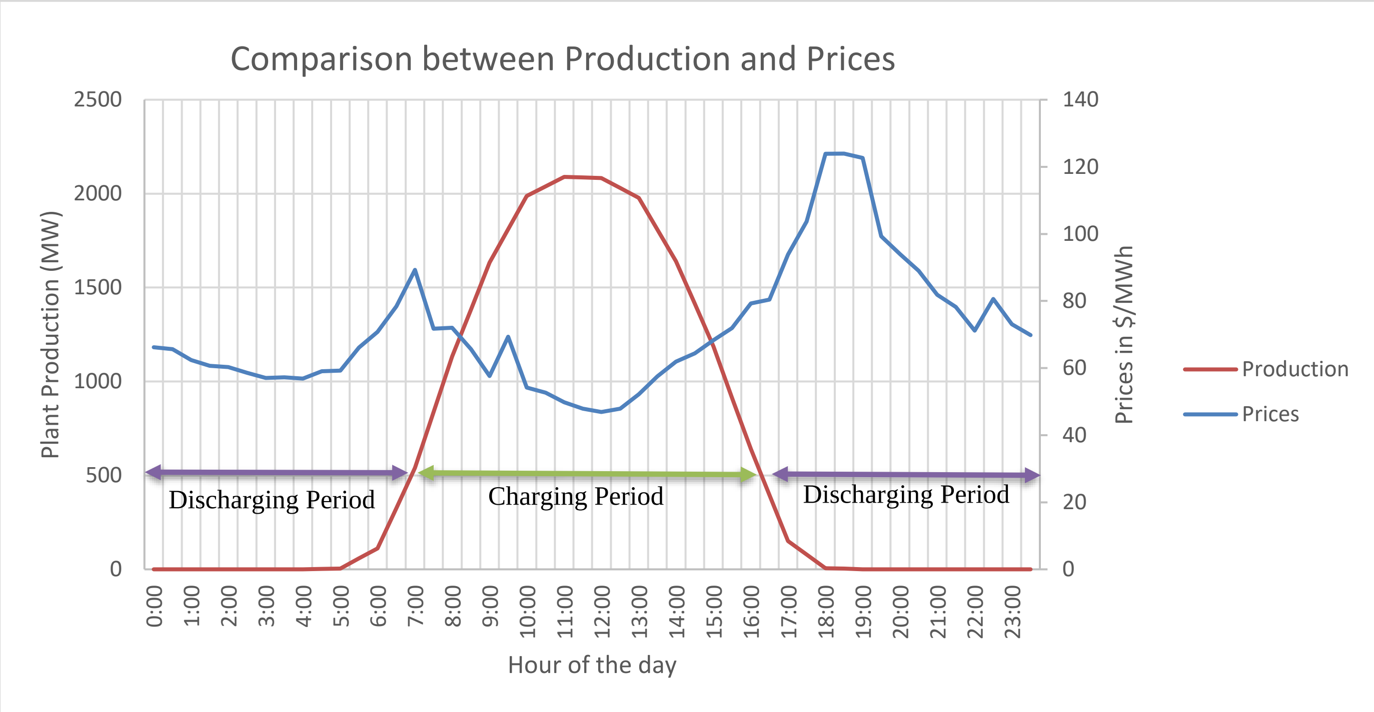

Figure 53: Charging and Discharging periods

It is remarkable that commercial batteries available for this use, developed by subsidiary E22, are provided with an algorithm, based on machine learning techniques, making them able to obtain the different maximum and minimum prices that will occur throughout the day, and the optimal charge and discharge technique. This algorithm is considerably expensive and has not been provided for the development of the project. This limitation will be explained in the section Limitations and Future Studies. Consequently, the way to study the profit provided by the battery will be as follows: The algorithm will find the maximum value out of the charging period and will charge the battery (independently of the amount of power being produced at the moment). Posteriorly, it will find the maximum value out of the discharging period and sell all the energy stored previously. The data used to obtain this approximation will be the spot market prices from Queensland in 2019.

It must be noted that the charging and discharging period are subject to change according to the characteristics of the batteries offered. Given that the production study has been carried out in 30-minute periods, then if the battery allows one-hour storage, the algorithm will find the second minimum and the second maximum to charge and discharge the battery, respectively.

Figure 53 describes the evolution of charging and discharging cycles. However, the exact hour of transition between charging and discharging has not been indicated. This is another part of the algorithm, where the optimal period transition can be obtained for every battery in order to set it to the most profitable period.

Once the functioning of the battery has been solved, the most adequate one in terms of capacity and power will be studied. The selection of the optimal battery will mainly depend on the energy production of the solar plant and the evolution of the spot prices. However, with the available resources, it is not possible to obtain the optimal capacity and power of the battery. Even if it was, energy storage systems are not made to measure. The complexity of batteries makes extremely expensive to create one tailor-made. As so, different batteries will be proposed by E22, detailing their capacity, power, CAPEX and OPEX. With this information, the algorithm explained above will be tested with the different batteries in order to obtain the total revenue of the plant plus the storage system, which will then be fitted into the cash flow to obtain the IRR of the whole project. Once this process has been completed with the different batteries, then the optimal battery will be the one that presents a higher IRR. This study will be made in the following section.

4.4 ECONOMIC STUDY

4.4.1 OTHER REVENUE SOURCES

4.4.1.1 Frequency Control Ancillary Services (FCAS)

As explained in 4.2.1, the battery could be programmed to act against contingencies that could occur in the energy generation, levelling the frequency to normal limits when needed. There are different contingencies markets, in which a battery will take part according to the capability to face these events. The bigger the capacity of the battery, the longer it can face contingencies. It must be noted that the profit given by the participation on the contingency market is a function of the volume of capacity bid into the FCAS markets, the way this volume is bid across each of the three contingency raise markets, the prevailing market prices, and the agreement with the company that operates the battery, if there is one (Wilson, Esterhuysen and Hains, 2020).

However, the unpredictability of the events that lead to an actuation facing contingencies makes it impossible to obtain with certainty the revenue associated with the participation on this market. According to the location and type of the battery installed in the University of Queensland, it can be considered a reliable reference to make an approximation of the revenue obtained from contingency's response. This approximation will be made below.

4.4.1.2 Virtual Cap Contract

A virtual cap contract is a form of insurance against the volatility of the wholesale market prices. There is a possibility where, usually during the evening price peaks, the cost of energy becomes significantly expensive. The utility of a virtual cap contract is to limit the price which energy can reach. This is made by offering all the energy stored in the battery to reduce this price. As a consequence, the battery stops being part of the arbitrage for this interval, and the revenue is given by the buyer of the cap contract. For example, if the wholesale price of an interval was 1500 $/MWh, and the cap price was 300 $/MWh (which is the usual threshold), the energy producer would obtain the difference between the spot price (1500) and the cap price (300) times the energy that can be offered to lower that price.

As in the response to contingencies, the revenue obtained by the virtual cap contract is impossible to predict with the available resources, and an approximation will be made to predict these benefits. Virtual cap contracts are normally signed depending on each project and are not standardised.

4.4.1.3 Study of UQ battery's revenue

Figure 54 shows the breakdown of results given by the University of Queensland's 1.1MW/2.15MWh battery in the first quarter of 2020. All three income sources explained (arbitrage, FCAS and cap contract) can be observed in the figure:

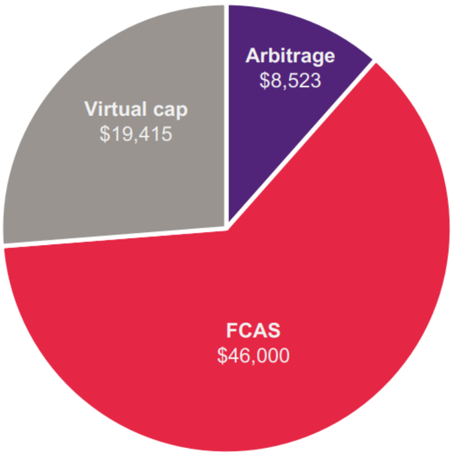

Figure 54: UQ's battery financial results (Wilson, Esterhuysen and Hains, 2020)

The results show that what was considered to be the main income source (arbitrage) suppose only a 12% of the total revenue obtained from the battery. The income breakdown results in a 12% benefit from arbitrage, a 26% benefit from the cap contract and a 62% benefit from the response to contingencies.

Although the similarity between this battery and the one studied is significant (they are located in the same state, have a similar programmed functioning and both are Lithium-Ion based), the income given by this battery cannot be completely extrapolated to the one studied as:

- The battery used for the project may not have the same capacity and power. If the most profitable battery for the studied project is smaller, then the profit from contingencies and cap contracts would be reduced. In the case of contingencies, the capacity reduction will permit the battery to participate in less contingency markets than UQ's battery. In the case of the cap contract, as the profit is obtained by the difference of prices times the available energy, it results in a proportional diminution of income.
- Both FCAS and cap contract are subject to contract's conditions. The resources available do not permit a simulation of any of these contracts, hence the actual conditions achieved for the solar plant studied might be worse than the ones offered in the project.

All aspects considered; it is reasonable enough to deduct that the income obtained from the whole battery will be greater than the one obtained only from the arbitrage study. As so, the economic study of the optimal battery will be carried out according to the arbitrage revenue, and once the BESS has been chosen, then an estimated benefit obtained from these sources will be simulated and added to the cash flow.

4.4.2 SELECTION OF THE OPTIMAL BATTERY

After contacting Gransolar's subsidiary E22, the following Lithium-Ion storage systems have been proposed for this project. The CAPEX price is noted in the right-hand side of the table:

Storage (MWh)	*Nameplate (MW)*	*CAPEX AUD/KWh*	*CAPEX FINAL AUD*
0,25	0,5	700	175000
0,5	0,5	650	325000
0,5	1	680	340000
1	1	630	630000
1	2	650	650000
2	2	600	1200000

Table 22: Proposed Batteries

This price includes the cost of the battery and the installation. It must be noted that the installation of the battery is fairly simple, as it is directly connected to the inverter. Consequently, no added information will be provided for the battery installation.

The evolution of prices of the battery is logical: the higher the power or capacity, the more expensive the battery is. As stated before, it is not possible to deduct which will be the optimal battery until all batteries are studied through the algorithm. It has been pointed out that these batteries can accomplish 1-hour cycles. This means that for both charge and discharge the battery can work for up to one hour continuously or intermittently. Consequently, as explained in 4.3.2, the two-day minimums and the two-day maximums will be used to calculate the revenue obtained from the battery for one day. It is reminded that the algorithm will also calculate the optimal charging and discharging period, according to the revenue obtained.

The standard OPEX required to operate a battery has been indicated to be 2% of the total CAPEX of each battery. This will be added to the cash flow.

4.4.2.1 Functioning of the algorithm

Table 20 shows an example of the functioning of the developed algorithm for one random day. It can be found in the following page, which has been changed to a horizontal disposition for clarity's sake.

	Storage (MWh)	Nameplate (MW)	Max. Storage 1/2h (MWh)
Battery	0,25	0,5	0,25

	Time
Beginning Solar Product	6:00
End Solar Production	12:00

Hour	Sun production Hours	RRP QLD 2019 $/MWh	Revenue (1/2 h) $	Charge Time T/F	Discharge Time T/F	Battery State MWh	Loses $	Benefits $
6:00	TRUE	58,02	5,52289479	TRUE	FALSE	0,0951895	-5,52289479	0
6:30	TRUE	63,63	25,75786941	TRUE	FALSE	0,25	-9,850592115	0
7:00	TRUE	76,13	30,81795691	FALSE	FALSE	0,25	0	0
7:30	TRUE	74,57	53,43939738	FALSE	FALSE	0,25	0	0
8:00	TRUE	81,43	58,35550662	FALSE	FALSE	0,25	0	0
8:30	TRUE	82,95	80,12277368	FALSE	FALSE	0,25	0	0
9:00	TRUE	84,26	81,38812429	FALSE	FALSE	0,25	0	0
9:30	TRUE	87,51	98,26458521	FALSE	FALSE	0,25	0	0
10:00	TRUE	89,06	100,0050732	FALSE	FALSE	0,25	0	0
10:30	TRUE	82,56	100,4324237	FALSE	FALSE	0,25	0	0
11:00	TRUE	83,99	102,1719872	FALSE	FALSE	0,25	0	0
11:30	TRUE	84,44	104,0559609	FALSE	FALSE	0,25	0	0
12:00	TRUE	91,27	112,4726143	FALSE	FALSE	0,25	0	0
12:30	FALSE	97,28	114,0856064	FALSE	FALSE	0,25	0	0
13:00	FALSE	123,52	144,8586976	FALSE	TRUE	0	0	30,88
13:30	FALSE	121,26	123,7807529	FALSE	TRUE	0	0	0
14:00	FALSE	106,01	108,2137359	FALSE	FALSE	0	0	0

Table 23: Example of the developed algorithm

The explanation of each section can be found below:

- Battery section (top left corner): The characteristics of the battery studied (capacity and power) are specified to the algorithm. The column 'Max. Storage 1/2h' specifies the maximum storage that can be reached at full power charge or discharge for half an hour. This limits the amount of energy that can be transferred to or from the battery in a half-an-hour period.
- Solar production section (top right corner): The period when the battery is allowed to charge is specified. Consequently, the discharging periods are the ones before and after these limit hours (refer to Figure 50).
- Battery charging and discharging section (main table): The battery state is calculated every 30 minutes according to the following factors:
  - Sun production hours: States the period where the battery is allowed to charge (true when in the solar production section period).
  - Revenue (1/2h): Calculates the revenue of the PV Plant itself (refer to 3.2.2).
  - Charge Time: Calculates the two minimum values out of the sun production hours.
  - Discharge Time: Calculates the two maximum values out of the not-production hours (in this case, from 12:00 to 6:00 of the following day).
  - Battery State (MWh): Indicates the amount of energy present in the battery. It is directly charged from the energy production of the solar plant and has the limit of the maximum energy charged in 30 minutes indicated in the battery section. It can be charged until the maximum capacity.
  - Loses ($): Indicates the amount of money lost by charging the battery and not selling the energy used to charge it to the spot market. In the case that the plan produces sufficient energy to charge the battery completely, then the benefit of the excess (sold to the spot market) is considered.
  - Benefits ($): Indicates the amount of money earned by selling the energy to the spot market in the not-production period.

To check the correct functioning of the developed algorithm, the most descriptive information it provides will be plotted in different graphs.

Using the example above (0.5MW/0.25MWh, charging hours from 06:00 to 12:00), the graph showing the mean energy stored in the battery during the simulated year can be seen in Figure 55:

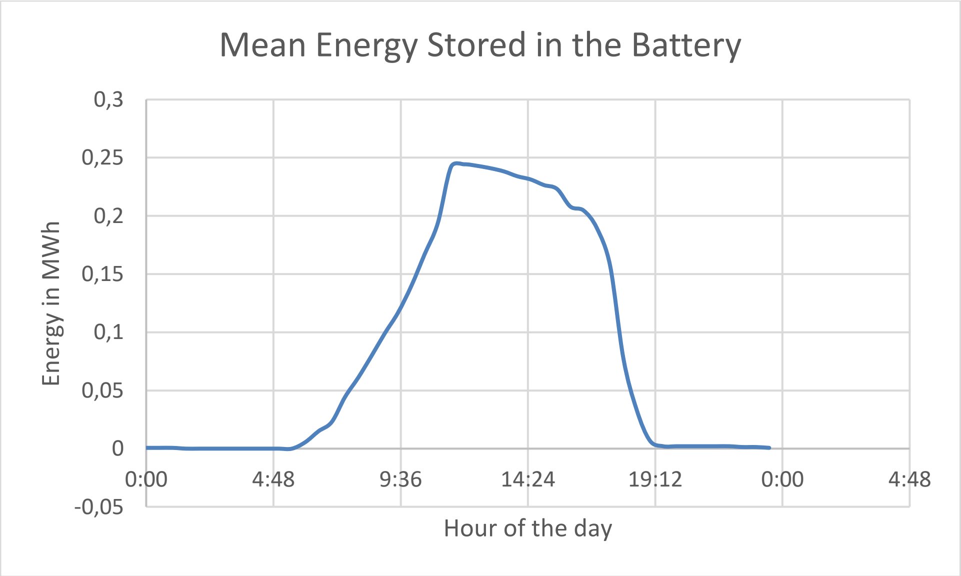

Figure 55: Mean energy stored in the battery

Given that the charging period is from 6:00 to 12:00, and that the evening peak is usually greater than the morning peak, the battery will charge between those hours and almost always discharge between 18:00 and 20:00, hours when the peak is produced. The loses and the benefits can also be studied for each hour, resulting in Figure 56:

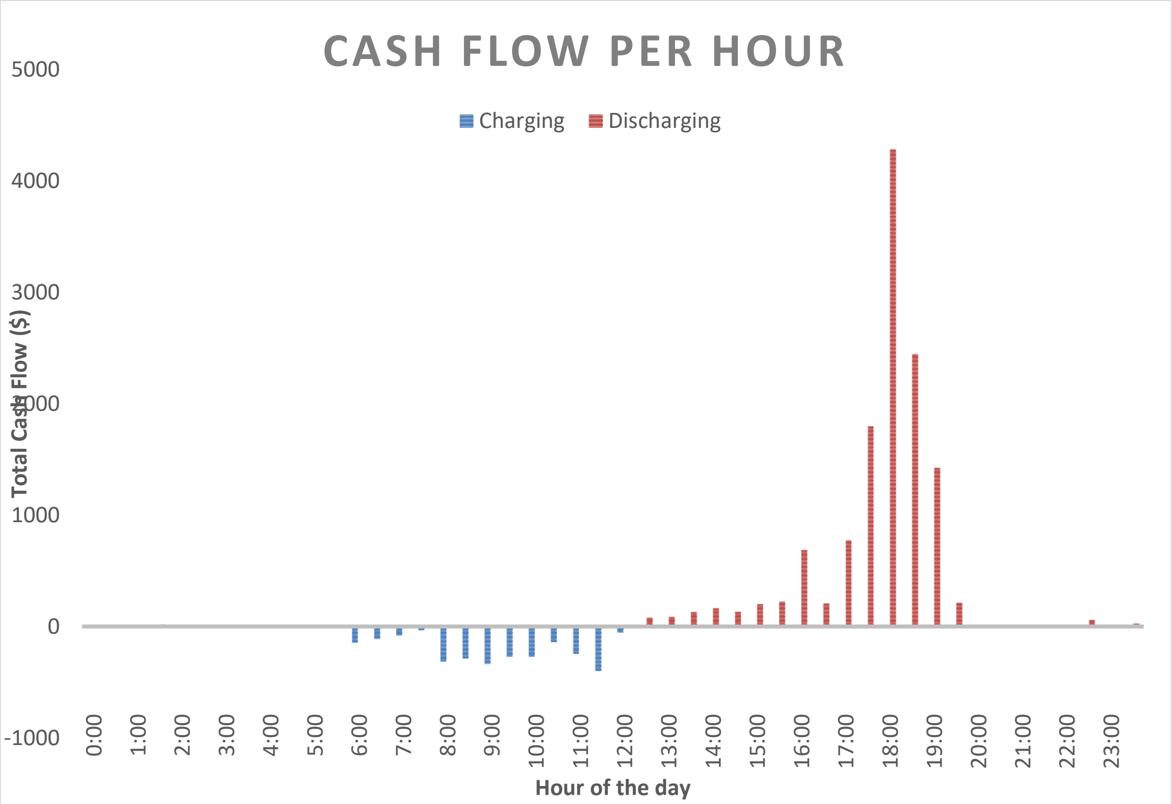

Figure 56: Cash flow per hour

For the example shown, the loses associated to charging are almost uniform for all the charging period, usually starting at 8:00. However, it can be seen that the benefits provided by discharging are concentrated between 16:00 and 19:30, being 18:00 the most profitable hour with more than 4000 $ revenue.

Both graphs show the correct functioning of the algorithm as they confirm the hypothesis made in its development. This study could be made for every battery proposed; however, it will only be completed for the final chosen battery.

In order to obtain the most profitable battery, all different proposed batteries have been tested through the developed algorithm. Once all periods have been analysed, then the benefits given by the PV plant itself are compared with the ones given by the PV Plant and the BESS, obtaining the percentage increase. A data table has been created to find the most profitable charging and discharging periods, obtaining the following results:

The most profitable charging cycle is from **7:30 to 14:00** for all different batteries.

Storage (MWh)	Nameplate (MW)	PV Plant Revenue ($)	PV Plant+BESS Revenue ($)	Increase
0,25	0,5	323.533,04	347.557,58	7,43%
0,5	0,5	323.533,04	344.013,26	6,33%
0,5	1	323.533,04	344.783,36	6,57%
1	1	323.533,04	363.594,37	12,38%
1	2	323.533,04	365.101,29	12,85%
2	2	323.533,04	395.251,40	22,17%

Table 24: BESS Benefit Increase

As the costs associated with each battery are different, it would be incorrect to affirm that the battery with the highest increase is the most profitable one. The only way to confirm the suitability of the battery is to consider both CAPEX and OPEX into the cash flow. The total CAPEX of PV Plant and BESS is the CAPEX calculated in chapter 3.3 plus the total cost of the battery. The total OPEX of the project is the OPEX calculated in chapter 3.4 plus the OPEX associated with the maintenance of the battery. A full breakdown of both will be developed when the battery is chosen.

Having defined how the most suitable battery will be chosen, the cash flow study is completed, using the same procedure as in 3.5. The results obtained are as follows:

	0,5MW/0,25MWh	0,5MW/0,5 MWh	1MW/0,5MWh	1MW/1MWh	2MW/1MWh	2MW/2MWh
CAPEX Base	3.429.925,57	3.429.925,57	3.429.925,57	3.429.925,57	3.429.925,57	3.429.925,57
Cost	175.000,00	325.000,00	340.000,00	630.000,00	650.000,00	1.200.000,00
TOTAL COST	3.604.925,57	3.754.925,57	3.769.925,57	4.059.925,57	4.079.925,57	4.629.925,57
PV+BESS BENEFIT	334.274,95	344.013,26	344.783,36	363.594,37	365.101,29	395.251,40
OPEX	3.500,00	6.500,00	6.800,00	12.600,00	13.000,00	24.000,00
TOTAL OPEX	143.500,00	146.500,00	146.800,00	152.600,00	153.000,00	164.000,00
Project's IRR	**4,40%**	4,35%	4,33%	4,25%	4,26%	3,91%

Table 25: IRR Comparison

Consequently, the most profitable battery is the **0,5MW/0,25MWh**. According to the IRR calculation, the other batteries are not worth the inversion, mainly because the cost of the battery does not make profitable the profit obtained from it. The most remarkable characteristics this battery provides are:

- Fast response: Less than 70 ms from charge to discharge
- Ease of environmental permits obtention
- Low maintenance costs (around 2% of battery CAPEX per year)
- E22’s Battery Management System (BMS): As stated in 4.3.2, the battery has an algorithm integrated that controls the functioning of the battery, charging and discharging it in the most adequate periods according to the use of the battery. The developed algorithm tries to emulate this system.

Once the battery has been chosen, the full offer will be proposed and compared with the PV plant one, choosing the optimal one. It must be noted that no datasheet will be shown for the proposed battery, as they are developed depending on the project.

Chapter 5. ANALYSIS OF THE FINAL PROPOSAL

5.1 PV PLANT + BESS TOTAL CASH FLOW

As indicated above, the chosen battery is 0,5MW/0.25MWh. According to the prices proposed by E22, the CAPEX of the total project is as seen in Table 26:

CAPEX

Main Equipment Price	Data	Units	EUR	USD	AUD	Total AUD Equivalent	AUDeq/Wdc
PV Modules	0,21	USD/Wp	-	662.287,5	-	973.952,21	0,3088
Inverter	275.000	AUD	-	-	275.000	275.000,00	0,0872
Structure (Tracker)	34	EUR/Mod	246.500	-	-	404.098,36	0,1281
BOS	0,5	AUD/Wp	-	-	1.576.875	1.576.875,00	0,5000
Interconnection	200.000	AUD	-	-	200.000	200.000,00	0,0634
BESS	700	AUD/KWh	-	-	175.000	175.000,00	0,0555
TOTAL	-	-	246.500	662.287,5	2.226.875	3.604.925,57	1,1431

Table 26: CAPEX PV Plant + BESS Study

The total CAPEX equivalent is 3.604.925,57 AUD$, which equivalates to 1,1431AUD$/$W_{DC}$.

The OPEX of the total PV Plant + BESS project is:

OPEX

Analysis	Data	Units	EUR	USD	AUD	Total AUD Equivalent	AUDeq/Wdc
Plant Manager	140.000	AUD	-	-	140.000	140.000	0,0444
Battery Maintenance	3.500	AUD	-	-	3.500	3.500	0,0011
TOTAL	-	-	-	-	143.500	143.500	0,0455

Table 27: OPEX PV Plamt + BESS Study

The total OPEX equivalent is 143.500 AUD$, which equivalates to 0,0455AUD$/$W_{DC}$.

The same procedure used in 3.5 will be completed for the BESS project. Refer to this chapter for a complete explanation.

PV PLANT	Data	Units
Peak Power (MWdc)	**3,154**	MWdc
Total CAPEX (1,14 $/Wp)	**3.604.925,57**	$
OPEX Year 1	**143.500**	$
Production Year 1	**5.541**	MWh
Degradation	**-0,40%**	-
Income Year 1	**334.275**	$
Inflation	**3,0%**	-

Table 28: Data used for Calculating IRR

CASH FLOW						
	Yr 0	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5
CAPEX	**-3.604.926**					
Production		5.541	5.519	5.497	5.475	5.453
Profit		**334.275**	**342.926**	**351.801**	**360.906**	**370.246**
OPEX		143.500	147.805	152.239	156.806	161.511
Operative CF		**190.775**	**195.121**	**199.562**	**204.099**	**208.735**
	-3.604.926	190.775	195.121	199.562	204.099	208.735
Project's IRR - 25 Years	**4,40%**					

Table 29: Total Project Cash Flow

5.2 INCLUSION OF OTHER REVENUE SOURCES

The initial comparison between both projects is clear: both share a similar IRR (4.49% for the PV Plant versus 4.40% for the PV Plant and battery). Following this reasoning, the installation of the battery would be feasible, as it obtains similar profitability levels than the plant itself. However, as explained in 4.4.1, installing the battery as a peak-hours battery can provide revenue from two other sources: the contingency market and the signature of a virtual cap contract. For the UQ's battery, which has similar characteristics as the one in the project, it has been studied that both sources suppose a 767% higher revenue than the arbitrage revenue.

Nonetheless, as stated in 4.4.1.3, this value cannot be completely extrapolated to the project's battery because of two different factors: the chosen battery is smaller than UQ's one, which leads to a participation in less contingency markets, and because of the virtual cap contract signature itself, as it is subject to the conditions offered. Consequently, the benefit obtained from both sources will be less than the one studied, but it will definitely suppose more benefit than the one given only by arbitrage.

Three different scenarios will be studied for this approximation, which will all be an increase from the benefits obtained from arbitrage. It is emphasised that there is no other way of obtaining the total revenue rather than making approximations: the contingency market is completely unpredictable and the spot prices from this market are not available, contrarily to the electricity wholesale market. Also, it is not possible to simulate a virtual cap contract for the specific characteristics of the battery due to the complexity and relative innovation of the project.

Those scenarios will be a 15%, 100% and 250% increase from the arbitrage's revenue. These scenarios will be analysed below:

5.2.1 SIMULATION 1: 15% INCREASE FROM ARBITRAGE'S REVENUE

Modifying Table 23 with the simulated increase, results in:

Storage (MWh)	Nameplate (MW)	PV Plant Revenue ($)	PV Plant+BESS Revenue ($)	Total Increase
0,25	0,5	323.533,04	336.267,34	3,94%

Table 30: Simulation 1 Revenue

Now the total benefits obtained are 336.267,34 AUD$. Taking this increase into the IRR's calculation, following the same procedure as in 3.5:

	0,5MW/0,25MWh
CAPEX Base	3.429.925,57
Cost	175.000,00
TOTAL COST	3.604.925,57
PV+BESS BENEFIT	336.267,34
OPEX	3.500,00
TOTAL OPEX	143.500,00
Project's IRR	**4,49%**

Table 31: Simulation 1 IRR

The IRR obtained in the first simulation is 4,49%.

5.2.2 SIMULATION 2: 100% INCREASE FROM ARBITRAGE'S REVENUE

Modifying Table 23 with the simulated increase, results in:

Storage (MWh)	Nameplate (MW)	PV Plant Revenue ($)	PV Plant+BESS Revenue ($)	Total Increase
0,25	0,5	323.533,04	347.557,58	7,43%

Table 32: Simulation 2 revenue

Now the total benefits obtained are 347.557,58 AUD$. Taking this increase into the IRR's calculation, following the same procedure as in 3.5:

	0,5MW/0,25MWh
CAPEX Base	3.429.925,57
Cost	175.000,00
TOTAL COST	3.604.925,57
PV+BESS BENEFIT	347.557,58
OPEX	3.500,00
TOTAL OPEX	143.500,00
Project's IRR	**5,01%**

Table 33: Simulation 2 IRR

The IRR obtained in the second simulation is 5,01%.

5.2.3 SIMULATION 3: 250% INCREASE FROM ARBITRAGE'S REVENUE

Modifying Table 21 with the simulated increase, results in:

Storage (MWh)	Nameplate (MW)	PV Plant Revenue ($)	PV Plant+BESS Revenue ($)	Total Increase
0,25	0,5	323.533,04	367.481,52	13,58%

Table 34: Simulation 3 Revenue

Now the total benefits obtained are 367.481,52 AUD$. Taking this increase into the IRR's calculation, following the same procedure as in 3.5:

	0,5MW/0,25MWh
CAPEX Base	3.429.925,57
Cost	175.000,00
TOTAL COST	3.604.925,57
PV+BESS BENEFIT	367.481,52
OPEX	3.500,00
TOTAL OPEX	143.500,00
Project's IRR	**5,90%**

Table 35: Simulation 3 IRR

The IRR obtained in the third simulation is 5,90%.

5.3 FINAL COMPARISON AND CONCLUSION

The PV Plant itself offers a 25-year IRR of 4.49%. Having chosen the optimal battery for the solar plant (0,5MW/0,25MWh) according to the arbitrage revenue, the 25-year IRR of the total project of PV Plant + BESS is 4.4%. However, all possible profits that can be obtained from the battery configured as peak-hours (contingencies and cap contract) must be considered.

UQ's battery study state that the total profit from these two sources can be 767% higher than the one obtained only by arbitrage (Wilson, Esterhuysen and Hains, 2020). With respect to our battery, if the added profit was only 15%, the IRR of the whole project of PV Plant and BESS would be as viable as the PV Plant itself, as both projects' IRR are the same. Other two scenarios have been simulated: a 100% increase supposes a final IRR of 5.01%, and a 250% increase supposes a final IRR of 5,90%, which is significantly greater than the project of the PV Plant itself and makes profitable the installation of the battery. Consequently, the project chosen will be the PV Plant and a 0,5MW/0,25MWh Lithium-ion battery. The final proposal that would be sent to the client can be found in Annex III (Commercial Proposal). This paper itself provides enough information about the technical aspects of the plant and can be considered a technical proposal.

Once all simulations have been completed, a final conclusion can be made about the viability of the project.

There are several conclusions that can be made according to these facts. First, the installation of the PV Plant itself is already profitable and would be worth the initial inversion. A 4.49% IRR is sufficient for a project of this type to be constructed. Also, it must be noted that the prices obtained for the elements and BOS are reliable enough to pose the real construction of the project.

Second, the installation of a BESS integrated to the solar plant has different lectures. If the battery was set only in arbitrage mode, the project of PV Plant and BESS has similar profitability than the project of the PV plant itself and its feasible. However, if the battery is programmed to participate in the contingency market, and a cap contract is signed, the profits would be enough to make profitable the installation of the battery. There is not possible way to determine the final income of both sources, but the estimations made according to a battery of similar characteristics than the one studied (UQ's Tesla Battery) infer that the installation of the battery is profitable enough: UQ's contingency and cap contract result in a 767% increase of the income of arbitrage. For the battery studied, if the increase was only of a 10%, it would make the project as viable as the PV Plant itself. In addition, the rest of scenarios suggest that the installation of the battery would be viable and would offer better profitability than the first project.

<u>As a whole, the project formed by PV Plant and BESS increases significantly the profitability than the PV Plant alone if all revenue sources are considered</u>. It is reminded to the reader what was already stated in 1.6: what makes profitable the use of a battery is the current situation of the Australian's electricity market. Eventually, by the increment of batteries present on the grid, the shape of the price curve will be completely flat. Until that moment arrives, projects with integrated storage systems will always be more profitable, as they take advantage of the current volatility of the curve.

Chapter 6. LIMITATIONS AND FUTURE STUDIES

6.1 LIMITATIONS

The main limitation observed in the project has been in the battery storage system section. As it is a fairly innovative technology, the data available to provide a reliable study is not as accurate as the available for the PV Plant. Also, the algorithms that control the battery are expensive and require extensive resources which are not available for the project. In order to provide an idea of the inaccuracy present in batteries, the comparison between the expected revenue and the actual revenue obtained by the UQ's battery can be seen in Figure 51:

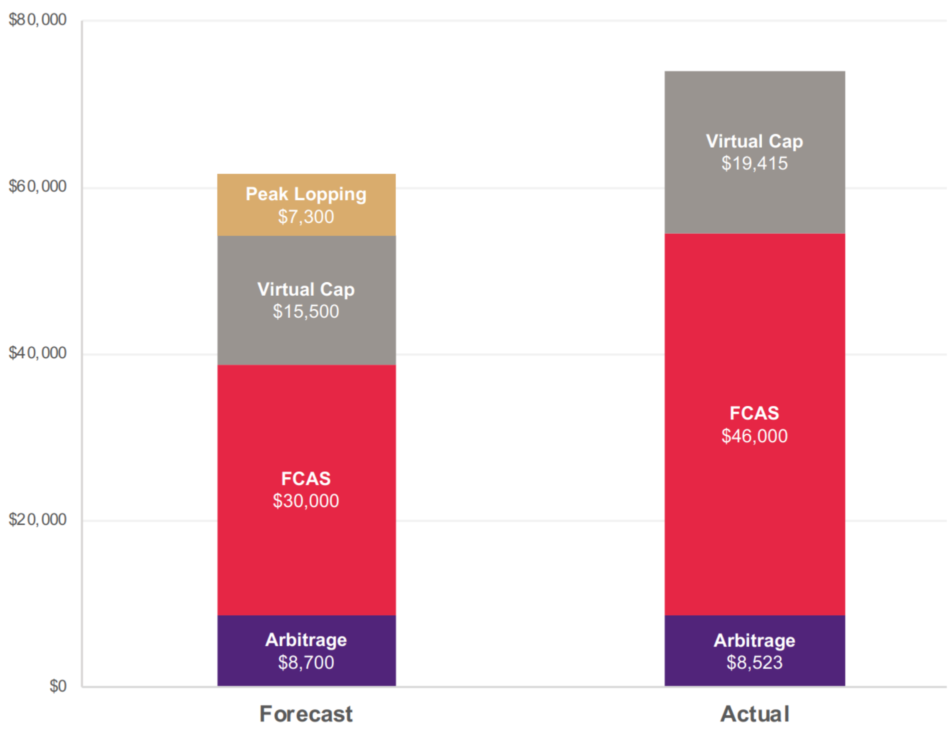

Figure 57: Comparison between forecast and actual UQ's battery revenue (Wilson, Esterhuysen and Hains, 2020)

As it can be seen, the only accurate revenue obtained was the arbitrage. For contingencies and virtual cap contract, the revenue obtained varies significantly with the one expected. Considering the resources and financial capability of the University of Queensland, this shows how difficult is to predict the behaviour of the battery in both aspects.

Thanks to the data and information provided by Gransolar and its subsidiary E22, the study of the installation of the PV Plant, alongside with the prices of all the components, has been accurate and has not presented any limitations.

6.2 FUTURE STUDIES

The optimal study that would complement this project is the development of a machine learning technique that could simulate accurately the behaviour of the battery. It must be noted that the algorithm developed for the battery considers the two daily minimums and two daily maximums of the prices given in 2019 to charge and discharge the battery. However, the actual algorithm used by the batteries is much more complex. Considering a basic example: if the minimum prices for a day were almost equal, but the production in some hours was greater at later hours of the morning, the developed algorithm would charge the battery in the first two hours although it could charge more energy later in the day for the same price. If a machine learning technique was developed, the battery would accurately charge at the optimal period.

The algorithm integrated in batteries for this use takes into account an infinite number of situations. Most likely, its development would be of similar size than the project studied, reason why it has not been attempted.

Other studies that would complement this project would be a study of the evolution of the electricity market's prices, in order to obtain an even more accurate approximation of the benefits obtained by the solar plant. The trend the market has been following during the past years makes the studied simulation accurate. However, it is unknown how the market will behave in the future years – reason why PPA's are signed (refer to 1.2) – and a study of the exact behaviour of the market would be helpful to study the project's feasibility.

In addition, if the project was going to be constructed, a further study of the disposition of the elements in the available terrain, alongside with the different wiring needed would be necessary.

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ANNEX I: SUSTAINABLE DEVELOPMENT GOALS

The nature of this project makes it significantly related with the sustainable development goals, as a photovoltaic plant is a source of energy which uses the sun to produce and does not pollute in its energy production.

According to the 17 goals proposed by the United Nations to achieve a better and more sustainable future by 2030 (United Nations, 2018), the studied project does contribute to an important number of them, but directly relates to goal 7: affordable and clean energy. Nowadays, energy is the dominant contributor to climate change, accounting for around 60% of total global greenhouse gas emissions (Martin, 2018). This does nothing but confirm the importance of green energy sources in our world.

The studied PV Plant, alongside with the integrated battery system, are an optimal example of how to contribute to achieve this goal. The only pollution produced by this project is the one associated to the production of the different elements that belong to the plant. This is directly related to goal 12: responsible consumption and production, and has been thoroughly checked that the different providers from which the plant's elements are imported have all permits needed for an environmentally friendly production.

The critical step to completely accomplish goal 7 is to correctly recycle the toxic materials that compose the battery storage system. It must be noted that all vanadium compounds are considered to be toxic, and it is the main material used in the battery. It has been pointed out by the supervisor of the project that Gransolar provides an effective removal process when PV Plants end their useful life, and ensures that no pollution is produced in this process, recycling adequately the materials needed.

Apart from goal 7, the PV Plant contributes to goal 13: Take urgent action to combat climate change and its effects. The relation between greenhouse gas emissions and climate change has been tested multiple times. As energy production contributes to 60% of the total greenhouse emissions, its contribution to climate change is unequivocal. Consequently, stimulating energy companies to continue their transition to a renewable energy production is important. Gransolar is an EPC that only constructs photovoltaic projects, which contributes significantly to these goals studied. These companies are now feasible: green energy is cheaper than non-renewable energies and governments are stimulating their creation.

This project collaborates as well with the accomplishment of goal 9: industry, innovation and infrastructure and goal 11: sustainable cities and communities. The relation of both goals with the project is clear. The creation of sources of renewable energy with energy storage systems suppose an innovation in the energy industry that contribute to the sustainable development and, in the long term, will form sustainable cities and communities. It is also important to note that installing green energy sources in developing countries would signify a form to cheapen energy costs and contributing to reduce poverty in the long term, going alongside with Goal 1, which objective is to eradicate poverty completely by 2030.

As a whole, the contribution of photovoltaic projects to the sustainable development goals is undeniable. The correct use and recycling of all parts of the studied project mean a non-polluting energy source, which should be a priority for all countries when it comes to energy production and consumption.

ANNEX II: DATASHEETS

1. Longi Hi-MO LR4-72HPH-435M

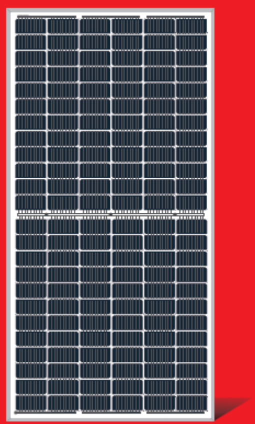
LR4-72HPH

425~455M

Hi-MO 4m

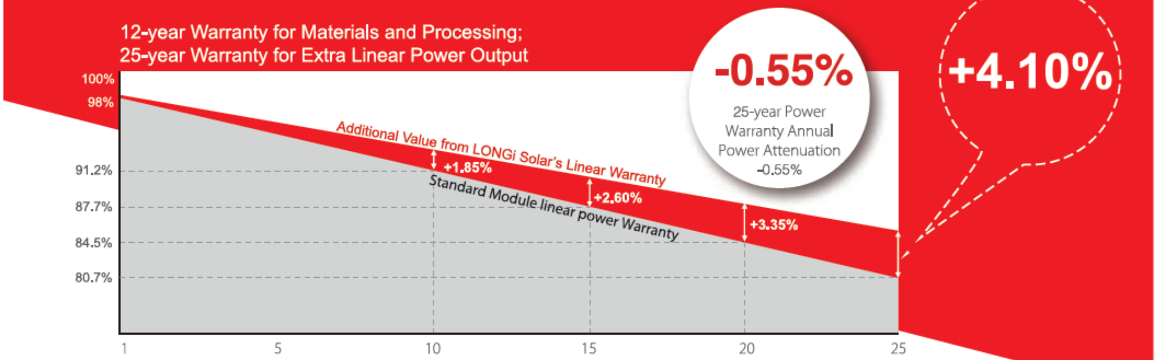
NEW

High Efficiency
Low LID Mono PERC with
Half-cut Technology



*Both 6BB & 9BB are available

12-year Warranty for Materials and Processing;
25-year Warranty for Extra Linear Power Output



Complete System and Product Certifications

IEC 61215, IEC 61730, UL 61730

ISO 9001:2008: ISO Quality Management System

ISO 14001: 2004: ISO Environment Management System

TS62941: Guideline for module design qualification and type approval

OHSAS 18001: 2007 Occupational Health and Safety

* Specifications subject to technical changes and tests.
LONGi Solar reserves the right of interpretation.

Positive power tolerance (0 ~ +5W) guaranteed

High module conversion efficiency (up to 20.9%)

Slower power degradation enabled by Low LID Mono PERC technology: first year <2%, 0.55% year 2-25

Solid PID resistance ensured by solar cell process optimization and careful module BOM selection

Reduced resistive loss with lower operating current

Higher energy yield with lower operating temperature

Reduced hot spot risk with optimized electrical design and lower operating current

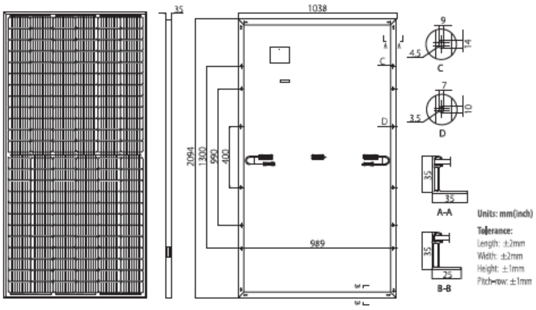
Room 801, Tower 3, Lujiazui Financial Plaza, No.826 Century Avenue, Pudong Shanghai, 200120, China
Tel: +86-21-80162606 E-mail: module@longi-silicon.com Facebook: www.facebook.com/LONGi Solar

Note: Due to continuous technical innovation, R&D and improvement, technical data above mentioned may be of modification accordingly. LONGi have the sole right to make such modification at anytime without further notice; Demanding party shall request for the latest datasheet for such as contract need, and make it a consisting and binding part of lawful documentation duly signed by both parties.

20200401V11

LR4-72HPH **425~455M**

Design (mm)



Mechanical Parameters

Cell Orientation: 144 (6×24)
Junction Box: IP68, three diodes
Output Cable: 4mm², 300mm in length, length can be customized
Glass: Single glass 3.2mm coated tempered glass
Frame: Anodized aluminum alloy frame
Weight: 23.5kg
Dimension: 2094×1038×35mm
Packaging: 30pcs per pallet
150pcs per 20'GP
660pcs per 40'HC

Operating Parameters

Operational Temperature: -40℃ ~ +85℃
Power Output Tolerance: 0 ~ +5 W
Voc and Isc Tolerance: ±3%
Maximum System Voltage: DC1500V (IEC/UL)
Maximum Series Fuse Rating: 20A
Nominal Operating Cell Temperature: 45±2℃
Safety Class: Class Ⅱ
Fire Rating: UL type 1 or 2

Electrical Characteristics

Test uncertainty for Pmax: ±3%

Model Number	LR4-72HPH-425M		LR4-72HPH-430M		LR4-72HPH-435M		LR4-72HPH-440M		LR4-72HPH-445M		LR4-72HPH-450M		LR4-72HPH-455M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	425	317.4	430	321.1	435	324.9	440	328.6	445	332.3	450	336.1	455	339.8
Open Circuit Voltage (Voc/V)	48.3	45.3	48.5	45.5	48.7	45.7	48.9	45.8	49.1	46.0	49.3	46.2	49.5	46.4
Short Circuit Current (Isc/A)	11.23	9.08	11.31	9.15	11.39	9.21	11.46	9.27	11.53	9.33	11.60	9.38	11.66	9.43
Voltage at Maximum Power (Vmp/V)	40.5	37.7	40.7	37.9	40.9	38.1	41.1	38.3	41.3	38.5	41.5	38.6	41.7	38.8
Current at Maximum Power (Imp/A)	10.50	8.42	10.57	8.47	10.64	8.53	10.71	8.59	10.78	8.64	10.85	8.70	10.92	8.75
Module Efficiency(%)	19.6		19.8		20.0		20.2		20.5		20.7		20.9	

STC (Standard Testing Conditions): Irradiance 1000W/m², Cell Temperature 25℃, Spectra at AM1.5

NOCT (Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20℃, Spectra at AM1.5, Wind at 1m/S

Temperature Ratings (STC)

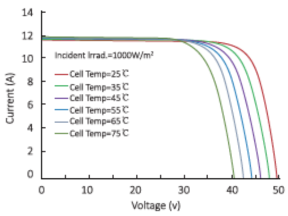
Temperature Coefficient of Isc	+0.048%/℃
Temperature Coefficient of Voc	-0.270%/℃
Temperature Coefficient of Pmax	-0.350%/℃

Mechanical Loading

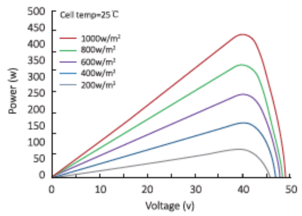
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

I-V Curve

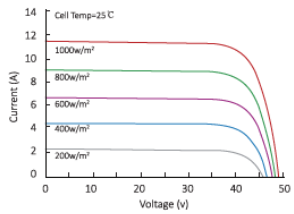
Current-Voltage Curve (LR4-72HPH-440M)



Power-Voltage Curve (LR4-72HPH-440M)



Current-Voltage Curve (LR4-72HPH-440M)



LONGi

Room 801, Tower 3, Lujiazui Financial Plaza, No.826 Century Avenue, Pudong Shanghai, 200120, China
Tel: +86-21-80162606 E-mail: module@longi-silicon.com Facebook: www.facebook.com/LONGi Solar

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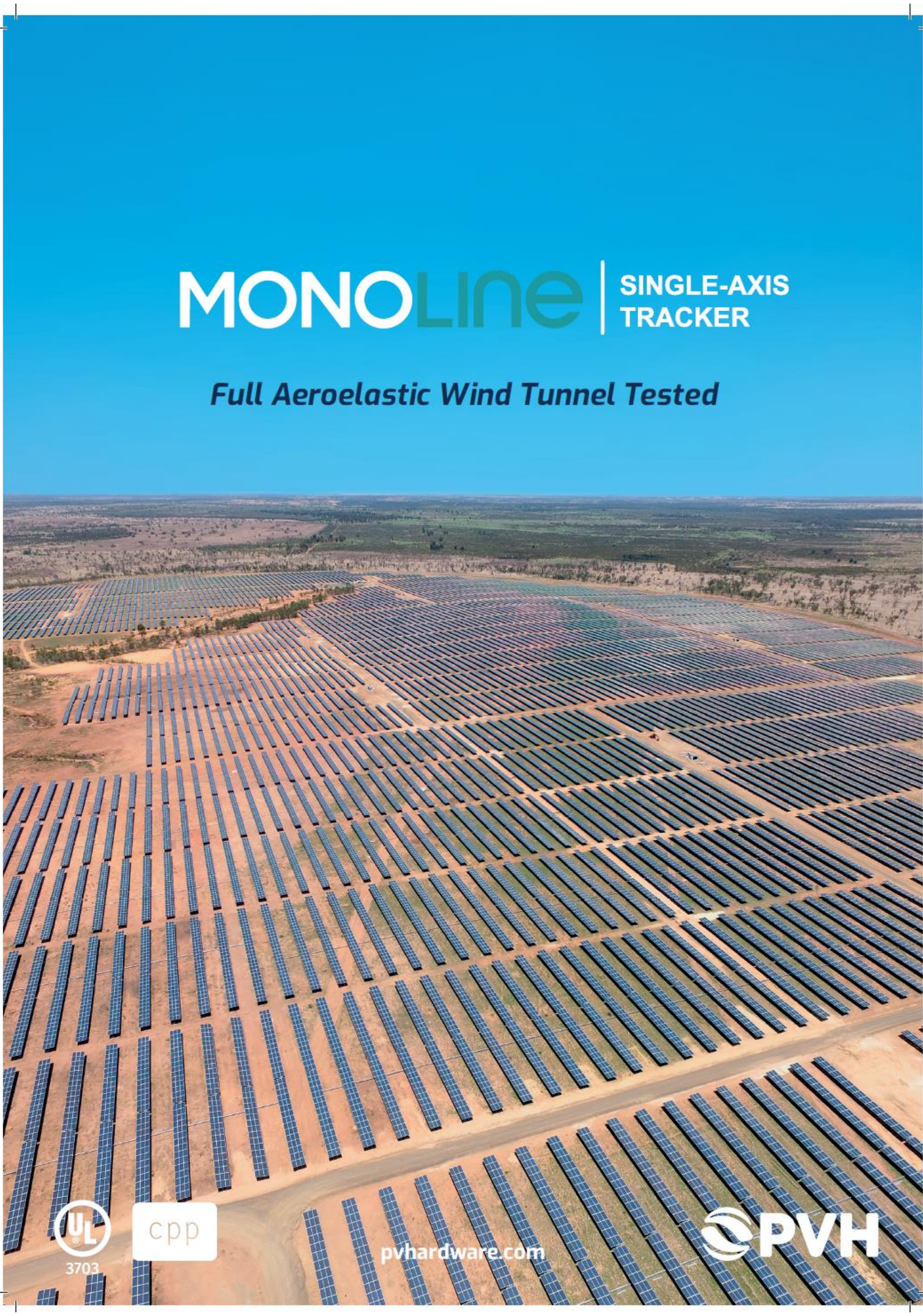
20200401V11

2. PVH Monoline 3H


MONOLINE
SINGLE-AXIS TRACKER
Full Aeroelastic Wind Tunnel Tested
UL 3703
cpp
pvhardware.com
PVH

MONOLINE SINGLE-AXIS TRACKER

STRUCTURAL & MECHANICAL SPECIFICATIONS

Tracker	*Independent-row horizontal single-axis*
Rotational range	*+/-60º*
Motor	*DC Motor*
Motors per MWp (390 Wp modules)	*51.58 (Monoline2V), 34.39 (Monoline 3H)*
Modules supported	*All market available modules, including thin film and bifacial*
Slope tolerances	*N-S: up to 14%, E-W: unlimited*
Module configuration	*2 modules in portrait / 3 modules in landscape*
Module attachment	*Direct mount to panel rail (configurable for clamps)*
Structural materials	*Magnelis / Hot-dipped galvanized steel per ASTM A123 or ISO 1461*
Allowable wind load	*Tailored to site specific conditions up to 120 mph/193 kph*
Grounding system	*Self-grounded via serrated fixation hardware*
Storm alarm for high winds	*Yes, stow position in up to 5 minutes*
Wind speed sensors	*Ultrasonic anemometer*
Solar tracking method	*Astronomical algorithm*
TBox	*Central control unit manages up to 200 trackers through serial (rs485) or wireless communication*
SCADA interface	*Modbus TCP*
Nighttime stow	*Yes, configurable*
Backtracking	*Yes*
In-field manufacturing	*No*
On-site training and commissioning	*Yes, included in tracker supply*
Standard warranties	*Structure: 10 years. Electromechanical components: 5 years*
Certifications	*UL3703, IEC 62817*
Structural adaptation to local codes	*Yes, verified by third-party structural engineers if required*

WIND TUNNEL TEST CERTIFIED
FLUTTER FREE
PVH

MONOLINE 3H *90 panels per row*

MONOLINE 2V *60 panels per row*

MONOLINE 2V BIFACIAL *60 panels per row*

UL 3703 cpp contact@pvhardware.es PVH

3. Skids

MV POWER STATION FOR AUSTRALIA
5000-S-AU / 5500-S-AU / 6000-S-AU

Robust
- Complete system and all individual components type-tested
- Optimally suited to extreme ambient conditions

Easy to Use
- Plug and play concept
- Completely pre-assembled for easy set-up and commissioning

Cost-Effective
- Easy planning and installation
- Low transport costs due to 40-foot skid

Flexible
- Numerous options
- Compatible with MVPS 2500-S-AU / MVPS 2750-S-AU / MVPS 3000-S-AU

MV POWER STATION 5000-S-AU / 5500-S-AU / 6000-S-AU

Turnkey Solution for PV Power Plants in Australia

With the power of the new robust central inverters, the Sunny Central or Sunny Central Storage, and with perfectly adapted medium-voltage components, the new MV Power Station offers even more power density as a turnkey solution dedicated for Australia. The solution is the ideal choice for new generation PV power plants operating at 1500 V_{DC}. Delivered pre-configured on a 40-foot skid, the solution is easy to transport and quick to assemble and commission. The MVPS and all components are type-tested. The MV Power Station combines rigorous plant safety with maximum energy yield and minimized deployment and operating risk.

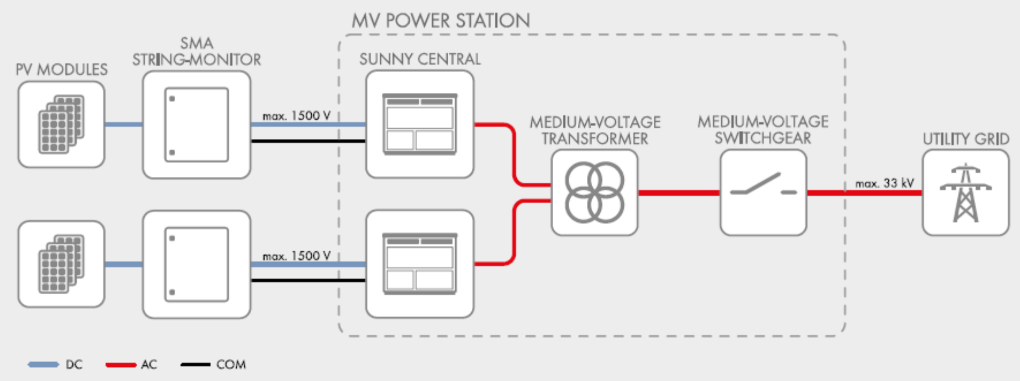
MV POWER STATION
5000-S-AU / 5500-S-AU / 6000-S-AU

Technical Data	MV Power Station 5000-S-AU	MV Power Station 5500-S-AU
Input (DC)		
Available inverters	2 x SC 2500-EV or 2 x SCS 2500-EV	2 x SC 2750-EV or 2 x SCS 2750-EV
Max. input voltage	1500 V	1500 V
Max. input current	2 x 3200 A	2 x 3200 A
Number of DC inputs	2 x 24 double pole fused (32 single pole fused)	
Integrated zone monitoring	○	○
Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 500 A	
Output (AC) on the medium-voltage side		
Standard power at 1000 m and cos φ = 1 (at 35 °C / at 50 °C / at 55 °C)[1]	5000 kVA / 4500 kVA / 0 kVA	5500 kVA / 5000 kVA / 0 kVA
Typical nominal AC voltages	11 kV, 22 kV, 33 kV	11 kV, 22 kV, 33 kV
AC power frequency	50 Hz	50 Hz
Transformer vector group Dy11	●	●
Transformer cooling methods ONAN[2]	●	●
Max. output current at 33 kV	88 A	97 A
Transformer no-load losses at 33 kV	3.55 kW	3.75 kW
Transformer short-circuit losses at 33 kV	34.5 kW	40 kW
Max. total harmonic distortion	< 3%	< 3%
Reactive power feed-in	○ up to 60% of AC power	
Power factor at rated power / displacement power factor adjustable	1 / 0.8 overexcited to 0.8 underexcited	
Inverter efficiency		
Max. efficiency[3]	98.6%	98.7%
European efficiency[3]	98.3%	98.6%
CEC weighted efficiency[4]	98.0%	98.5%
Protective devices		
Input-side disconnection point	DC load-break switch	
Output-side disconnection point	Medium-voltage vacuum circuit breaker	
DC overvoltage protection	Surge arrester type I	
Galvanic isolation	●	
Internal arc classification medium-voltage control room (according to AS 62271-202)	IAC A 20 kA 1 s	
General Data		
Dimensions of the 20-foot skid (W / H / D)[5]	12192 mm / 3010 mm / 2438 mm	
Weight	< 26.5 t	
Self-consumption (max. / partial load / average)[1]	< 16.2 kW / < 3.6 kW / < 4.0 kW	
Self-consumption (stand-by)[1]	< 740 W	
Degree of protection according to IEC 60529	Switchgear compartment IP23D, inverter electronics IP65	
Environment: standard / harsh	● / ○	
Degree of protection according to IEC 60721-3-4 (4C1, 4S2 / 4C2, 4S2)	● / ○	
Maximum permissible value for relative humidity	15% to 95%	
Max. operating altitude above mean sea level 1000 m / 2000 m	● / ○ (earlier temperature-dependent de-rating)	
Fresh air consumption of inverter and transformer	13000 m³/h	
Features		
DC terminal	Terminal lug	
AC connection	Outer-cone angle plug	
Skid enclosure color	RAL 7033 / N42	
Low voltage transformer 30 kVA	●	
Medium-voltage switchgear 3 feeders 2 cable feeders with load-break switch, 1 transformer feeder with circuit breaker, internal arc classification IAC A FL 20 kA 1 s according to AS 62271-200	●	
Accessories for medium-voltage switchgear: without / auxiliary contacts / remote control	● / ○ / ○	
Oil containment	●	
Industry standards (for other standards see the inverter datasheet)	AS 62271-202, AS 62271-200, AS 60076, AS 3000, AS 2067, AS 1170	
● Standard features ○ Optional features – Not available		
Type designation	MVPS-5000-S-AU-10	MVPS-5500-S-AU-10

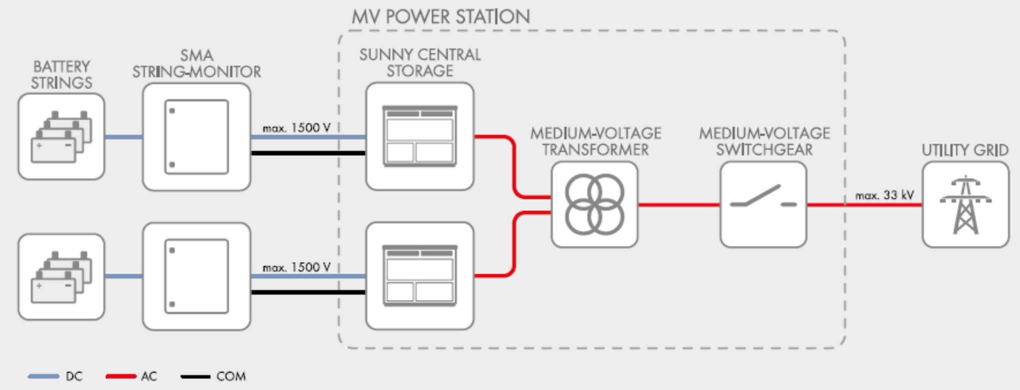
1) Data based on inverter
2) ONAN = Mineral oil with natural air cooling
3) Efficiency measured at inverter without internal power supply
4) Efficiency measured at inverter with internal power supply
5) Transport dimensions

Technical Data	MV Power Station 6000-S-AU
Input (DC)	
Available inverters	2 x SC 3000-EV or 2 x SCS 3000-EV
Max. input voltage	1500 V
Max. input current	2 x 3200 A
Number of DC inputs	2 x 24 double pole fused (32 single pole fused)
Integrated zone monitoring	○
Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 500 A
Output (AC) on the medium-voltage side	
Standard power at 1000 m and cos φ = 1 (at 35°C / at 50°C / at 55°C)[1]	6000 kVA / 5400 kVA / 0 kVA
Typical nominal AC voltages	11 kV, 22 kV, 33 kV
AC power frequency	50 Hz
Transformer vector group Dy11	●
Transformer cooling methods ONAN[2]	●
Max. output current at 33 kV	105 A
Transformer no-load losses at 33 kV	3.75 kW
Transformer short-circuit losses at 33 kV	40 kW
Max. total harmonic distortion	< 3%
Reactive power feed-in	○ up to 60% of AC power
Power factor at rated power / displacement power factor adjustable	1 / 0.8 overexcited to 0.8 underexcited
Inverter efficiency	
Max. efficiency[3]	98.8%
European efficiency[3]	98.6%
CEC weighted efficiency[4]	98.5%
Protective devices	
Input-side disconnection point	DC load-break switch
Output-side disconnection point	Medium-voltage vacuum circuit breaker
DC overvoltage protection	Surge arrester type I
Galvanic isolation	●
Internal arc classification medium-voltage control room (according to AS 62271-202)	IAC A 20 kA 1 s
General Data	
Dimensions of the 20-foot skid (W / H / D)[5]	12192 mm / 3010 mm / 2438 mm
Weight	< 26.5 t
Self-consumption (max. / partial load / average)[1]	< 16.2 kW / < 3.6 kW / < 4.0 kW
Self-consumption (stand-by)[1]	< 740 W
Degree of protection according to IEC 60529	Switchgear compartment IP23D, inverter electronics IP65
Environment: standard / harsh	● / ○
Degree of protection according to IEC 60721-3-4 (4C1, 4S2 / 4C2, 4S2)	● / ○
Maximum permissible value for relative humidity	15% to 95%
Max. operating altitude above mean sea level 1000 m / 2000 m	● / ○ (earlier temperature-dependent de-rating)
Fresh air consumption of inverter and transformer	13000 m³/h
Features	
DC terminal	Terminal lug
AC connection	Outer-cone angle plug
Skid enclosure color	RAL 7033 / N42
Low voltage transformer 30 kVA	●
Medium-voltage switchgear 3 feeders 2 cable feeders with load-break switch, 1 transformer feeder with circuit breaker, internal arc classification IAC A FL 20 kA 1 s according to AS 62271-200	●
Accessories for medium-voltage switchgear: without / auxiliary contacts / remote control	● / ○ / ○
Oil containment	●
Industry standards (for other standards see the inverter datasheet)	AS 62271-202, AS 62271-200, AS 60076, AS 3000, AS 2067, AS 1170
● Standard features ○ Optional features – Not available	
Type designation	MVPS-6000-S-AU-10

System diagram with Sunny Central



System diagram with Sunny Central Storage



www.SMA-Australia.com.au **SMA Solar Technology**

4. Sunny Central 3000-EV

SUNNY CENTRAL
2200 / 2475 / 2500-EV / 2750-EV / 3000-EV

Efficient
- Up to 4 inverters can be transported in one standard shipping container
- Overdimensioning up to 225% is possible
- Full power at ambient temperatures of up to 35 °C

Robust
- Intelligent air cooling system OptiCool for efficient cooling
- Suitable for outdoor use in all climatic ambient conditions worldwide

Flexible
- Conforms to all known grid requirements worldwide
- Q on demand
- Available as a single device or turnkey solution, including medium-voltage block

Easy to Use
- Improved DC connection area
- Connection area for customer equipment
- Integrated voltage support for internal and external loads

SUNNY CENTRAL 2200 / 2475 / 2500-EV / 2750-EV / 3000-EV

The new Sunny Central: more power per cubic meter

With an output of up to 3000 kVA and system voltages of 1100 V DC or 1500 V DC, the SMA central inverter allows for more efficient system design and a reduction in specific costs for PV power plants. A separate voltage supply and additional space are available for the installation of customer equipment. True 1500 V technology and the intelligent cooling system OptiCool ensure smooth operation even in extreme ambient temperature as well as a long service life of 25 years.

SUNNY CENTRAL 1000 V

Technical Data	Sunny Central 2200	Sunny Central 2475*
Input (DC)		
MPP voltage range V_{DC} (at 25 °C / at 35 °C / at 50 °C)	570 to 950 V / 800 V / 800 V	638 V to 950 V / 800 V / 800 V
Min. input voltage $V_{DC,min}$ / Start voltage $V_{DC,Start}$	545 V / 645 V	614 V / 714 V
Max. input voltage $V_{DC,max}$	1100 V	1100 V
Max. input current $I_{DC,max}$ (at 35°C / at 50°C)	3960 A / 3600 A	3960 A / 3600 A
Max. short-circuit current $I_{DC,sc}$	6400 A	6400 A
Number of DC inputs	24 double pole fused (32 single pole fused)	
Max. number of DC cables per DC input (for each polarity)	2 x 800 kcmil, 2 x 400 mm²	
Integrated zone monitoring	○	
Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 500 A	
Output (AC)		
Nominal AC power at cos φ =1 (at 35°C / at 50°C)	2200 kVA / 2000 kVA	2475 kVA / 2250 kVA
Nominal AC power at cos φ =0.8 (at 35°C / at 50°C)	1760 kW / 1600 kW	1980 kW / 1800 kW
Nominal AC current $I_{AC,nom}$ = Max. output current $I_{AC,max}$	3300 A	3300 A
Max. total harmonic distortion	< 3% at nominal power	< 3% at nominal power
Nominal AC voltage / nominal AC voltage range[1) 8)]	385 V / 308 V to 462 V	434 V / 347 V to 521 V
AC power frequency / range	50 Hz / 47 Hz to 53 Hz 60 Hz / 57 Hz to 63 Hz	
Min. short-circuit ratio at the AC terminals[9)]	> 2	
Power factor at rated power / displacement power factor adjustable[8) 10)]	● 1 / 0.8 overexcited to 0.8 underexcited ○ 1 / 0.0 overexcited to 0.0 underexcited	
Efficiency		
Max. efficiency[2)] / European efficiency[2)] / CEC efficiency[3)]	98.6% / 98.4% / 98.0%	98.6% / 98.4% / 98.0%
Protective Devices		
Input-side disconnection point	DC load break switch	
Output-side disconnection point	AC circuit breaker	
DC overvoltage protection	Surge arrester, type I	
AC overvoltage protection (optional)	Surge arrester, class I	
Lightning protection (according to IEC 62305-1)	Lightning Protection Level III	
Ground-fault monitoring / remote ground-fault monitoring	○ / ○	
Insulation monitoring	○	
Degree of protection: electronics / air duct / connection area (as per IEC 60529)	IP65 / IP34 / IP34	
General Data		
Dimensions (W / H / D)	2780 / 2318 / 1588 mm (109.4 / 91.3 / 62.5 inch)	
Weight	< 3400 kg / < 7496 lb	
Self-consumption (max.[4)] / partial load[5)] / average[6)])	< 8100 W / < 1800 W / < 2000 W	
Self-consumption (standby)	< 300 W	
Internal auxiliary power supply	Integrated 8.4 kVA transformer	
Operating temperature range[8)]	−25°C to 60°C / −13°F to 140°F	
Noise emission[7)]	64.7 dB(A)	
Temperature range (standby)	−40°C to 60°C / −40°F to 140°F	
Temperature range (storage)	−40°C to 70°C / −40°F to 158°F	
Max. permissible value for relative humidity (condensing / non-condensing)	95% to 100% (2 month/year) / 0% to 95%	
Maximum operating altitude above MSL[8)] 1000 m / 2000 m[11)] / 3000 m[11)] / 4000 m[11)]	● / ○ / ○ / ○	
Fresh air consumption	6500 m³/h	
Features		
DC connection	Terminal lug on each input (without fuse)	
AC connection	With busbar system (three busbars, one per line conductor)	
Communication	Ethernet, Modbus Master, Modbus Slave	
Communication with SMA string monitor (transmission medium)	Modbus TCP / Ethernet (FO MM, Cat-5)	
Enclosure / roof color	RAL 9016 / RAL 7004	
Supply transformer for external loads	○ (2.5 kVA)	
Standards and directives complied with	CE, IEC / EN 62109-1, IEC / EN 62109-2, BDEW-MSRL, IEEE1547, UL 840 Cat. IV, Arrêté du 23/04/08	
EMC standards	IEC / EN 61000-6-4, IEC / EN 61000-6-2, EN 55022, IEC 62920, FCC Part 15 Class A, Cispr 11, DIN EN55011:2017	
Quality standards and directives complied with	VDI/VDE 2862 page 2, DIN EN ISO 9001	
● Standard features ○ Optional * preliminary		
Type designation	SC-2200-10	SC-2475-10

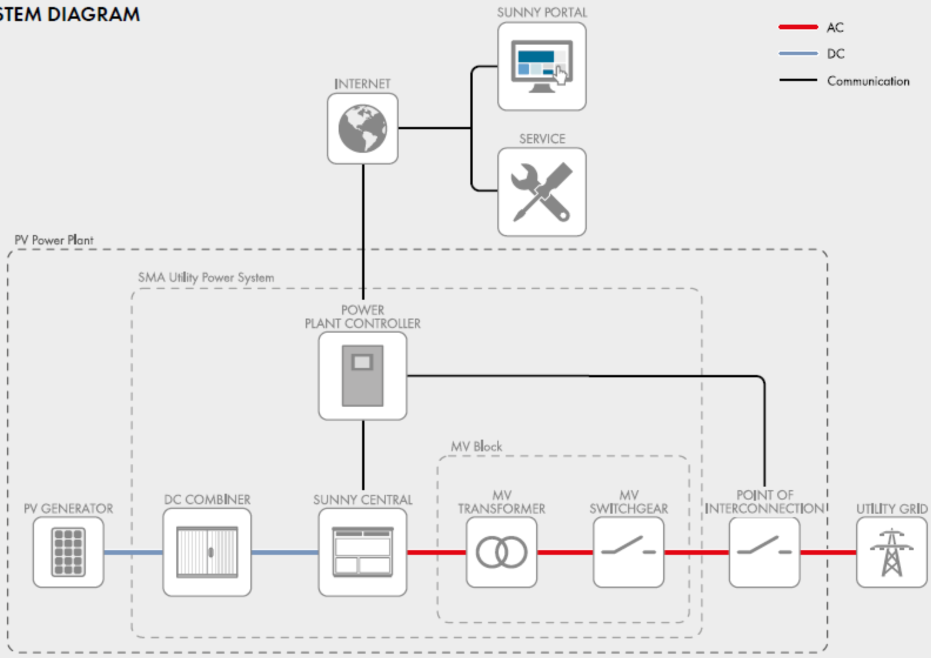
1) At nominal AC voltage, nominal AC power decreases in the same proportion
2) Efficiency measured without internal power supply
3) Efficiency measured with internal power supply
4) Self-consumption at rated operation
5) Self-consumption at < 75% Pn at 25°C
6) Self-consumption averaged out from 5% to 100% Pn at 25°C
7) Sound pressure level at a distance of 10 m
8) Values apply only to inverters. Permissible values for SMA MV solutions from SMA can be found in the corresponding data sheets.
9) A short-circuit ratio of < 2 requires a special approval from SMA
10) Depending on the DC voltage
11) Earlier temperature-dependent de-rating and reduction of DC open-circuit voltage

SUNNY CENTRAL 1500 V

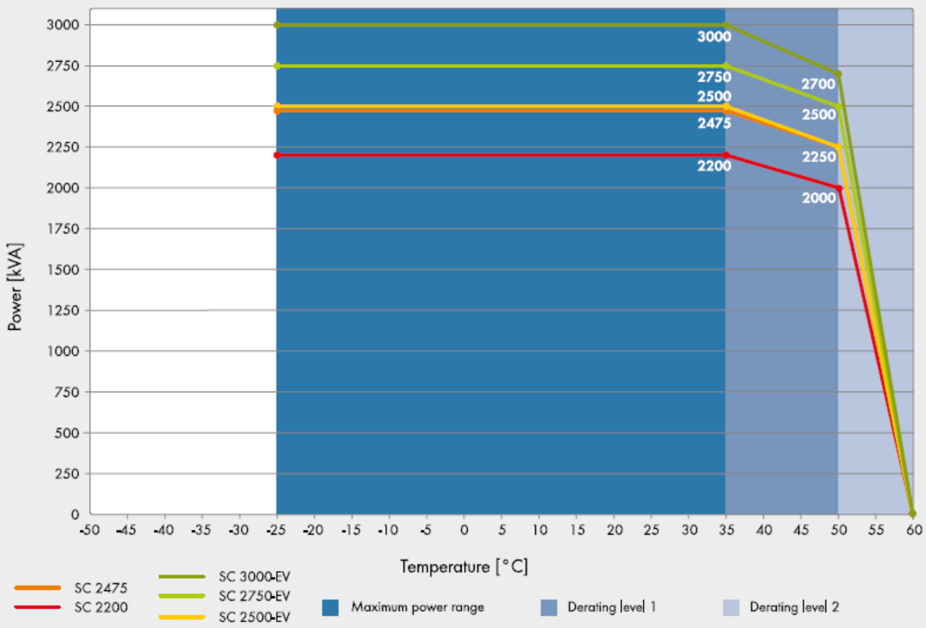
Technical Data	Sunny Central 2500-EV	Sunny Central 2750-EV	Sunny Central 3000-EV
Input (DC)			
MPP voltage range V_{DC} (at 25°C / at 35°C / at 50°C)	850 V to 1425 V / 1200 V / 1200 V	875 V to 1425 V / 1200 V / 1200 V	956 V to 1425 V / 1200 V / 1200 V
Min. input voltage $V_{DC, min}$ / Start voltage $V_{DC, Start}$	778 V / 928 V	849 V / 999 V	927 V / 1077 V
Max. input voltage $V_{DC, max}$	1500 V	1500 V	1500 V
Max. input current $I_{DC, max}$ (at 35°C / at 50°C)	3200 A / 2956 A	3200 A / 2956 A	3200 A / 2970 A
Max. short-circuit current rating	6400 A	6400 A	6400 A
Number of DC inputs	24 double pole fused (32 single pole fused) for PV		
Number of DC inputs with optional DC battery coupling	18 double pole fused (36 single pole fused) for PV and 6 double pole fused for batteries		
Max. number of DC cables per DC input (for each polarity)	2 x 800 kcmil, 2 x 400 mm²		
Integrated zone monitoring	○		
Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 500 A		
Output (AC)			
Nominal AC power at cos φ =1 (at 35°C / at 50°C)	2500 kVA / 2250 kVA	2750 kVA / 2500 kVA	3000 kVA / 2700 kVA
Nominal AC power at cos φ =0.8 (at 35°C / at 50°C)	2000 kW / 1800 kW	2200 kW / 2000 kW	2400 kW / 2160 kW
Nominal AC current $I_{AC, nom}$ = Max. output current $I_{AC, max}$	2624 A	2646 A	2646 A
Max. total harmonic distortion	< 3% at nominal power	< 3% at nominal power	< 3% at nominal power
Nominal AC voltage / nominal AC voltage range[1) 8)]	550 V / 440 V to 660 V	600 V / 480 V to 690 V	655 V / 524 V to 721 V[9)]
AC power frequency	50 Hz / 47 Hz to 53 Hz 60 Hz / 57 Hz to 63 Hz		
Min. short-circuit ratio at the AC terminals[10)]	> 2		
Power factor at rated power / displacement power factor adjustable[8) 11)]	● 1 / 0.8 overexcited to 0.8 underexcited ○ 1 / 0.0 overexcited to 0.0 underexcited		
Efficiency			
Max. efficiency[2)] / European efficiency[2)] / CEC efficiency[3)]	98.6% / 98.3% / 98.0%	98.7% / 98.5% / 98.5%	98.8% / 98.6% / 98.5%
Protective Devices			
Input-side disconnection point	DC load-break switch		
Output-side disconnection point	AC circuit breaker		
DC overvoltage protection	Surge arrester, type I & II		
AC overvoltage protection (optional)	Surge arrester, class I & II		
Lightning protection (according to IEC 62305-1)	Lightning Protection Level III		
Ground-fault monitoring / remote ground-fault monitoring	○ / ○		
Insulation monitoring	○		
Degree of protection: electronics / air duct / connection area (as per IEC 60529)	IP65 / IP34 / IP34		
General Data			
Dimensions (W / H / D)	2780 / 2318 / 1588 mm (109.4 / 91.3 / 62.5 inch)		
Weight	< 3400 kg / < 7496 lb		
Self-consumption (max.[4)] / partial load[5)] / average[6)])	< 8100 W / < 1800 W / < 2000 W		
Self-consumption (standby)	< 370 W		
Internal auxiliary power supply	Integrated 8.4 kVA transformer		
Operating temperature range[8)]	−25 to 60°C / −13 to 140°F		
Noise emission[7)]	67.8 dB(A)		
Temperature range (standby)	−40 to 60°C / −40 to 140°F		
Temperature range (storage)	−40 to 70°C / −40 to 158°F		
Max. permissible value for relative humidity (condensing / non-condensing)	95% to 100% (2 month / year) / 0 % to 95%		
Maximum operating altitude above MSL[8)] 1000 m / 2000 m[12)] / 3000 m[12)]	● / ○ / –	● / ○ / –	● / ○ / –
Fresh air consumption	6500 m³/h		
Features			
DC connection	Terminal lug on each input (without fuse)		
AC connection	With busbar system (three busbars, one per line conductor)		
Communication	Ethernet, Modbus Master, Modbus Slave		
Communication with SMA string monitor (transmission medium)	Modbus TCP / Ethernet (FO MM, Cat-5)		
Enclosure / roof color	RAL 9016 / RAL 7004		
Supply transformer for external loads	○ (2.5 kVA)		
Standards and directives complied with	CE, IEC / EN 62109-1, IEC / EN 62109-2, BDEW-MSRL, IEEE1547, Arrêté du 23/04/08		
EMC standards	CISPR 11, CISPR 22, EN55011:2017, EN 55022, IEC/EN 61000-6-4, IEC/EN 61000-6-2, IEC 62920, FCC Part 15 Class A	CISPR 11, CISPR 22, EN55011:2017, EN 55022, IEC 62920, FCC Part 15 Class A	
Quality standards and directives complied with	VDI/VDE 2862 page 2, DIN EN ISO 9001		
● Standard features ○ Optional – not available			
Type designation	SC-2500-EV-10	SC-2750-EV-10	SC-3000-EV-10

1) At nominal AC voltage, nominal AC power decreases in the same proportion
2) Efficiency measured without internal power supply
3) Efficiency measured with internal power supply
4) Self-consumption at rated operation
5) Self-consumption at < 75% Pn at 25°C
6) Self-consumption averaged out from 5% to 100% Pn at 35°C
7) Sound pressure level at a distance of 10 m
8) Values apply only to inverters. Permissible values for SMA MV solutions from SMA can be found in the corresponding data sheets.
9) AC voltage range can be extended to 753V for 50Hz grids only (option „Aux power supply: external" must be selected, option "housekeeping" not combinable).
10) A short-circuit ratio of < 2 requires a special approval from SMA
11) Depending on the DC voltage
12) Available as a special version, earlier temperature-dependent de-rating and reduction of DC open-circuit voltage

SYSTEM DIAGRAM



TEMPERATURE BEHAVIOR (at cos φ =1 and installation altitudes of up to 1,000 m*)



*) For the temperature behavior for installations at above 1,000 m see the Technical Information document.

5. Transformer

INGECON SUN

Power Dual B Series
1,500 Vdc

Up to 3.6 MVA at 1500 V

TRANSFORMERLESS DUAL SOLUTION WITH TWO B SERIES INVERTERS

Maximum power density
These PV central inverters feature more power per cubic foot. Thanks to the use of high-quality components, this inverter series performs at the highest possible level.

Latest generation electronics
The B Series inverters integrate an innovative control unit that runs faster and performs a more efficient and sophisticated inverter control, as it uses a last-generation digital signal processor. Furthermore, the hardware of the control unit allows some more accurate measurements and very reliable protections.

These inverters feature a low voltage ride-through capability and also a lower power consumption thanks to a more efficient power supply electronic board.

Integrated AC connections
The output connections are integrated into the same cabinet, facilitating close-coupled connection with the MV transformer, as well as maintenance and repair work.

Maximum protection
These PV inverters can guarantee the maximum protection thanks to the their motorized DC switch to decouple the PV generator from the inverter.

Moreover, they are also supplied with a motorized AC circuit breaker. Optionally, they can be supplied with DC fuses, grounding kit and input current monitoring.

Maximum efficiency values
Through the use of innovative electronic conversion topologies, efficiency values of up to 98.9% can be achieved.

Enhanced functionality
This new INGECON® SUN Power range features a revamped, improved enclosure which, together with its innovative air cooling system, makes it possible to increase the ambient operating temperature.

www.ingeteam.com
solar.energy@ingeteam.com

Ingeteam

INGECON SUN Power Dual B Series 1,500 Vdc

Long-lasting design

These inverters have been designed to guarantee a long life expectancy. Standard 5 year warranty, extendable for up to 25 years.

Grid support

The INGECON® SUN Power B Series has been designed to comply with the grid connection requirements, contributing to the quality and stability of the electric system. These inverters therefore feature a low voltage ride-through capability, and can deliver reactive power and control the active power delivered to the grid. Moreover, they can operate in weak power grids with a low SCR.

Ease of maintenance

All the elements can be removed or replaced directly from the inverter's front side, thanks to its new design.

Easy to operate

The INGECON® SUN Power inverters feature an LCD screen for the simple and convenient monitoring of the inverter status and a range of internal variables. The display also includes a number of LEDs to show the inverter operating status with warning lights to indicate any incidents. All this helps to simplify and facilitate maintenance tasks.

Monitoring and communication

Ethernet communications supplied as standard. The following applications are included at no extra cost: INGECON® SUN Manager, INGECON® SUN Monitor and its Smartphone version Web Monitor, available on the App Store. These applications are used for monitoring and recording the inverter's internal operating variables through the Internet (alarms, real time production, etc.), in addition to the historical production data.

Two communication ports available for each inverter (one for monitoring and one for plant controlling), allowing fast and simultaneous plant control.

PROTECTIONS

- DC Reverse polarity.
- Short-circuits and overloads at the output.
- Anti-islanding with automatic disconnection.
- Insulation failure DC.
- Up to 15 pairs of fuse-holders per power block.
- Lightning induced DC and AC surge arresters, type II.
- Motorized DC switch to automatically disconnect the inverter from the PV array.
- Low voltage ride-through capability.
- Motorized AC circuit breaker.
- Hardware protection via firmware.
- Additional protection for the power stack, as it is air-cooled by a closed loop.

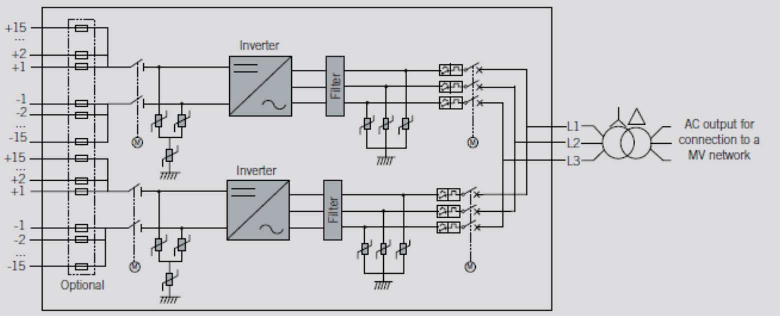
OPTIONAL ACCESSORIES

- Auxiliary services feeder.
- Grounding kit.
- Heating kit, for operating at an ambient temperature of down to -30 °C.
- DC surge arresters type I+II.
- DC fuses.
- Monitoring of the group currents at the DC input.
- PID prevention kit (PID: Potential Induced Degradation).
- Night time reactive power injection.
- Sand trap kit.
- Integrated DC combiner box.

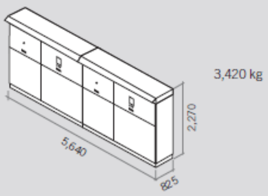
ADVANTAGES OF THE B SERIES

- Higher power density.
- Latest generation electronics.
- More efficient electronic protection.
- Night time supply to communicate with the inverter at night.
- Enhanced performance.
- Easier maintenance thanks to its new design and enclosure.
- Lightweight spares.
- It allows to ground the PV array.
- Components easily replaceable.

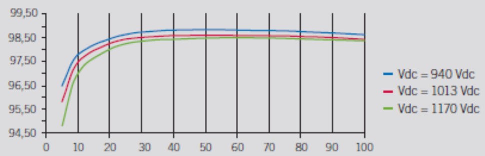
Power B Series



Size and weight (mm and kg)



Efficiency DUAL INGECON® SUN 1690TL B650



INGECON SUN Power Dual B Series 1,500 Vdc

	2340 kVA DUAL INGECON® SUN 1170TL B450	2800 kVA DUAL INGECON® SUN 1400TL B540	3000 kVA DUAL INGECON® SUN 1500TL B578	3120 kVA DUAL INGECON® SUN 1560TL B600	3200 kVA DUAL INGECON® SUN 1600TL B615
Input (DC)					
Recommended PV array power range[1]	2,314 - 3,040 kWp	2,778 - 3,648 kWp	2,974 - 3,904 kWp	3,086 - 4,054 kWp	3,164 - 4,154 kWp
Voltage Range MPP[2]	655 - 1,300 V	782 - 1,300 V	837 - 1,300 V	868 - 1,300 V	889 - 1,300 V
Maximum voltage[3]	1,500 V				
Maximum current	1,850 A per power block				
Nº inputs with fuse-holders	6 up to 15 per power block (up to 12 with the combiner box)				
Fuse dimensions	63 A / 1,500 V to 500 A / 1,500 V fuses (optional)				
Type of connection	Connection to copper bars				
Power blocks	2				
MPPT	2				
Input protections					
Overvoltage protections	Type II surge arresters (type I+II optional)				
DC switch	Motorized DC load break disconnect				
Other protections	Up to 15 pairs of DC fuses (optional) / Reverse polarity / Insulation failure monitoring / Anti-islanding protection / Emergency pushbutton				
Output (AC)					
Power IP54 @30 ºC / @50 ºC	2,338 kVA / 2,104 kVA	2,806 kVA / 2,525 kVA	3,004 kVA / 2,703 kVA	3,118 kVA / 2,806 kVA	3,196 kVA / 2,876 kVA
Current IP54 @30 ºC / @50 ºC	3,000 A / 2,700 A				
Power IP56 @27 ºC / @50 ºC[4]	2,338 kVA / 2,070 kVA	2,806 kVA / 2,484 kVA	3,004 kVA / 2,660 kVA	3,118 kVA / 2,760 kVA	3,196 kVA / 2,830 kVA
Current IP56 @27 ºC / @50 ºC[4]	3,000 A / 2,656 A				
Rated voltage[5]	450 V IT System	540 V IT System	578 V IT System	600 V IT System	615 V IT System
Frequency	50 / 60 Hz				
Power Factor[6]	1				
Power Factor adjustable	Yes. Smax=2,338 kVA	Yes. Smax=2,806 kVA	Yes. Smax=3,004 kVA	Yes. Smax=3,118 kVA	Yes. Smax=3,196 kVA
THD (Total Harmonic Distortion)[7]	<3%				
Output protections					
Overvoltage protections	Type II surge arresters				
AC breaker	Motorized AC circuit breaker with door control				
Anti-islanding protection	Yes, with automatic disconnection				
Other protections	AC short-circuits and overloads				
Features					
Operating efficiency	98.9%				
CEC	98.5%				
Max. consumption aux. services	9,400 W (50 A)				
Stand-by or night consumption[8]	< 180 W				
Average power consumption per day	4,000 W				
General Information					
PV inverters included	Two units of the INGECON® SUN 1170TL B450	Two units of the INGECON® SUN 1400 B450	Two units of the INGECON® SUN 1500TL B578	Two units of the INGECON® SUN 1560TL B600	Two units of the INGECON® SUN 1600TL B615
Ambient temperature	-20 ºC to +57 ºC				
Relative humidity (non-condensing)	0-100% (Outdoor)				
Protection class	IP54 (IP56 with the sand trap kit)				
Maximum altitude	4,500 m (for installations beyond 1,000 m, please contact Ingeteam's solar sales department)				
Cooling system	Air forced with temperature control (230 V phase+ neutral power supply)				
Air flow range	0 - 7,800 m^3/h per power block				
Average air flow	2 x 4,200 m^3/h				
Acoustic emission (100% / 50% load)	<66 dB(A) at 10m / <54.5 dB(A) at 10m				
Marking	CE				
EMC and security standards	EN 61000-6-1, EN 61000-6-2, EN 61000-6-4, EN 61000-3-11, EN 61000-3-12, EN 62109-1, EN 62109-2, IEC62103, EN 50178, FCC Part 15, AS3100				
Grid connection standards	IEC 62116, Arrêté 23-04-2008, CEI 0-16 Ed. III, Terna A68, G59/2, BDEW-Mittelspannungsrichtlinie:2011, P.O.12.3, South African Grid code (ver 2.6), Chilean Grid Code, Ecuadorian Grid Code, Peruan Grid code, Thailand PEA requirements, IEC61727, UNE 206007-1, ABNT NBR 16149, ABNT NBR 16150, IEEE 1547, IEEE1547.1, GGC&CGC China, DEWA (Dubai) Grid code, Jordan Grid Code				

Notes: [1] Depending on the type of installation and geographical location. Data for STC conditions [2] Vmpp.min is for rated conditions (Vac=1 p.u. and Power Factor=1) [3] Consider the voltage increase of the 'Voc' at low temperatures [4] With the sand trap kit [5] Other AC voltages and powers available upon request [6] For P_{out}>25% of the rated power [7] For P_{out}>25% of the rated power and voltage in accordance with IEC 61000-3-4 [8] Consumption from PV field when there is PV power available.

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INGECON SUN Power Dual B Series 1,500 Vdc

	3280 kVA DUAL INGECON® SUN 1640TL B630	3330 kVA DUAL INGECON® SUN 1665TL B640	3380 kVA DUAL INGECON® SUN 1690TL B650	3480 kVA DUAL INGECON® SUN 1740TL B670	3600 kVA DUAL INGECON® SUN 1800TL B690
Input (DC)					
Recommended PV array power range[1]	3,240 - 4,256 kWp	3,292 - 4,324 kWp	3,344 - 4,392 kWp	3,446 - 4,526 kWp	3,550 - 4,660 kWp
Voltage Range MPP[2]	911 - 1,300 V	925 - 1,300 V	939 - 1,300 V	968 - 1,300 V	996 - 1,300 V
Maximum voltage[3]	1,500 V				
Maximum current	1,850 A per power block				
Nº inputs with fuse-holders	6 up to 15 per power block (up to 12 with the combiner box)				
Fuse dimensions	63 A / 1,500 V to 500 A / 1,500 V fuses (optional)				
Type of connection	Connection to copper bars				
Power blocks	2				
MPPT	2				
Input protections					
Overvoltage protections	Type II surge arresters (type I+II optional)				
DC switch	Motorized DC load break disconnect				
Other protections	Up to 15 pairs of DC fuses (optional) / Reverse polarity / Insulation failure monitoring / Anti-islanding protection / Emergency pushbutton				
Output (AC)					
Power IP54 @30 ºC / @50 ºC	3,274 kVA / 2,946 kVA	3,326 kVA / 2,993 kVA	3,378 kVA / 3,040 kVA	3,482 kVA / 3,134 kVA	3,586 kVA / 3,226 kVA
Current IP54 @30 ºC / @50 ºC	3,000 A / 2,700 A				
Power IP56 @27ºC / @50ºC[4]	3,274 kVA / 2,898 kVA	3,326 kVA / 2,944 kVA	3,378 kVA / 2,990 kVA	3,482 kVA / 3,082 kVA	3,586 kVA / 3,174 kVA
Current IP56 @27ºC / @50ºC[4]	3,000 A / 2,656 A				
Rated voltage[5]	630 V IT System	640 V IT System	650 V IT System	670 V IT System	690 V IT System
Frequency	50 / 60 Hz				
Power Factor[6]	1				
Power Factor adjustable	Yes. Smax=3,274 kVA	Yes. Smax=3,326 kVA	Yes. Smax=3,378 kVA	Yes. Smax=3,482 kVA	Yes. Smax=3,589 kVA
THD (Total Harmonic Distortion)[7]	<3%				
Output protections					
Overvoltage protections	Type II surge arresters				
AC breaker	Motorized AC circuit breaker with door control				
Anti-islanding protection	Yes, with automatic disconnection				
Other protections	AC short-circuits and overloads				
Features					
Operating efficiency	98.9%				
CEC	98.5%				
Max. consumption aux. services	9,400 W (50 A)				
Stand-by or night consumption[8]	< 180 W				
Average power consumption per day	4,000 W				
General Information					
PV inverters included	Two units of the INGECON® SUN 1640TL B630	Two units of the INGECON® SUN 1665TL B640	Two units of the INGECON® SUN 1690TL B650	Two units of the INGECON® SUN 1740TL B670	Two units of the INGECON® SUN 1800TL B690
Ambient temperature	-20 ºC to +57 ºC				
Relative humidity (non-condensing)	0-100% (Outdoor)				
Protection class	IP54 (IP56 with the sand trap kit)				
Maximum altitude	4,500 m (for installations beyond 1,000 m, please contact Ingeteam's solar sales department)				
Cooling system	Air forced with temperature control (230 V phase+ neutral power supply)				
Air flow range	0 - 7,800 m³/h per power block				
Average air flow	2 x 4,200 m³/h				
Acoustic emission (100% / 50% load)	<66 dB(A) at 10m / <54.5 dB(A) at 10m				
Marking	CE				
EMC and security standards	EN 61000-6-1, EN 61000-6-2, EN 61000-6-4, EN 61000-3-11, EN 61000-3-12, EN 62109-1, EN 62109-2, IEC62103, EN 50178, FCC Part 15, AS3100				
Grid connection standards	IEC 62116, Arrêté 23-04-2008, CEI 0-16 Ed. III, Terna A68, G59/2, BDEW-Mittelspannungsrichtlinie:2011, P.O.12.3, South African Grid code (ver 2.6), Chilean Grid Code, Ecuadorian Grid Code, Peruan Grid code, Thailand PEA requirements, IEC61727, UNE 206007-1, ABNT NBR 16149, ABNT NBR 16150, IEEE 1547, IEEE1547.1, GGC&CGC China, DEWA (Dubai) Grid code, Jordan Grid Code				

Notes: [1] Depending on the type of installation and geographical location. Data for STC conditions [2] Vmpp.min is for rated conditions (Vac=1 p.u. and Power Factor=1) [3] Consider the voltage increase of the 'Voc' at low temperatures [4] With the sand trap kit [5] Other AC voltages and powers available upon request [6] For P_{out}>25% of the rated power [7] For P_{out}>25% of the rated power and voltage in accordance with IEC 61000-3-4 [8] Consumption from PV field when there is PV power available.

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6. Harmonic Filter

Filter 1 33kV 4.5MVar 4.5th C type Filter Bank

1.0	**GENERAL**	Unit	Puchaser	Vendor
1.1	Manufacturer	-	VTS	Eaton
1.2	Manufacturer Location	-	VTS	China
1.3	Design Standard	-	AS	IEC
1.4	Technical Specification	-	Manufacturer Standard	Manufacturers Standard
1.5	Design Life	Years	30	30
1.6	System Voltage	kV	33	33
1.7	Supply Frequency	Hz	50	50
1.8	No. of Phases	-	3	3
1.9	System Earthing Type	-	Impedance (1000A)	-
1.10	Auxiliary DC Voltage	V	110V	-
1.11	Auxiliary AC Voltage	V	400/230V	-
2.0	**ENVIRONMENTAL**			
2.1	Location	-	Outdoor	Outdoor
2.2	Altitude Above Sea Level	m	<1000m	<1000m
2.3	Seismic Condition	-	AS1170.4, Cat I	Noted
2.4	Highest Monthly average temperature	℃	32.3	Noted
2.5	Lowest Monthly average temperature	℃	4	Noted
2.6	Yearly average temperature	℃	17	Noted
2.7	Highest ambient temperature	℃	45.5	Noted
2.8	Lowest ambient temperature	℃	-3.2	Noted
2.9	Service wind speed to AS 1170.2	m/s	VTS	Noted
2.10	Ultimate wind sped to AS 1170.2	m/s	VTS	Noted
3.0	**HARMONIC FILTER 1**			
3.1	Connection Scheme		Ungrounded Double Star	Ungrounded Double Star
3.2	Rated Reactive Power	MVAr	4.5	4.5
3.3	Rated Current	In [A]	VTS	78.73
3.4	Rated Short Circuit Current (Symmetrical RMS)	kA/s	25/1s	Comply
3.5	Rated Short Circuit Peak Current	kA/s	40	Comply
3.6	Rated Short Time Power Frequency Withstand	kV	VTS	70kV
3.7	Rated Impulse Withstand Voltage	kV	VTS	170kV BIL
3.8	Resistor Maximum Voltage after discharge	V / min	75 / 10	75/10
3.9	Pollution Degree		Heavy (III), ~~25~~ 31 mm/kV	31mm/kV
3.10	Total kW losses	kW	VTS	3.7
3.11	Incomer Power cable	qty / size	1C 630mm2 per phase	Comply
3.12	Colour External		Manufacturer Standard	RAL7035
3.13	Paint Specification		Manufacturer Standard	Total Thickness 80-120um
3.14	Bird Caps	Y/N	Included	NO
3.15				
3.16	**Capacitors:**			
3.17	Model / Type	Note 2	VTS	EX-7Li
3.18	Rated Capacitance	µF	VTS	C1: 126.5 C2: 19.73
3.19	Rated Voltage	kV	VTS	C1:1.269 C2: 1.035
3.20	Rated Current	A	VTS	C1: 50.43 C2: 62.2:
3.21	Short Term Over Voltage Capacity	%Vn / mins	VTS	
3.22	Short Term Over Current Capacity	%In / hrs	VTS	
3.23	Long Term Continuous Over Voltage Capacity	%Vn / mins	VTS	110%

3.24	Long Term Continuous Over Current Capacity	%In / hrs	VTS	130%
3.25	Manufacturing / Design Tolerance	unit % / bank %	VTS	±5%
3.26	**Reactors:**			
3.27	Model / Type	Note 2	VTS	CKGKL-33-90.73A, 40.02mH
3.28	Rated Inductance	mH	VTS	40.02
3.29	Rated Resistance	Ohm	VTS	0.123
3.30	Rated Current	A	VTS	90.73
3.31	Short Term Over Voltage Capacity	%Vn / mins	VTS	TBC
3.32	Short Term Over Current Capacity	%In / hrs	VTS	1.515kA/2s
3.33	Long Term Continuous Over Voltage Capacity	%Vn / mins	VTS	110%
3.34	Long Term Continuous Over Current Capacity	%In / hrs	VTS	135%
3.35	Tapping Range		NA	TBC
3.36	Manufacturing / Design Tolerance	rated % / phase to phase	VTS	0-+5%
3.37	**Resistors:**			
3.38	Model / Type	Note 2	VTS	FRA 33-2X100/2X43
3.39	Rated Resistance	Ohm	VTS	100ΩX2
3.40	Rated Current	A	VTS	20.73AX2
3.41	Short Term Over Voltage Capacity	%Vn / mins	VTS	4637V/10S
3.42	Short Term Over Current Capacity	%Pn / hrs	VTS	46.37A/10S
3.43	Long Term Continuous Over Voltage Capacity	%Vn / mins	VTS	2280V
3.44	Long Term Continuous Over Current Capacity	%Pn / hrs	VTS	22.80A
3.45	Manufacturing / Design Tolerance	rated % / phase to phase	VTS	±5%
3.46	Tapping Range		NA	TBC
3.47	**Protection:**			
3.48	Protection relay - Model	-	By Others	
3.49	Protection CT Manufacturer	-	VTS	
3.50	Protection CT Burden \ Class \ Ratio	-	VTS	
3.51	Undercurrent protection	Y/N	By Others	
3.52	Thermal Overload protection	Y/N	NO	
3.53	Undervoltage / Overvoltage	Y/N	By Others	
3.54	Capacitor Unbalance Current	Y/N	YES	
3.55	Capacitor Internal Fuses	Y/N	YES	
3.56	Surge arrestors	Y/N	Provide as Option	
	NOTES			
	1. Vendor to complete all empty fields or where noted as "VTS" (Vendor to State)			
	2. Vendor to supply product brochure with Tender			
	Abbreviations			
	NA = Not Applicable			
	VTS = Vendor to State			
	TBC = To be Confirmed			

ANNEX III: COMMERCIAL PROPOSAL

Commercial Proposal

EPC Price

The EPC price proposed for **the studied solar plant of 3,153 MW$_{DC}$** is the following:

	EUR	USD	AUD	Total AUD equivalent	AUDeq/ Wdc
Balance of System (BOS)					
The Balance of System includes the prices for: Design & Preliminary Studies Civil Works Mechanical Works -incl. Piles- Start Up & Commissioning Electrical Package Meteorological Stations Security System Logistics Project and financial management costs **These features are out of the scope of the project, consequently, an average value of 0,5 AUDeq/Wdc will be used for the BOS**					
TOTAL BOS PRICE			**1.576.875**	**1.576.875**	**0,50**

MAIN EQUIPMENT					
PV Modules	0	662.287,5	0	973.952,21	0,309
Power Conversion Station/Skid (Inversor + Transformer)	0	0	275.000	275.000	0,087
Structure	246.500	0	0	404.098,36	0,128
Lithium-Ion 0,5MW/0,25MWh Battery	0	0	175.000	175.000	0,0555
TOTAL EPC PRICE W/O SUBSTATION	**246.500**	**662.287,5**	**2.026.875**	**3.404.925,57**	**1,079**

INTERCONNECTION					
Interconnection (Switch Gear and Harmonic Filter)	0	0	200.000	200.000	0,0634
TOTAL EPC PRICE W/O SUBSTATION	**246.500**	**662.287,5**	**2.051.875**	**3.604.925,57**	**1,1431**

BREAKDOWN OF PRICES

PV Modules: 0,21 USD/Wp

Inverter: 275.000 AUD

Tracker (Structure): 34 EUR/PV Module

FX Rates as shown below:

1 EUR = 0,61 AUD
1 USD = 0,68 AUD

All prices shown are excluding GST (GST in Australia is usually 10%)