**FEDERAL UNIVERSITY OF ITAJUBA**
**Post-Graduation Program**
**In Energy Engineering**

# ANALYSIS OF HIGH DC/AC RATIOS FOR PV PLANTS WITH BESS INTEGRATION ON THE DC SIDE

Douglas Piazza Meneghel

Itajuba, July 2019

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Dissertation submitted to the Post-Graduation Program in Energy Engineering as part of the requirements for obtaining the Title of Master of Science in Energy Engineering.

Area of Study: Energy Systems

Advisor: Edson da Costa Bortoni, Ph.D.

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Dissertation approved by the board of examiners on July 30th, 2019, conferring to the author the title of Title of Master of Science in Energy Engineering.

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To my wife Vanessa, my life partner, that supported me during this challenging endeavor and my son Paulo that is always inspiring me with his passion and resolution towards life.

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I definitely did not anticipate that being a student, while being a parent, husband and professional, would be this tough. Lessons learned is definitely not a buzzword and despite the unquenchable desire to take on the next challenge, it will not be before a decent hiatus.

Finally, I thank to God, for letting me through the difficulties and his everlasting love.

# ABSTRACT

The integration of Photovoltaic and Battery Energy System (PV-BESS) has absorbed a lot of attentions in recent years within the renewable energy communities. The solar industry has shown significant interests in combining storage with solar installations as grid integration benefits have increased and at the same time the cost of storage system has decreased. Driven by best returns, variability of resources, solar module degradation and the best usage of inverters and medium voltage systems and step-up substation, the power conversion units, set of inverters and low voltage to medium voltage transformers, are usually rated for AC power values lower than those installed on their DC side for utility scale solar plants. This dissertation demonstrates that by boosting the DC/AC ratio of the PV plant, it would be feasible to improve the controllability of the solar generation and the project economics with integration of proper BESS size in the system. Data analysis on DC/AC ratio for PV plant with DC-Side BESS integration will be provided to demonstrate the typical price break down with the cost-benefit analyses based on financial evaluation metrics, for the economic assessment of PV plants subject to strong variation when applied to BESS assessment. Another advantage of the proposed system is to increase the amount of energy available in the hybrid plant, only by boosting its DC/AC ratio, keeping the whole AC system (i.e. cables, main power transformers, transmission lines) essentially the same. That solely might present a good advantage over the typical BESS applications which essentially only arbitrates AC energy already available in the system. In addition, the economic benefits that can be realized from a BESS depend on the application, the size of the PV system, the sophistication of the system's control equipment, the customer's rate structure and the operating costs. This work covers the literature review necessary to stablish the basis of the reasoning for further development of a methodology to determine the energy flow between the solar modules and the battery system, as well as the analysis of the financial indicator that serve to gauge the feasibility of an investment.

**KEYWORDS:**

DC/AC Ratio, Photovoltaic (PV), Battery Energy Storage System (BESS), Renewables

# RESUMO

A integração do sistema de energia fotovoltaica e de bateria (PV-BESS) absorveu muitas atenções nos últimos anos nas comunidades de energia renovável. A indústria solar demonstrou interesse significativo em combinar armazenamento com instalações solares, pois os benefícios da integração à rede aumentaram e, ao mesmo tempo, o custo do sistema de armazenamento diminuiu. Impulsionadas pelos melhores retornos, variabilidade de recursos, degradação de módulos solares e o melhor uso de inversores e sistemas de média tensão e subestação de subida, as unidades de conversão de energia, conjunto de inversores e transformadores de baixa e média tensão, geralmente são classificadas para energia CA valores inferiores aos instalados no lado CC para usinas solares em escala de utilidade. Esta dissertação demonstra que, ao aumentar a relação CC / CA da usina fotovoltaica, seria possível melhorar a controlabilidade da geração solar e a economia do projeto com a integração do tamanho BESS adequado no sistema. A análise de dados sobre a razão CC / CA para usina fotovoltaica com integração BESS no lado DC será fornecida para demonstrar a quebra de preço típica com as análises de custo-benefício baseadas em métricas de avaliação financeira, para a avaliação econômica de usinas fotovoltaicas sujeitas a forte variação quando aplicada à avaliação do BESS. Outra vantagem do sistema proposto é aumentar a quantidade de energia disponível na planta híbrida, apenas aumentando sua relação CC / CA, mantendo todo o sistema CA (ou seja, cabos, principais transformadores de energia, linhas de transmissão) essencialmente o mesmo. Isso apenas pode apresentar uma boa vantagem sobre as aplicações típicas do BESS, que essencialmente apenas arbitram a energia CA já disponível no sistema. Além disso, os benefícios econômicos que podem ser obtidos a partir de um BESS dependem da aplicação, do tamanho do sistema fotovoltaico, da sofisticação do equipamento de controle do sistema, da estrutura de taxas do cliente e dos custos operacionais. Este trabalho abrange a revisão de literatura necessária para estabelecer as bases do raciocínio para o desenvolvimento de uma metodologia para determinar o fluxo de energia entre os módulos solares e o sistema de bateria, bem como a análise do indicador financeiro que serve para medir a viabilidade de um investimento.

**PALAVRAS CHAVE:**

Relação DC/AC, Fotovoltaicos (PV), Armazenamento de energia, Baterias (BESS), Renováveis.

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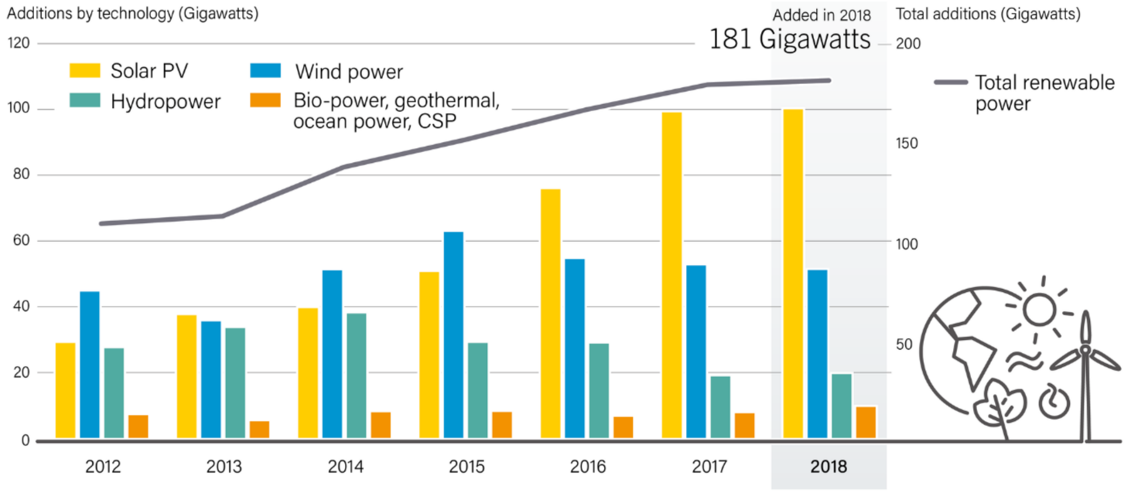
| | |
|---|---|
| AC | Alternate Current |
| BESS | Battery Energy Storage System |
| CAES | Compressed Air Energy Storage |
| CAGR | Compound Annual Growth Rate |
| CAPEX | Capital Expenditure |
| DC | Direct Current |
| ESS | Energy Storage System |
| FESS | Flywheels Energy Storage System |
| FRT | Frequency Ride Through |
| HESS | Hydrogen Energy Storage System |
| IRR | Internal Rate of Return |
| ISO | Independent System Operator |
| MPPT | Maximum Power Point Tracker |
| NPV | Net Present Value |
| OPEX | Operational Expenditure |
| PPA | Power Purchase Agreements |
| PV | Photovoltaic |
| VRT | Voltage Ride Through |

# SUMMARY

# 1 INTRODUCTION

The integration of Photovoltaic-Battery Energy System (PV-BESS) has absorbed a lot of attentions in recent years within the renewable energy communities [1]. The power generation based on renewable resources such as solar (or wind) can be very effective in reducing the carbon dioxide emissions and zero waste byproduct due to generation type, so there is minimal impact on the environment relative to the traditional generation plants. However, one of the fundamental limiting factors for these renewable plants is the stochastic nature due to their source of energy. Because of the need for the generation and load of the electric grid to be exactly synchronized, the loss of renewable power shall be mitigated elsewhere by more traditional methods.

The Figure 1 shows the 2018 additions of renewable power capacity [2], by technology and total and how solar PV exceeds the other technologies by far, in terms of new additions in 2016, 2017 and 2018.



Note: Solar PV capacity data are provided in direct current (DC).

Figure 1 – Annual additions of renewable power capacity, 2012-2018

The sole renewable energy is a variable resource of energy, depending on the environment and it cannot be dispatched, unlike conventional generation plant. The solar industry has shown significant interest in combining storage with solar installations as grid integration benefits have increased and at the same time the cost of storage system have decreased.

Several research works has been performed on intermittency of PV technology which is due to the output power reduction caused by the environment (i.e. the movement of clouds over PV modules), as well as its typical lack of production during the night period. This intermittency causes most of the downside effects, such as voltage variation, fluctuation of active and reactive power, potential voltage and frequency variation, etc.

One of the approaches is to utilize a BESS to be able to control the power flow flexibly, which could facilitate increased penetration of PV systems by minimizing their intermittency [3]. Although the cost and limited service life of the batteries continues to restrict their mainstream implementation, these factors are changing recently because of lowering costs of battery technology from new chemical compositions, as well as improvement in existing compositions with PV plants. In integrated systems design considerations can help the system to be more cost-effective, reliable, and efficient [4]. The BESS control algorithm for power and energy in PV application and energy shift has been also covered on literature [5].

## 1.1. JUSTIFICATION

The motivation of this dissertation is to start to assess battery energy storage systems in a hybrid or integrated with renewables context, on the Federal University of Itajuba. The dissertation is justified by its academic contribution to the development of the study of battery energy systems co-located with renewable resources, its application to the electrical systems by means of energy arbitrage and other grid services and also as a tool that would allow the diffusion of such knowledge.

## 1.2. METHODOLOGY

This research started from analyzing benefits of integrating storage systems into solar PV systems in order to optimize the usage of the energy generate into the solar panels, reducing losses originated by the clipping effect and was later expanded to discuss what are the benefits of having the intermittency of renewable resources mitigated. This dissertation is relevant, since the use of storage systems, how to tap into the expected benefits and integration to renewable systems have been receiving a lot of attention globally, with differences in scale of application and maturity. Countries such as Australia, Germany and the United Kingdom, together with some ISO’s in the United States have been receiving a lot of attention due to its most active and transparent market for energy storage [6].

Once the problem is defined, a robust literature review is required, considering the objectives of study, covering the following items: PV power plants, characteristics of energy storage system, focusing on battery storage system, grid services and benefits that storage systems can provide to the grid and photovoltaic generation.

Once the theoretical bases are covered, the reasoning for the problem is presented, which is the technical and economical assessment of a BESS coupled with a solar PV inverter, given a certain DC/AC ratio, with various battery sizes, coupled directly on the direct current (DC) buss of a bidirectional inverter. The various battery sizes will be considered in order to test the system in various regularization conditions.

This dissertation is divided in five chapters. The chapter two presents a literature review about the solar generation and utility scale projects, energy storage systems and its main technologies, grid services provides by energy storage systems and BESS (battery energy based storage systems) and it coupling with solar PV plants.

The third chapter describes the methodology used for the proposed case study, discussing energy estimation, how to determine that energy available in the systems that can be used for charging the batteries, discharging curves and projects returns.

The fourth chapter presents a case study of a utility scale solar plant, applying the methodology described on the Chapter 3, using a high DC-AC ratio and battery sizes, evaluating economically the addition of the storage system and also showing how a new energy profile can be created with the addition of the BESS. CAPEX numbers and project's returns will consider market conditions described on the literature review and marketing scouting, compared against estimated discount rates. The other technical benefits will be already covered on the literature review.

The conclusions and contributions for future works are presented on the Chapter 5.

## 1.3. OBJECTIVES

The sections 1.3.1 and 1.3.2 present, respectively, the general and specific objectives of this dissertation.

### 1.3.1. GENERAL

The aim of this dissertation is to analyze the benefits of a solar PV battery energy storage system, DC coupled, it's technical and economic aspects. By integrating with energy storage on the DC side, the combination of PV and BESS enhances their usability and improves the economic values. This will be achieved by analyzing the increase of the amount of energy to be processed with the same AC system (inverters, cables, step-up transformers, transmission lines) and increasing the revenues provided by this energy, by means of battery energy storage system coupled in the DC buss of the solar inverters.

## 1.3.2. SPECIFIC

The first objective of this work is to expand and deepen our understanding of what is the possibility in terms of the mitigation of variability in PV plant generation though the battery storage. In doing so, this work provides a comprehensive survey that presents the methodology and some of the common definitions with PV and BESS technologies. In addition, the past work and the literature survey of the combined technology of PV plant and battery energy storage system is covered.

This dissertation also investigates some of the major design factors in PV plant, DC to AC ratio for the inverter. The optimal inverter sizing has direct relation with economics of the project and need to be taken into account during the plant design phase [7]. One key factor of the studies is the "clipping loss", when the DC power feeding an inverter is more than the inverter can handle, the resulting power is "clipped" and lost. This work investigates the advantage of adding the BESS to the common DC bus of the power conversion unit, now this energy can be stored into to the batteries.

Second objective of this dissertation is to focus on important factor of increment the amount of energy available in the hybrid plant, only by boosting its DC/AC ratio, keeping the whole AC system (i.e. cables, main power transformers, transmission lines) essentially the same. That solely might present a good advantage over the typical BESS applications which essentially only arbitrage AC energy already available in the system [1].

With advancement in PV plants and the cheaper solar modules, it is possible to create a cost-effective project by adding more modules to the array and benefit from the gains in energy production during peak loads, even reducing clipping losses to nearly zero. Therefore, the focus is on the high increment of DC/AC ratios when the value of solar energy is high.

Third objective of this work focuses on the combination of PV and BESS that can enhance their usability and improve the economic values. This will be achieved by increasing the amount of energy to be processed with the same AC system (inverters, cables, step-up transformers, transmission lines) and increasing the revenues provided by this energy. Needless to say that this task is not possible with a sole PV system [8], [9]. A trade-off is stablished considering the optimal size of the battery energy of the storage system that includes the cost and the flatten output power generation. In addition, the benefits that can be realized from a BESS depend on the application, the size of the PV system, the sophistication of the system’s control equipment, the customer’s rate structure and the operating costs [10]. The economic benefits that can be realized from a BESS depend on the application, the size of the system, the sophistication of the system’s electronic control equipment, the operating cost [11].

# 2 LITERATURE REVIEW

This literature review will cover mains aspects of solar generation, focused on photovoltaic technology, application in utility scale and related components. The same will be done for Energy Storage Systems (ESS), focused on battery energy systems, their typical components and services and benefits provided to the electrical grid and the possibility of integrating is with solar PV plants.

## 2.1. SOLAR GENERATION

As electricity demand increases, with supply depending largely on conventional power plants, there is a growing concern with regards to carbon dioxide emissions in the environment. Renewable energy generation such as the technologies powered by the sun and wind, in particular, has absorbed a lot attention in the last decade. The challenge is on how to optimally harnessing the energy from these renewable as to meet demand. Solar energy can be captured for electricity production using:

1. Solar or photovoltaic (PV) cell, which converts sunlight into electricity using the photoelectric effect. Typically, photovoltaics are found on the residential and commercial scales. Additionally, utilities have constructed large photovoltaic facilities that require anywhere from 2 to 5.2 hectares per MW, depending on the technologies used and terrain limitations.
2. Concentrating solar power, which uses lenses or mirrors to concentrate sunlight into a narrow beam that heats a fluid, producing steam to drive a turbine that generates electricity. Concentrating solar power projects are larger-scale than residential or commercial PV and are often owned and operated by electric utilities.

The focus of this dissertation is on solar power plant, in particular the PV technology [12]. According to Center for Climate and Energy Solution [13], renewable energy is the fastest-growing energy source in the United States, increasing 67 percent from 2000 to 2016. Renewables made up nearly 15 percent of net U.S. electricity generation in 2016. Solar generation is projected to climb from 7 percent of total U.S. renewable generation in 2015 to about 36 percent by 2050, making it the fastest-growing electricity source. Globally, renewables made up 24 percent of electricity generation in 2014. For 2016, Renewables made up nearly 15 percent of electricity generation, with hydro, wind, and biomass making up the majority. That’s expected to rise to 25 percent by 2030. Most of the increase is expected to come from wind and solar. Non-hydro renewables have increased their share of electric power generation from less than 1 percent in 2005 to nearly 7 percent at the end of 2016 while demand for electricity has remained relatively stable.

However, the variability of renewable energy does not correspond with most demand and requires supplement. Therefore, there are still some issues in maintaining the reliability and economic viability of the renewable plant that solely depend on the solar or wind. These issues can be summarized as following:

- The maximum power output of a renewable plant fluctuates according to the real-time availability of sunlight (or wind).
- Fluctuations can be forecasted only a few hours to days in advance, but not for long-term.
- Solar plants use devices known as power converter units (PCUs) in order to connect to the grid. The stability of the grid shall be preserved in accordance with these power electronic devices.
- PV plants are modular and can be deployed in a much more distributed fashion. Simply the PV panels are joined together to form strings. Similarly strings of modules form the solar field.
- Availability of sunlight and resources might be away from the load center, and while renewable energy resources are available in many areas, the best resources are frequently located at a distance from load. Therefore it might require the increasing connection costs of transmission lines.

Figure 2 shows the relative availability of solar energy resources throughout the United States, the results are obtained from DOE National Renewable Energy Laboratory [14].

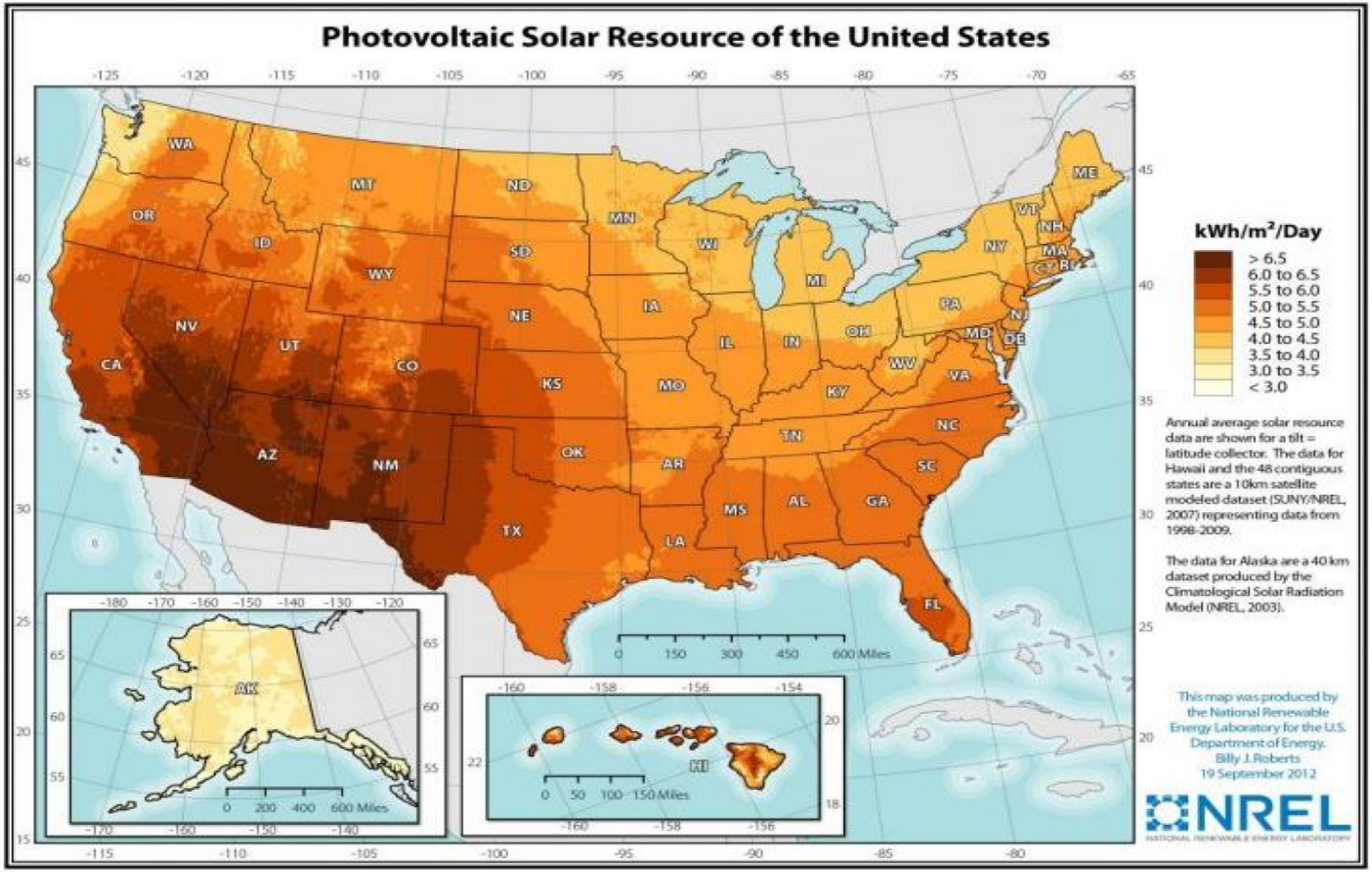


Figure 2 – US PV Solar Resources of the United Stated

The focus here is on adequacy of energy supply long-term and also the environmental implications of particular sources. Electricity demand is for continuous, reliable supply that has traditionally been provided by conventional power plants. Some is for shorter-term (as an example peak-load) requirements on a predictable basis. Therefore, if renewable sources are connected to an electric grid, the concern of back-up capacity arises, which is one of the objective of this dissertation in presenting the storage system and to be surveyed completely.

PV power generation systems are rated in peak kilowatt (kWp). This is the amount of electrical power that a new, clean system is expected to deliver when the sunlight is directly overhead on a clear day. It can be assumed that the actual output might not quite reach this value. The system output will be compromised by atmospheric conditions, dust on the collector panels, and deterioration of the components, etc. As an example, a serious grid integration problem with solar PV is that cloud cover can reduce the output of a typical solar plant by 70% in the time span of almost one minute. In addition, when comparing the PV generation system to conventional power generations, one should note that the PV systems are productive on day-time [15]. Therefore, energy storage - battery and other means are being developed to slow this to 10% per minute, which is more manageable.

In this survey there are two indices that are commonly used for the economical assessment of the renewable plants [16]. The first one is the levelized cost of electricity (LCOE). LCOE is used to indicate the average cost per unit of electricity generated, allowing for the recovery of all costs over the lifetime of the plant. It includes capital, financing, operation and maintenance, fuel (if any), and decommissioning. The second index is energy return on energy invested (EROI). EROI is the ratio of the energy delivered by a process to the energy used directly and indirectly in that process, and is part of lifecycle analysis.

According to International Renewable Energy Agency (IRENA) in 2012, the installed PV world capacity reached the 100 GW milestones, with 30.5 GW installed that year, and it reached 291 GW at the end of 2016. Utility-scale solar PV achieved a global weighted average LCOE of about $135/MWh ( 13.5 c/kWh) for projects completed in 2015 [17].

### 2.1.1. UTILITY SCALE SOLAR POWER PLANTS

The development of solar power plant has risen sharply in recent years. PV systems are considered to be one of the most efficient renewable energy resources (RESs) that are sustainable with no pollutant or carbon foot print. To be more precise the only emissions associated with PV systems are those from the production of its components. After their installation they generate electricity from the solar irradiation without any pollutant. Most of the PV power generation comes from grid-connected installations, where the power is fed in the electricity network, which is the major focus of this section. In fact, it is a growing business in developed countries. Due to the ease of design and installation, PV systems are widely applied in many countries. China, Japan, USA, Germany, Spain and United Kingdom are the leading countries in applying PV technologies. They include 80% of PV global installation. The bulk of added installed capacity during the 2014 was created by China with amount of 10.6 GW [18].

PV plant encompasses several components that are integrated together to generate the power. These components are selected depending on the site location, system type, and applications. PV systems contain a large amount of supporting equipment as well, which serves to balance the system and to make it sustainably operational. The extra components include wiring, controllers, trackers, mounting hardware, inverters, and grid connections. The schematic of utility scale PV plant, coupled with a battery energy storage system, is shown in Figure 3:

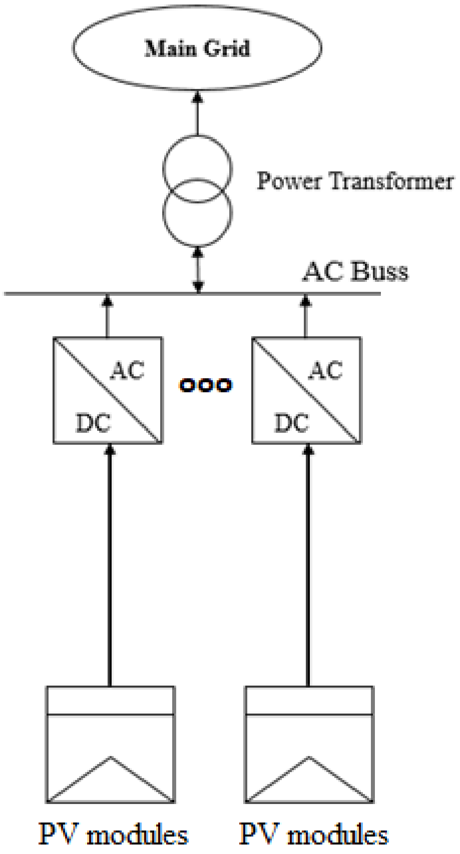


Figure 3 – Utility Scale PV Plant Components

- PV modules and Array- they are environmentally-sealed collection of PV cells which convert sunlight to electric energy. The most common PV cell size varies from 0.5 to 2.5 square meter. Normally bigger PV cells are used for the larger system. They are mostly made of silicon even though other materials are also used. Solar cells are able to convert electromagnetic radiation directly into electrical current. The charged particles generated by the incident radiation are separated conveniently to create an electrical current by an appropriate design of the structure of the solar cell [19]. Solar cells prices have decreased considerably during the last couple of years due to new developments in the film technology and the manufacturing process [20]. The PV array has to be operated at its highest conversion efficiency by continuously utilizing the maximum available output of the array. The electrical system powered by solar cells requires special design considerations because of the varying nature of the solar power generated resulting from unpredictable changes in weather conditions which affect the solar radiation level as well as the cell operating temperature.
- PV systems are typically modular in design, so that additional sections can be added to the plant or removed for repairs without significant disruption of its infrastructure. The energy flow at the PV plant runs through a variety of devices, which are connected by wire network and related hardware. This support infrastructure is often referred to as balance of system (BOS). The quality of the BOS is important for providing lasting and efficient operation. The industry goal is to provide PV systems with operational lifetime of at least 25 years [20], [21]. The important parts of BOS are mounting system and wiring system. Ground-fault protection is also included in the wiring system. It is responsible for the regulating the voltage and current coming from PV Panels and helps battery from overcharging and prolongs battery life.
- Charge controllers or regulators manage the flow of electricity between the solar arrays, energy storage, and loads. The standalone survey for the Battery Energy Storage System will be covered in next Section. In brief, the charge control algorithm and charging currents need to be matched for the batteries in the system. The main purpose of a charge controller is to prevent overcharging or excessive discharging and protect from damages. Typically, these devices operate in the switch on / switch off mode. The basic concept of feedback control loop is applied to the terminal voltages supplied from a PV system to the battery. If the measured voltage of supplied increases above a certain threshold value, the switch disconnects the PV array. The array is connected again when the terminal voltage drops below a certain limit. This cycle protects the battery from overcharging. Similarly,

charge controllers are used to prevent battery excessive discharging. When the current of the load connected to the battery is higher than the current delivered by the PV array, the load is disconnected as the terminal voltage falls below Vmin-off and is connected again when the terminal voltage increases above a certain threshold Vmin-on. Charge controllers also participate in voltage conversion and maximum power tracking [22], [23].

- Inverter- DC power coming from PV array is transformed to AC by the inverter. As with all power system components, the use of inverters results in energy losses due to interferences. Typical efficiency of an inverter well matched to the array is approximately 90%. Inverters are key components in both grid-connected and distributed power applications and usually are significant part of system cost. The AC current produced by inverters can have square, modified sine, and pure sine wave output. Needless to say that pure sine is high cost and has the best power quality. Inverters are common sources of electromagnetic noise, which can interfere with sound and video equipment. So, the inverters boxes must be grounded according to the National Electric Code (NEC) code requirement and safety reasons [24]. Most AC grid-ties inverters have anti-islanding feature, so the inverter will reduce power to zero within 2 seconds of the grid shut-down [25].

There are several factors in PV plant that can affect the efficiency of the whole system. The main factors are: the efficiency of the PV panel, the efficiency of the inverter and converters, and the efficiency of the maximum power point tracking algorithm. The more depth survey and analysis is provided in future section.

There are several factors in PV plant that can affect the efficiency of the whole system. The main factors are: the efficiency of the PV panel, the efficiency of the inverter and converters, and the efficiency of the maximum power point tracking algorithm.

The oversizing of the installed direct current capacity, by means of increasing the quantity of solar modules installed in the series and parallels of the project is integral part of the design and it allow a better usage of the AC components of the size, increases the amount of energy production that can be injected into the electrical grid, by an additional cost that is compensated by the added benefits, boosting project returns. It also factors the module degradation over the years. The Figure 4  shows what happens with the production during a power limiting day, i.e. when the energy available offsets the inverter’s capacity of processing that energy, of an oversized DC power plant. Figure 5 shows what happen with the production of a non-power limiting day.

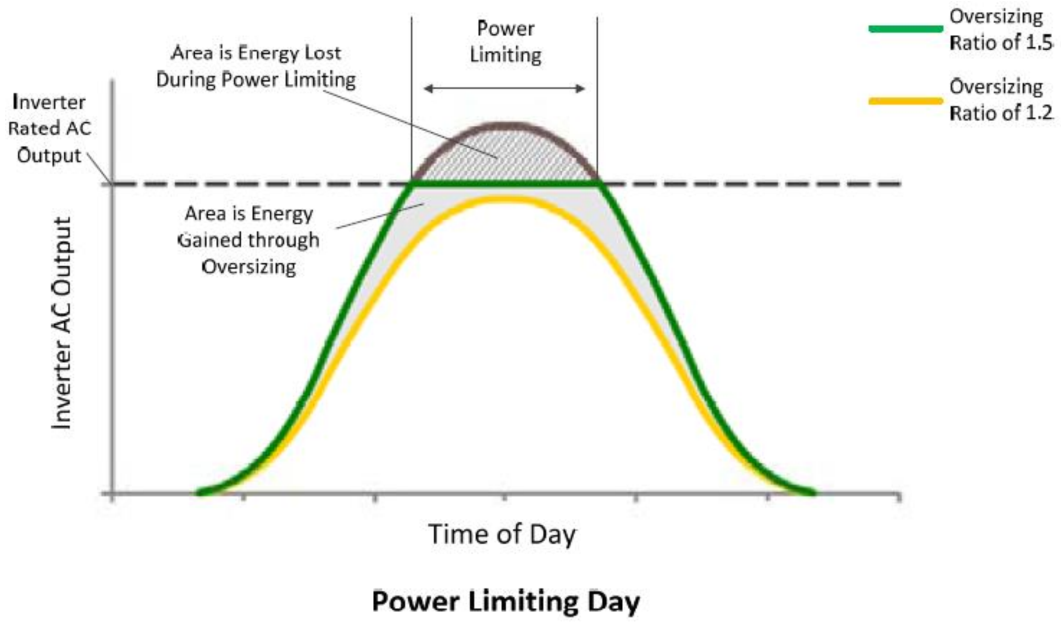


Figure 4 – Daily Production Profile Power Limiting Day

[26]

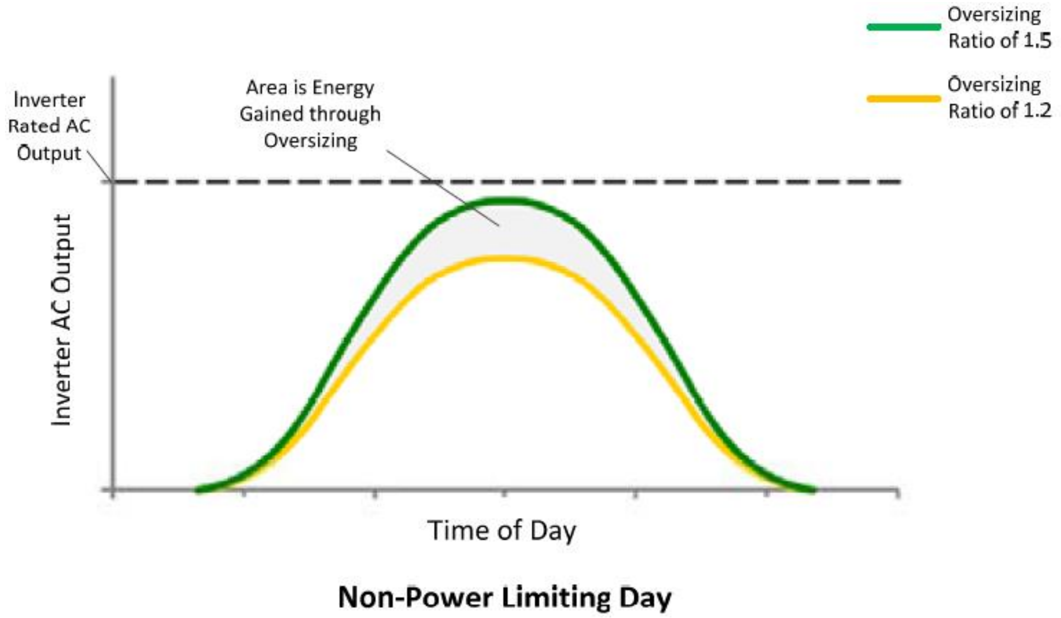


Figure 5 – Daily Production Profile Non-Power Limiting Day

[26]

During power limiting, when the solar arrays are producing more power than the inverters is able to process, the maximum power point tracker of the inverter, controls the input power of the array, by changing the voltage operating point to a higher voltage and lower current, along the array's current-voltage (I-V) curve, reducing its power output. This is shown in the Figure 6.

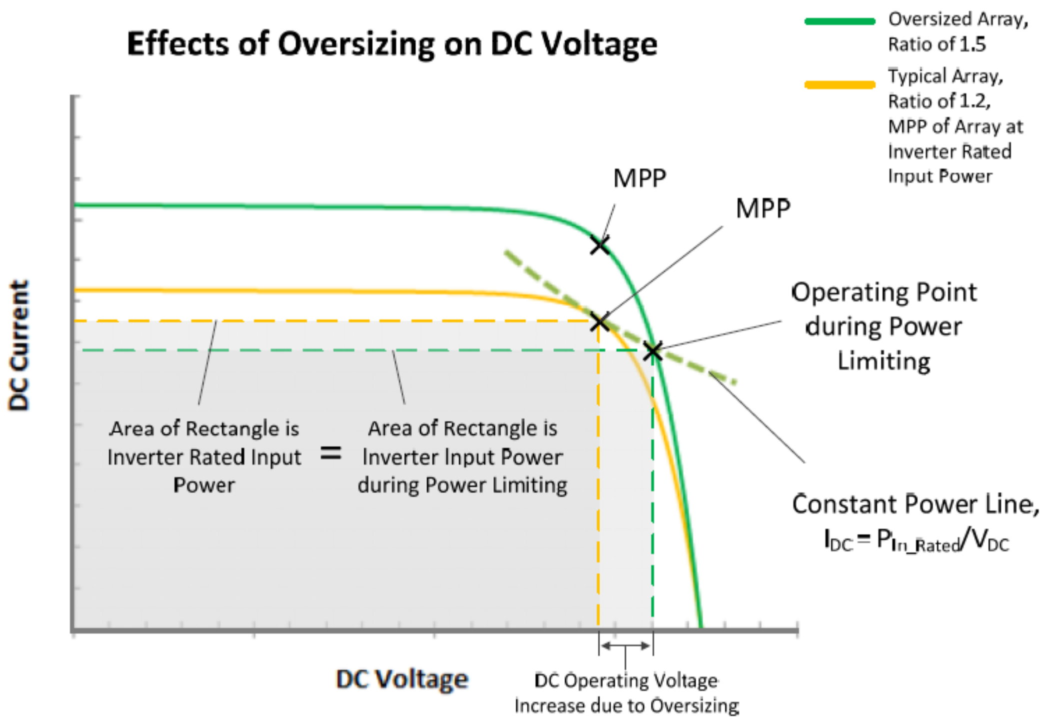


Figure 6 – Array I-V Curves and Operating Points of Typical and Oversized Arrays [26]

## 2.1.2. DUCK CURVE AND MITIGATION STRATEGY

As indicated in previous section the PV plants (and wind farms) are intermittent generation resources, and depending on their size and geographical locations their production is not tied or responsive to load consumption. Therefore, the increasing penetration of solar/wind creates a set of challenges for utility and power system operators with primary concern of continuous matching of the supply and demand of electricity. Utilities and system operators also require preserving the stability of the grid throughout their service territory. To clarify the issue, traditionally the rise and fall of the load was met via a combination of baseload power generation from coal fired or nuclear power plants and fast peaking plants or dis-patchable power from hydroelectric dams. But the addition of solar/wind power to the energy mix has altered the regular norm. As an example, wind often blows most steadily in the middle of the night when demand is at its minimum. In areas where there are a large number of wind farms, deliverable wind power can at times be greater than the total demand. Solar power can be more predictable than win on sunny days, the sun shines most strongly in the middle of the da but it creates its own challenges to the load curve. Solar power generation ramps up in the morning and stays constant until mid-afternoon before fading for the last few hours before sunset. Unfortunately, that diminishing power supply corresponds with the rising load in the late afternoon, meaning the net load – the difference between electricity demand and the portion met by solar power – rises even faster than the actual load. That means peaking power has to be added, with the fast rate.

In brief, the high levels of mid-day solar generation reduce net load on the system dramatically during sunlight hours and forcing many generators off-line. As the sun sets, a steep net load ramp occurs, requiring flexible generation assets to quickly return online to meet the evening load peak. High cost Peaker power plants and other In-efficient thermal-based generating units are dispatched to respond to this ramp. This phenomenon is well-documented in the case of the California Independent System Operator (CAISO) and known as "duck curve" phenomenon that described with the belly of the duck characterizing the low net load period during the sunlight hours, and the neck of the duck as the net load ramp toward the evening peak [27], [28].

With increasing solar plant installations comes not only the risk of negative net load in the middle of the day, but also a significant ramp to meet the system's evening peak. This can also create the additional challenge of straining a utility's grid infrastructure, presenting undesirable grid operating conditions [29]. Figure 7 shows the Duck Curve phenomena, the California Independent System Operator (CAISO) forecasting what would happen to the shape of hourly net electricity demand under high solar photovoltaic (PV) penetration scenarios [28].

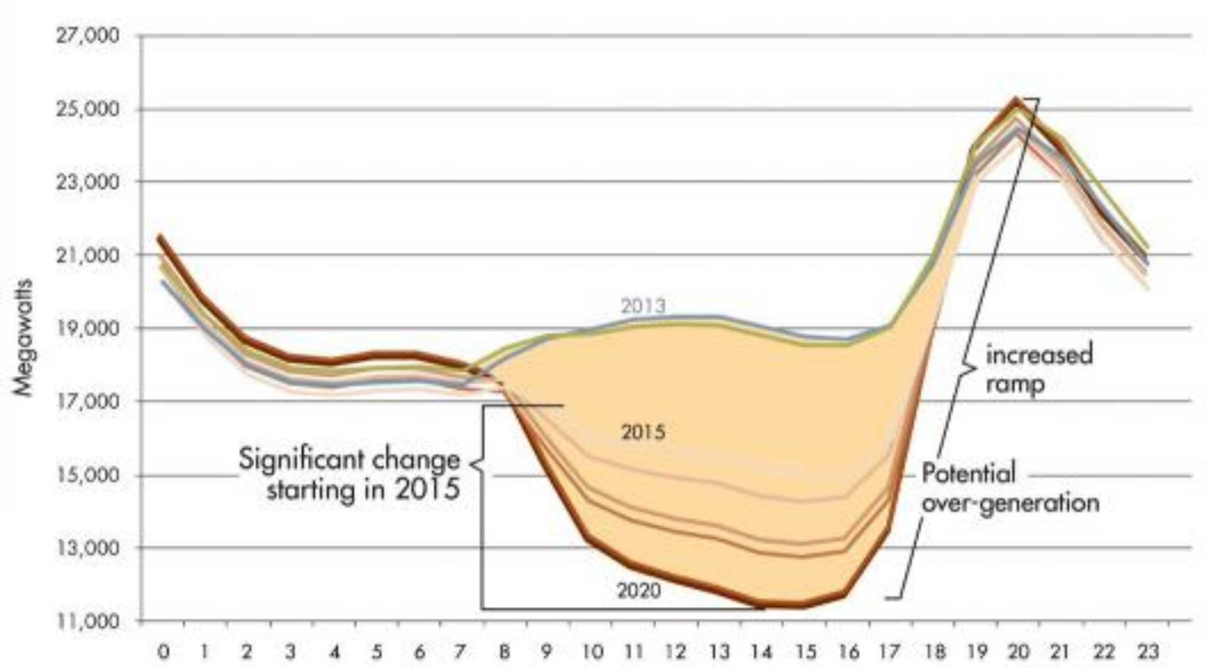


Figure 7 – Duck Curve Phenomena

What is of great importance here is how to provide an effective solution and mitigation services to this effect and flatten the curve. In general there are three mitigations to be considered:

- Add flexibility to the grid by adding the diverse energy source and increasing the diverse geographic area to balance the demand and supply and provide better prediction technologies. Particularly solar energy has the possibility to provide local energy demand in high use areas, reducing pressure on the grid.
- Incentivized evening energy use reduction, which can help reduce the ramping requirements as sun goes down (refer to the increased ramp on the duck curve). Incentivizing changes in energy consumption patterns can significantly flatten the demand curve. Decreasing low-demand energy prices can convince users to use more day-time electricity.
- Shift the power between PV solar and the energy storage system in timely manner. Battery storage system (BESS), as covered in previous section, can solve several simultaneous problems, from maintaining grid stability to deferred transmission and distribution. It provides both supply and load, although batteries are limited in how long they can produce power. Therefore there should be an optimal coordinated discharge across the plant and the available storage devices. The result is a minimized net load ramp, a reduction in evening peak consumption, and a flattened net load curve.

## 2.2. ENERGY STORAGE SYSTEM

The generation of electricity is mostly centralized and, often, a long distance away from load centers. Load levelling is initially based on the prediction of daily needs, but also, when production is not enough, energy storage systems can play important role. Decentralized production of electricity and the introduction of variable, fluctuating source such as renewable energy: solar, wind farms, increase the difficulty of stabilizing the power grid, mainly due to a supply–demand imbalance. It is therefore convenient to generate the power, transfer it, convert it, and then store it if need be. More than ever then, the energy storage system has become a necessity. This section covers the literature survey associate with energy storage applicable to electric grid.

Energy storage systems (ESS) have been around for a long time. Since the advent of electrical power grid, energy has typically been stored in the form of fuel, and then transformed to electricity to serve the loads. There are many possible techniques for energy storage, found in practically all forms of energy: mechanical, chemical, and thermal [30]. Figure 8 shows the various types of energy storage.

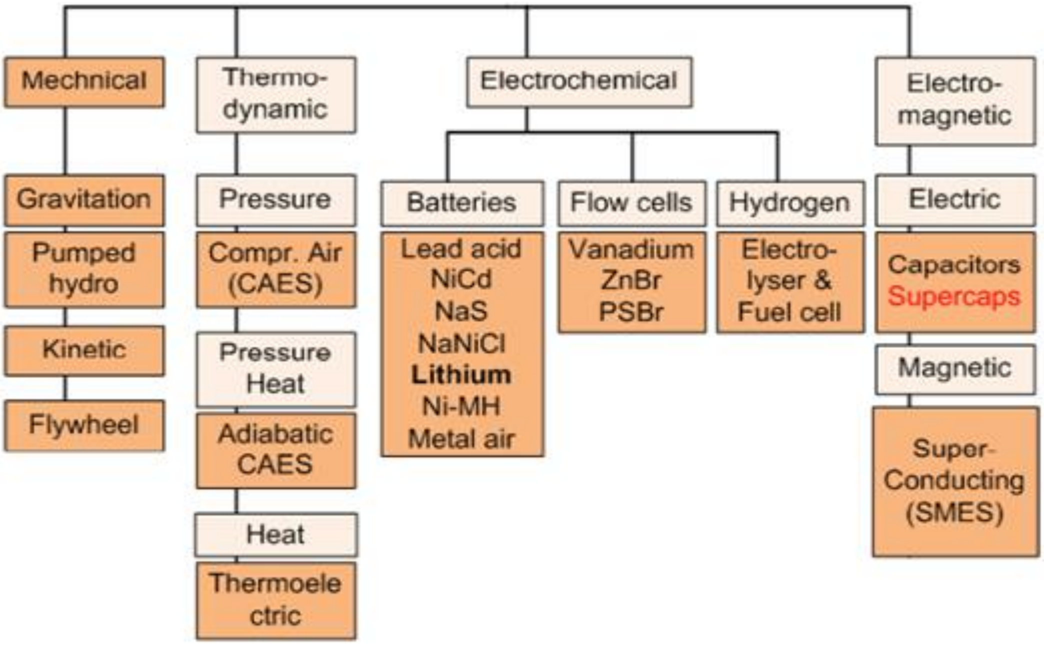


Figure 8 – Various types of energy storage

[30]

There are many possible techniques for energy storage, found in practically all forms of energy: mechanical, chemical, and thermal. The main focus is the storage technologies that answer to specific technical and economic criteria. The storage techniques can be divided into two following categories, according to their applications:

- Low-power and medium power applications which are in isolated areas, essentially to feed individual electrical system, town supply, etc. These are mainly small-scale systems where the energy could be stored as kinetic energy (flywheel), chemical energy, compressed air, hydrogen (fuel cells), or in supercapacitors or superconductors.
- Network connection application with peak leveling and power quality control applications. These are mainly for large-scale systems where the energy could be stored as mechanical energy storage (pumped hydro, compressed air, fly wheel), chemical energy (Battery technology, lead-acid, lithium ion, etc.), Electrical (capacitor and supercapacitor, super conducting magnetic storing system etc.).

The focus of this section is on latter category. As mentioned, a variety of technologies are available for energy storage in the power system. To identify the most relevant storage solutions it is necessary to include considerations of many relevant parameters, such as cost, lifetime, reliability, size, storage capacity, and environmental impact. All these parameters should be evaluated against the potential benefit of adding storage to reach a decision about the type of storage to be added.

By far the most common form of energy storage is pumped hydro, in which water is pumped up an elevation to a reservoir during times of low power demand, and allowed to flow back downhill through hydroelectric generators during time of high power demand. The pumped hydro storage is similar to a hydro power plant with the additional feature of using the generator as motor and the turbine for pumping the water up to the higher reservoir. The energy capacity depends on the volume in the higher reservoir and the height difference between the reservoirs. Pumped hydro technology has been the most commercially developed energy storage technology. As of 2012, Electric Power Research Institute (EPRI), USA, estimates that 99% of the global storage is in the form of pumped hydro, sizing to about 127 GW. The main advantages of pumped hydro plants are the high efficiency, large capacities, and scalability. However, the technology is limited by the geographical constraints and availability of large sites for the reservoirs and also the high cost of constructing. In addition, the environmental impact of pumped hydro facilities is becoming more of an issue, especially where existing reservoirs are not available. Environmental considerations such as impacts on fisheries, recreation, water quality, aesthetics, and land use have limited the further development of this technology [31], [32]. Figure 9 shows a typical pumped hydro power plant scheme, adapted from [33].

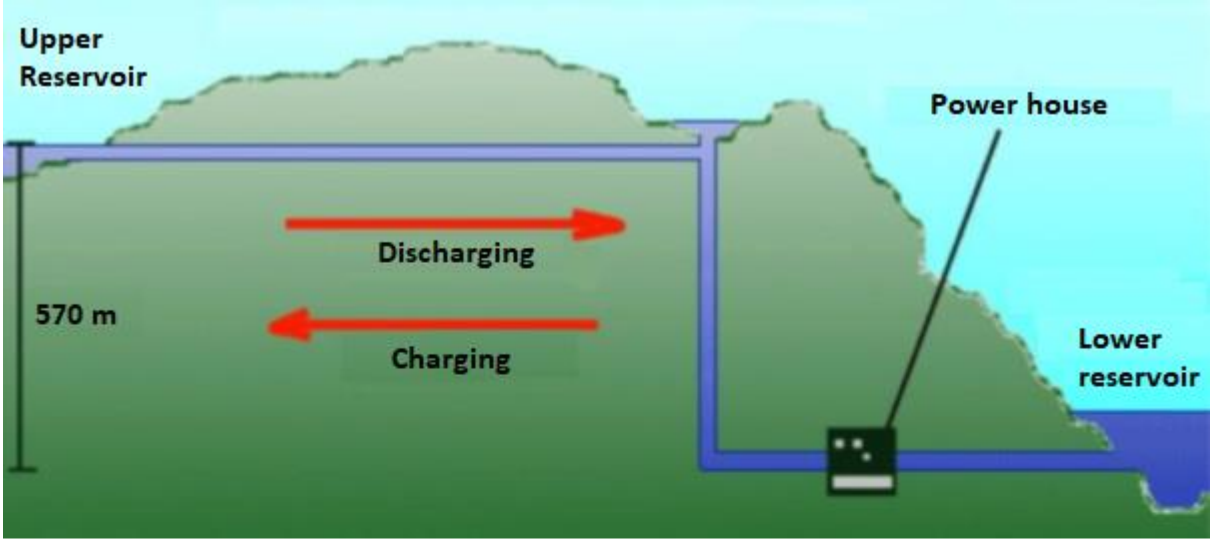


Figure 9 – Typical pumper hydro power plant scheme

The main advantages of hydro pumped storage are the long storage period, good partial load performance and low capital costs (400-800 $/kW) [31].

The compressed air technology is based on gas turbine principle. The charge and discharge process are two separate systems. During charge, electricity is absorbed to compress air into pressurized tanks. During discharge, the compressed air is preheated and expanded through high and low-pressure turbines. The air is also heated by burning fossil fuel (natural gas) in order to generate electricity. Turbines are connected to a generator, and consequently connected to the grid. However, the compressed air technology has same drawback as pumped hydro storage, finding suitable sites and locational constraints. In addition, plants require a large volume of compressed air to operate for extended periods of time [12]. Figure 10 shows a schematic of a compressed air energy storage plant with underground compressed air storage [34].

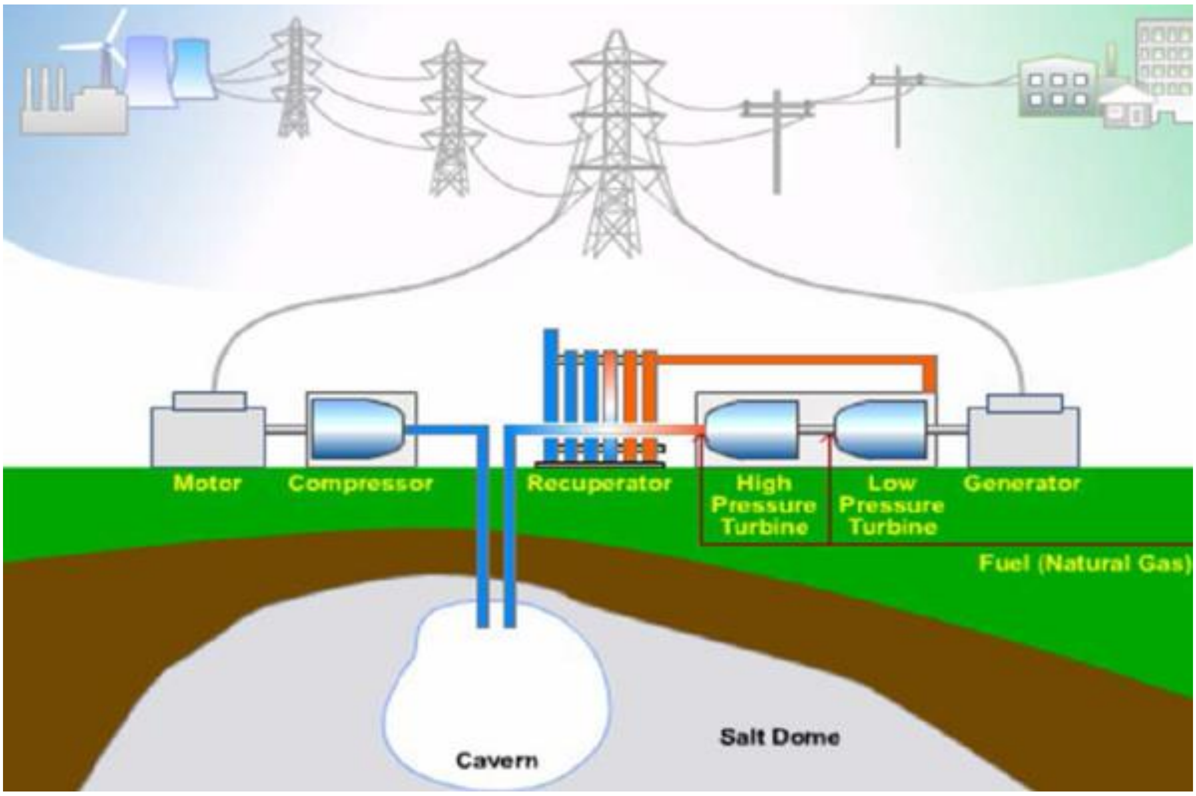


Figure 10 – Schematic of compressed air energy storage plant

With Flywheel technology, the idea is to store energy in the angular momentum in a rotating mass. The flywheel (mass) are connected via a shaft to a generator/motor and placed in high vacuum to reduce the energy losses due to air resistance. With this technology, energy capacity can be increased if the mass is spinning faster or has a larger weight or volume [12]. In a rotating mass, there will be a tensile stress that is a material property of the flywheel that limits the spinning velocity. Typically, flywheels are divided into two categories, low speed and high-speed flywheel. The flywheel rotates below 6000 rpm (short term and medium power applications) and 100,000 rpm (high power application) with respect to their category [35]. The flywheel energy storage main advantages are the low maintenance and long lifetime (charge-discharge cycles around 20000). The main disadvantage is the high hourly self-discharge up to 20%, low energy density, safety issues, and appropriate cooling systems. The energy stored by the flywheel system is depending on the size, square of the rotating speed and its inertia. Commercially, the axial-flux and radial flux permanent magnet machines are used as flywheel energy storage system [12], [36].

With chemical energy storage, the complete survey of different kind battery storage technology and applications will be provided in next section. A brief review is covered in this section.

The batteries consist of several electrochemical cells connected in series and parallel to obtain the desired voltage. The main important part is the functionality of a single cell. The electricity is transformed to chemical energy through a reduction-oxidation reaction (redox reaction). In an oxidation reaction electrons are lost and in a reduction reaction electrons are gained. When both an oxidation and reduction occur, the electrons move from one substance to another [36]. Typically these cells consist of two electrodes that are connected via an external load. Between the electrodes are electrolytes that can be in a solid, liquid. Batteries are one of the most cost-effective energy storage technologies available. They are modular, quiet, and non-polluting. They can be located almost anywhere and can be installed relatively quickly. Charging a battery causes reactions in the compounds, which then store the energy in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery and back to the grid with proper power electronic conversion units. A major disadvantage for the batteries is the limited lifetime, which depends on the specific cell. But the advantages are the high efficiency and fast response [23]. Some batteries can respond to load changes in about 20 milliseconds time frame, which is very fast response. The efficiency of battery modules is in the range of 60–80% [37]. Batteries, however, have some challenges as well. During an electrical charge and discharge cycle the temperature change in the battery must be controlled or it can affect the battery’s life expectancy. The type of battery being used will determine how resistant it is to life degradation due to temperature. In addition, there are also environmental concerns related to battery storage due to toxic gas generation during battery charge and discharge. The disposal of hazardous materials presents some battery disposal problems [38].

Electrical storage system includes supercapacitors and superconducting magnetic energy storage. The simplest capacitor consists of two electrodes (plates) with a non-conduction material in between known a dielectric. A power source is connected to the electrodes and similar to the electrochemical cell (one positive and one negative electrode). After applying the voltage, the electrons moves to the negative electrode. This causes an electric field and this potential is how the electricity is stored. Capacitors cannot store a large amount of energy; however, they can deliver a varying voltage. Therefore capacitor’s applications are power quality, high voltage power correction and smoothing the power output. However, they have low energy density and high self-discharge losses [23].

Supercapacitor can be considered as an improved capacitor with a higher energy density. Then difference between a capacitor and supercapacitor, is that the electrodes has an electrolyte between them for the supercapacitor and air for the capacitor. It is very similar to an electrochemical cell, but there are not redox reactions occurring and the energy is still stored as an electric field. Since, there are non-redox reactions the lifetime is not impacted by cycling the systems as for the batteries. They could cycle more than 105 cycles with high efficiency around 84-97 %. However, they have disadvantage of high daily self-discharge in range of 5-40%, high capital cost, and low energy density [32].

Super-conducting magnetic energy storage system stores the energy in the form of magnetic field, which is created by a dc-current flowing through the superconducting coil at a cryogenic temperature. Their components mainly consist of superconductive coil, cryostat system (cryogenic refrigerator and a vacuum insulated vessel) and a power conversion system [12], [31]. To maintain the super-conductive state of the inductive coil, it is immersed in liquid helium contained in a vacuum insulated cryostat. Typically, the inductive coil is made of niobium-titanium and the coolant will be liquid helium or super fluid helium. The energy stored depends on the self-inductance of the coil and square of the current flowing through it. The energy storage capacity of system can be increased by increasing the maximum current flowing through the coil. It is further depend on the operating temperature of the coil. The main disadvantages of this system are high cooling demand and expensive raw materials for superconductors.

In summary, by introducing the energy storage it is possible in making energy more available means making it more predictable, reliable and controllable. The prospect of energy storage is to remove fluctuations on shorter timescales (seconds to hours). Utilization of energy storage systems will be a major step in the solution to the use of renewable energy along with the current issues of reliability, stability, and power quality. This section presented a brief review on various energy storage systems including mechanical, electrical, and chemical systems.

### 2.2.1. GRID SERVICES AND BENEFITS OF THE ESS

The aim of this section is to provide a literature survey on services and benefits of integration of battery energy system with renewable plant (in particular PV plant) and how they can allow the increase on renewables deployment. Several research works has been performed on intermittency of PV technology which is due to the output power reduction caused by the environment (i.e. the movement of clouds over PV modules, weather conditions, etc.), as well as its typical lack of production during the night period. This intermittency causes most of the downside effects, such as voltage variation, fluctuation of active and reactive power, potential effects for overvoltage and over-current protections, etc.

The services and benefits that energy storage systems can provide to the electrical grid are summarized on the Table 1, Adapted from [33].

Table 1 – Services and benefits of energy storage systems

| | **Categories** | | | | |
|---|---|---|---|---|---|
| | Bulk Energy Storage | Ancillary Services | Transmission Infrastructure | Distribution Infrastructure | Costumer Energy Management |
| **Services** | Arbitrage | Frequency Regulation | Deferred network upgrades | Deferred network upgrades | Power Quality |
| | | Energy Reserve | | | Energy resilience |
| | | Voltage Support | Congestion management | Voltage Support | Energy Arbitrage |
| | Power support | Black-start | | | Demand management |
| | | Load following | | | |

Figure 11 shows an example of renewable power plant energy production in comparison with the forecasted energy production [39]. Due to intermittency factors, the output of the plants has high fluctuations, i.e. at some instances energy overflow and deficiency will appear.

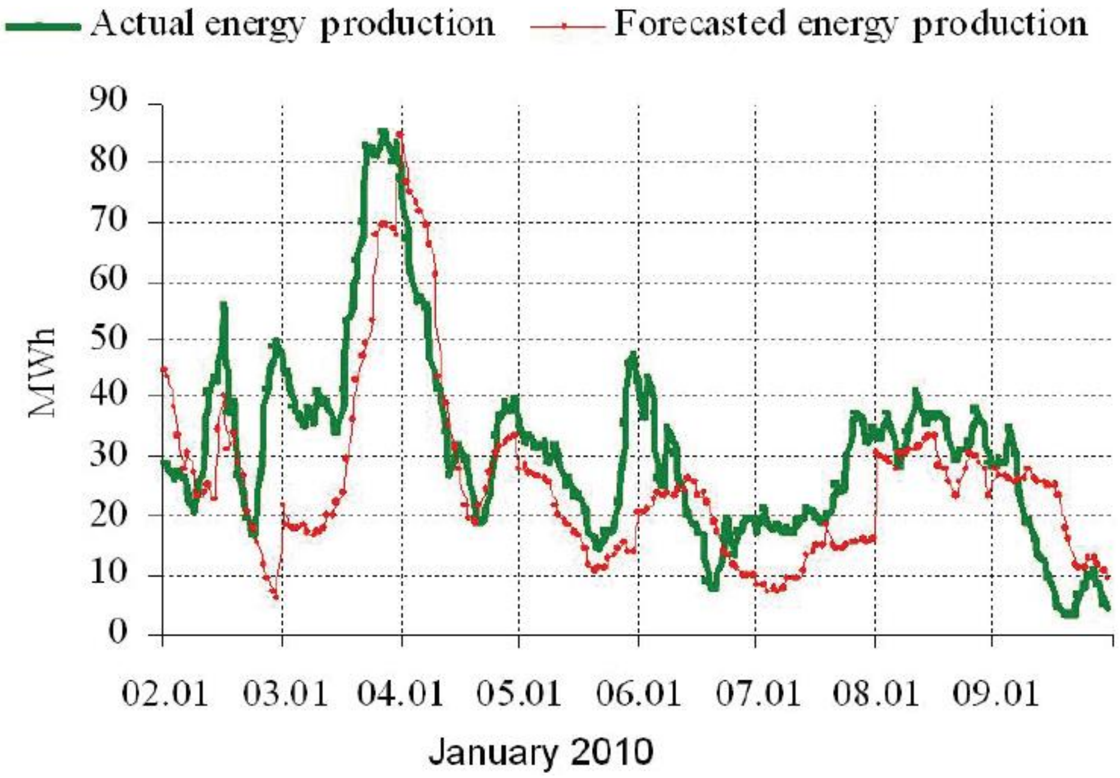


Figure 11 – Energy Production vs. Forecasted Energy in Renewable Plant

One of the approaches to mitigate such problems is to utilize a BESS to be able to control the power flow flexibly, which could facilitate increased penetration of PV systems by minimizing their intermittency [3]. As covered in section 2.4, there are many different BESS technologies, each with characteristic power and energy capacities, reaction times, lifetimes and costs [40]. Hence, their type and size vary strongly with the application and needs to be properly selected. An updated database of worldwide battery energy storage systems is provided by the U.S. Department of Energy, which is a comprehensive list of BESS technologies in the power and energy industry [41]. In integrated system design, the considerations of BESS technologies can help the system to be more cost-effective, efficient, and reliable [4]. As a clear example, refer to the BESS technology and control algorithm for power and energy in PV application and energy time shift as represented by S. A. Abdelrazek and etc. [5]. Control algorithms are simply employed to achieve longer lifetime, maximum output and optimal efficiency from energy storage devices.

The three main services of BESS integration with PV plants and grid interconnection are listed in following:

- Load following (with renewable time shift)
- Capacity firm or Ramp support
- Voltage Support

**Load following (with renewable time shift):** The stored energy by BESS can be discharged for different applications in PV plant. One possible application is to charge and discharge the BESS unit to follow the system load, or known as load following. The BESS system is charged during net surplus of renewable energy production and discharged during the deficit, as shown in Figure 12.

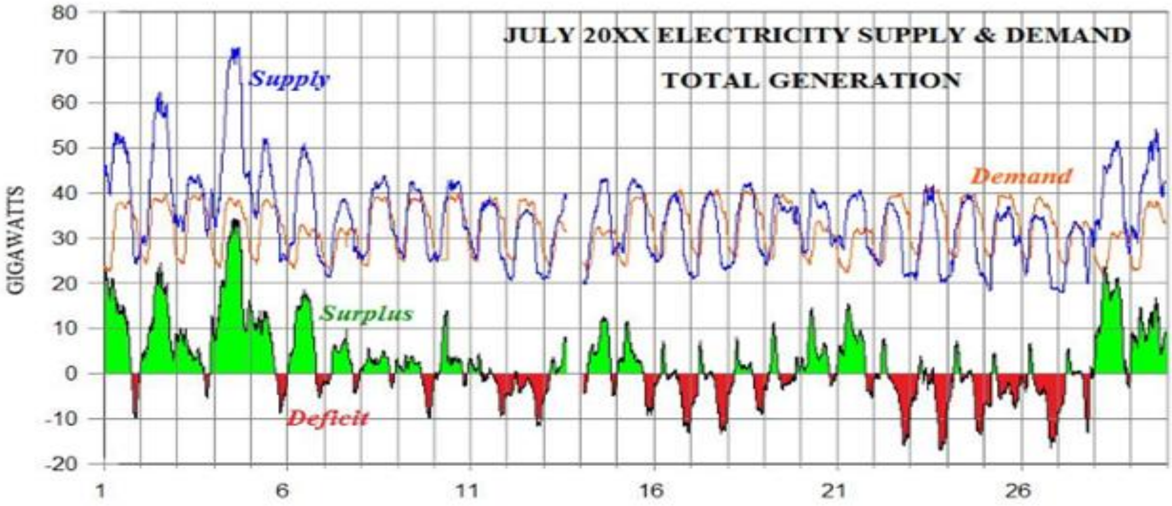


Figure 12 – Surplus and Deficit of Energy Production of Renewable Plant

Charging BESS with the surplus energy to fill the demand gap during low production and high demand has two benefits. First, power production peaks are reduced, thus leading to a better capacity factor and relieving of the grid infrastructure. Second, the curtailment and regulation of the plant will be reduced.

**Capacity Firm or Ramp Support:** The variable power output from PV plant can be maintained at a stable level for a period of time by smoothing the output and controlling the ramp rate (MW/min), known as capacity firming or ramp support. Capacity firming generally requires more storage capacity than ramp support as its main intent is to allow intermittent electricity supply resources to be used as near constant power source. Figure 13 illustrates an example on how the BESS system can be used to level the power output from a PV plant [42]. In order to regulate intermittent solar plant responsible parties usually predict the power production through solar forecast which are based on weather conditions, position of clouds and stochastic methods.

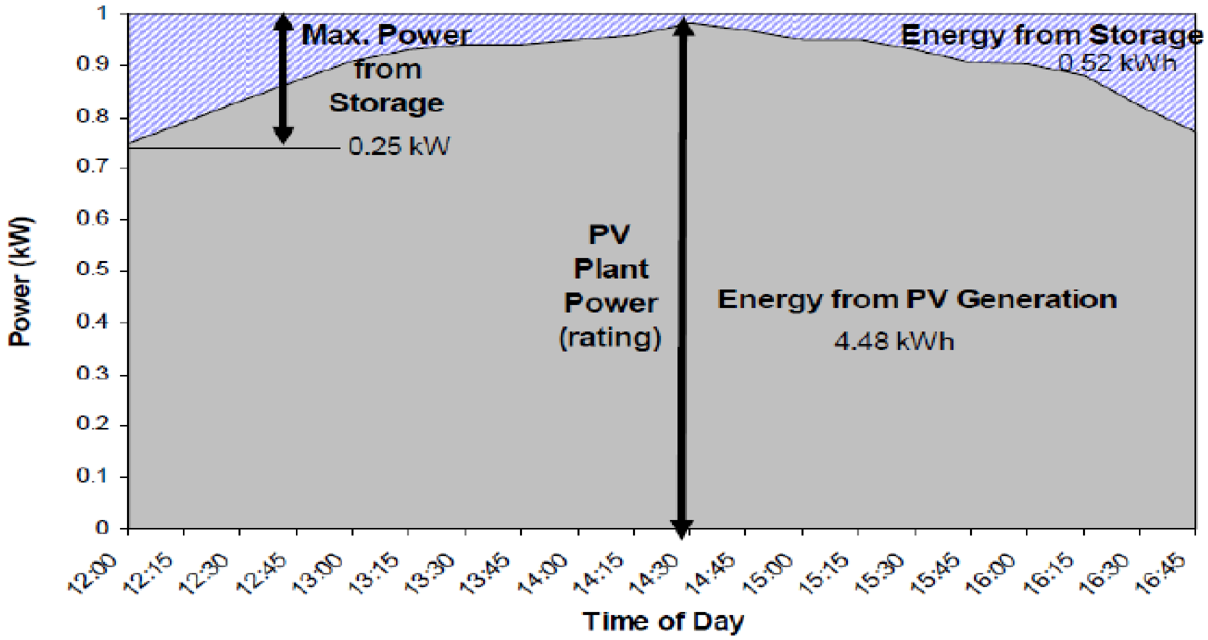


Figure 13 – Capacity firming of solar plant with BESS

Ramp support is the light version of capacity firming where the changes in power output over short durations from intermittent of PV plant are smoothened to decrease frequency fluctuations and other power quality issues.

**Voltage Support:** The active power injection to a feeder can cause voltage raises (ΔU) above the allowed limits. The voltage rise can be formulated as following [43]:

$$\Delta U = \frac{R\,P + X\,Q}{V_G} \tag{1}$$

$$\mathrm{P} = \mathrm{P_{PV}} - \mathrm{P_L} \tag{2}$$

Where R and X are the cable resistance and reactance at a distance from the transformer, P and Q are the active and reactive power exchanged with the grid at the point of interconnection, VG is the voltage of the grid. P is the difference between the power generated from a PV system minus the load power. At the interconnection point to the grid, when the voltage rises (due to increase of active and reactive power) the overvoltage forces the PV system to disconnect itself from the grid (without any reactive power control). This leads to losses in production and hence degrade efficiency and economical value for the off-takers. By connecting a BESS to a point in the grid where overvoltage can become problem a voltage support algorithm controlling the storage unit can mitigate the critical voltage rises or drops. By only absorbing or injecting minimal amounts of real power from a storage system the voltage fluctuations can effectively be damped.

Voltage support can also be provided by feeding reactive power into the grid. A voltage support algorithm can control the BESS reactive power output by measuring the output voltage and feed reactive power into the grid. However, it is important to note that amount of reactive power for voltage support will increase as PV penetration increases [22].

In Brief, this section provided a literature survey on three main services and benefits of integration of battery energy system with PV plant.

## 2.2.2. BATTERY ENERGY STORAGE SYSTEM

Although there are several technologies that have been developed for large-scale energy storage purposes such as pumped hydro, compressed air energy storage facilities, flywheels, capacitors, and superconducting magnetic storage, many are limited in their site dependence, overall capacity, or response-time capabilities. Electrochemical energy storage devices provides very flexibility in capacity, location (siting), and rapid response-time required to satisfy the application demands in comparison with many other types of storage. The battery energy storage systems (BESSs) have very fast growth recently due to their versatility, high energy density, and efficiency [44]. More grid applications have become suitable for BESSs as battery costs have decreased while performance and life have continued to increase [45]. BESSs have ability to react to grid demands nearly instantaneously, but also have the capacity to function over longer durations and have a wide range of storage and power capacities. Due to its technological maturity, the lead–acid chemistry has seen the most widespread use among large-scale BESS [46]. However, significant advancement in newer battery chemistries has allowed for a wide range of battery options for new storage applications and has increased the robustness and functionality of batteries within the electric grid.

A typical grid storage solution comprises a direct current (DC) system, a power conversion system (PCS), a Battery Management System (BMS), a supervisory control, and a grid connection. In the dc system, individual cells are assembled into modules which in turn are assembled into systems of sufficient capacity to satisfy the application requirements of the grid storage solution. Cells are connected in electrical series and parallel configurations to power a high voltage bus, which interfaces with the PCU. The PCU is a four-quadrant direct current/alternating current (DC/AC) converter connecting the dc system to the grid via a transformer. This architecture is shown in Figure 14.

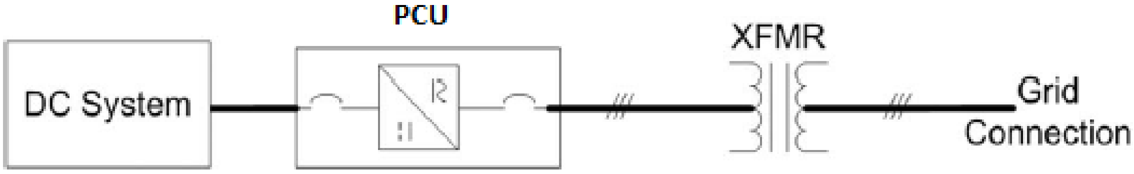


Figure 14 – Typical BESS configuration

The battery sets contain a series of auxiliary systems and devices that assure the proper function and reliability of the whole system, including, but not limited to:

- Battery cells, module and rack
- Mounting hardware
- Battery Management System (BMS)
- Power cables, control cables, protections and metering within scope of supply
- Thermal management
- Fire Suppression System
- Anti-intrusion system
- Container and/or any other enclosure including all its auxiliary system
- DC metering systems

The Battery Management System (BMS) is set of monitoring systems that protect and operate the batteries and works operated in conjunction with the overall plant's control system. The BMS provide safety management functions such as temperature monitoring and operational parameters controls tied to reliability and emergency actions, as well as operational management functions such as calculation of battery key performance indicators and manages the battery charge and discharge.

There are many types of battery that are used in BESS, with many different performance attributes such as peak charge/discharge rate, energy capacity, maximum depth of discharge, capacity factor and their charge and discharge efficiency. Six types of battery technology are covered in this survey, which are as follow [47], [48], [41]:

- Lead Acid Battery (Pb-Acid): These types of batteries are traditionally used in internal combustion automobiles as a method to supply power to lighting and ignition system. They have low overall energy to weight ratio. For the applications where weight and size are not in concerns, as grid-level energy storage telecommunication and UPS, they are commonly used. However, their capabilities in terms of energy and power density and average cycle life are low.  Their charge and di-charge efficiency is around 75%, with 1500 charge cycles and the overall life time cost of 135 $/kWh. The lead-acid batteries have been used in range of 10 to 20 MW in grid level applications. There are limited data is available on the operation and maintenance costs of lead-acid based storage systems for grid support.

- Nickel-cadmium (NiCd): These batteries are produced using the highly toxic metal cadmium, which is an environmental concern factor. They are relatively cheap and have a charge cycle energy efficiency of between 60% and 90%. They have an energy density of 40-60 Wh/kg, and the power density of 140-180 W/kg. The self-discharge rate is around 1% per day, and approximately 3000 charge cycles. They have higher overall life time cost in compare to Pb-Acid which is 540 $/kWh.
- Nickel-metal hybrid (NiMH): These batteries are not typically chosen for the grid level applications. The disadvantage of these batteries is the high rate of self-discharge relative to other battery technologies. They are well suited for high current drain applications, such as electronic devices, because of their low internal resistance. They have working life cycles between 500-2000 depending on the applications.
- Sodium-sulfur (NaS): These are molten salt battery that consists of positive and negative electrodes of liquid sulfur and liquid sodium, respectively, separated from one another by a beta alumina ceramic electrolyte in a solid state. They are ideal in grid storage applications. They have relatively good stated cycle life depending on the manner in which they are used. Their operating life is around 15 years, and the cycle is determined by the depth of discharge at which they are operated. With 100% depth of discharge, the cycle life will consist of 2500 cycles. With 85% depth of discharge, the cycle life will consist of 4500 cycles. Their charge and di-charge efficiency is around 89%, and the overall life time cost of around 450- 500 $/kWh.
- Lithium-ion (Li-ion): These batteries have good energy efficiency rates of 85-95%, and very high energy density and power density ratings of 100-200 Wh/kg and 360 W/kg, respectively. These batteries are the most dominant form of energy storage in consumer electronics. They have a relatively low self-discharge rate between 5% and 10% per month, depending on the specific type of Li-ion battery chemistry, and their working lifetime consists of approximately 3000 charge cycles. Their overall life time cost is relatively high for most applications in grid-level energy storage, which is around 1145 $/kWh. With technological advancement, it is predicted that the cost will decrease significantly.

- Vanadium Redox (VRB): These are flow type batteries which electrolyte is not stored within the cell, but instead outside of the cell. This has several benefits in terms of scalability, as well as in the operational lifetime of the battery. In flow battery, energy is stored as charged ions in two separate tanks of electrolytes, one of which stores electrolyte for positive electrode reaction while the other stores electrolyte for negative electrode reaction. Vanadium redox batteries are unique in that they use one common electrolyte, which provides potential opportunities for increased cycle life. When electricity is required, the electrolyte flows to a redox cell with electrodes, and current is produced. The electrochemical reaction can be reversed by applying an over potential, as with conventional batteries, allowing the system to be repeatedly discharged and recharged. Like other flow batteries, many variations of power capacity and energy storage are possible depending on the size of the electrolyte tanks. These batteries can be discharged completely without damaging the system components, and their stated cycle life is greater than 10,000 cycles. Depending on their manufacturing, their overall cycle efficiency ranges from 65% to 72%. Their overall lifetime cost is 915 $/kWh. One particular type of Vanadium redox is Zinc-bromine (Zn-Br). This battery uses zinc and bromine in solution to store energy as charged ions in tanks of electrolytes. As in vanadium redox systems, the Zn-Br battery is charged and discharged in a reversible process as the electrolytes are pumped through a reactor vessel. The field experience is currently limited, vendors claim estimated lifetimes of 20 years, long cycle lives, and operational ac-to-ac efficiencies of approximately 65% to 70%. The module sizes vary by manufacturer but limited within the range from 5 kW to 500 kW, with variable energy storage duration from 2 to 6 hours, depending on the application and need.

The technological and commercial maturity of these energy storage technologies also changes greatly. Some systems, such as lead-acid batteries, are proven technologies with many years of experience while others, such as flow batteries and emerging Li-ion batteries, are newer and have limited operational field experience. As a result, many utility scale PV solar designs analyze and incorporate storage capacity that provides power even during the night, like traditional power plants. Reference [49] described the projected future cost $/kWh of battery energy storage system, and those suitable for power and energy applications are illustrated in Figure 15 [49].

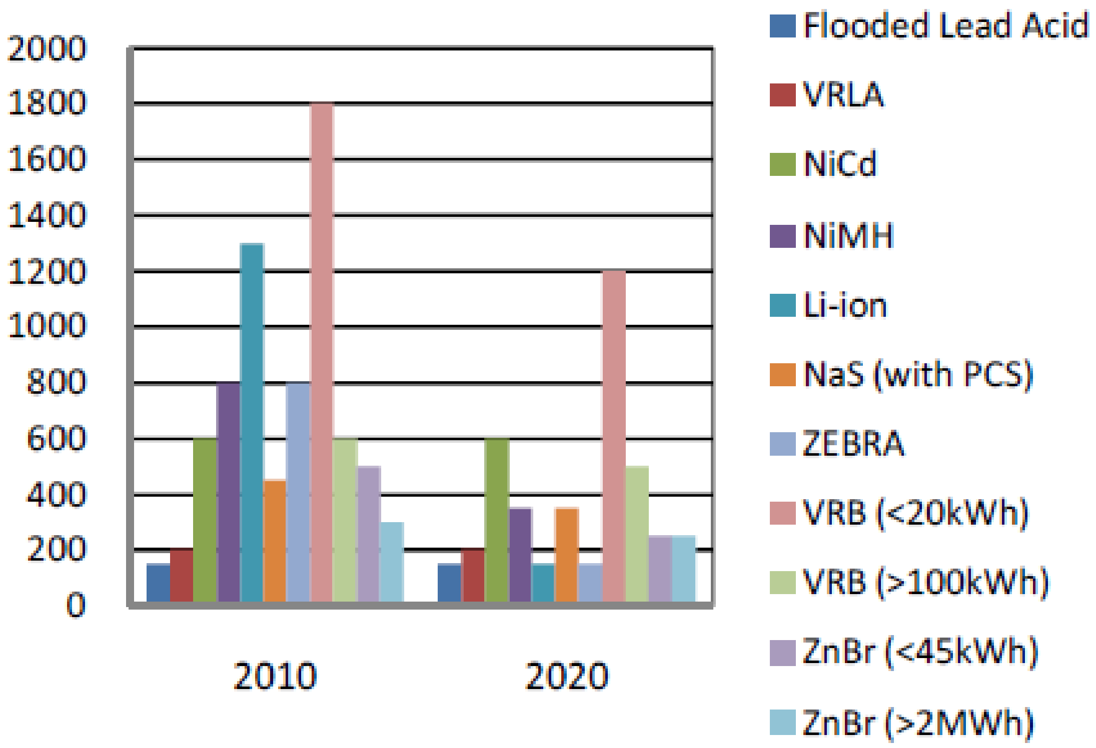


Figure 15 – Cost of Battery Energy Storage System ($/kWh) for Utility Applications

In literature survey, there has been several research and investigation on the topic of integration of BESS with utility scale PV plant which demonstrates improvement in power quality at the point of connection, and even increase the value of energy generated [50], [3].

## 2.3. COMBINING BESS WITH SOLAR PV

There are 2 ways of combining BESS and PV plants. The first, more traditional method is to combine both systems at medium voltage level connected to a common point of coupling, on the AC side. This systems allows that the batteries would be charging from either the solar PV system and from the grid itself. While it presents this flexibility, all the components needs to be doubled to account for all the energy to be processed and it increases the amount of MVAs installed.

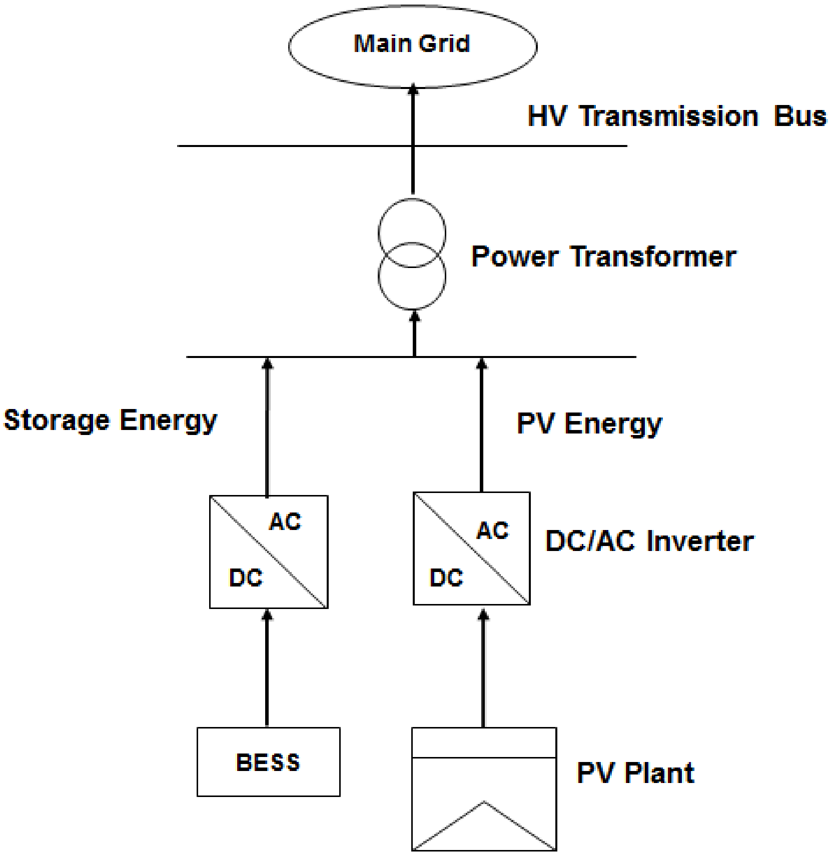


Figure 16 – BESS integrated with PV via AC coupling

The second way to do such integration is to do it directly on the DC side.

### 2.3.1. PV + BESS COUPLING ON DC BUSS

Combining energy storage with solar PV on the DC side can create value through shared infrastructure (e.g., inverters, interconnection), reducing the need to curtail production by delaying the dispatch of electricity onto the grid and/or by capturing the value of clipped solar production (e.g., solar PV output that is in excess of the system inverter) [6].

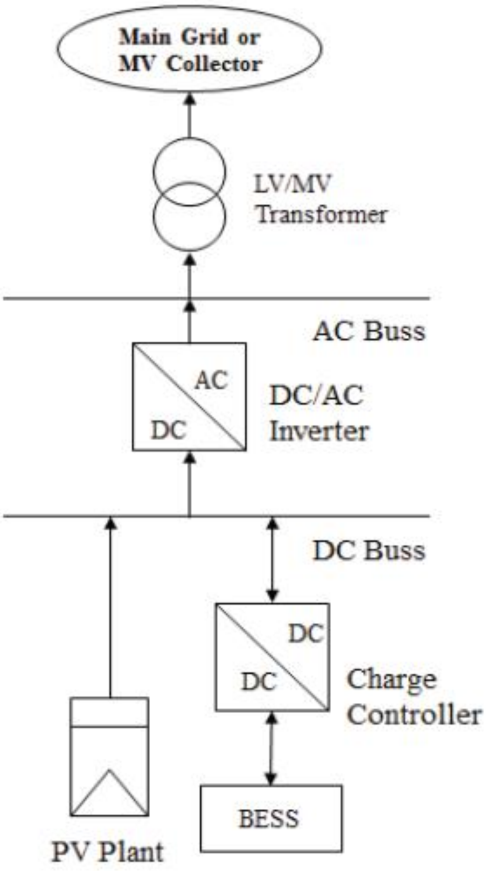


Figure 17 – BESS integrated with PV via DC coupling

[51]

The Figure 18 shows the amount of energy that can be generated at solar array in power plants with a very high DC/AC ratio and its potential to be stored in a battery system [51].

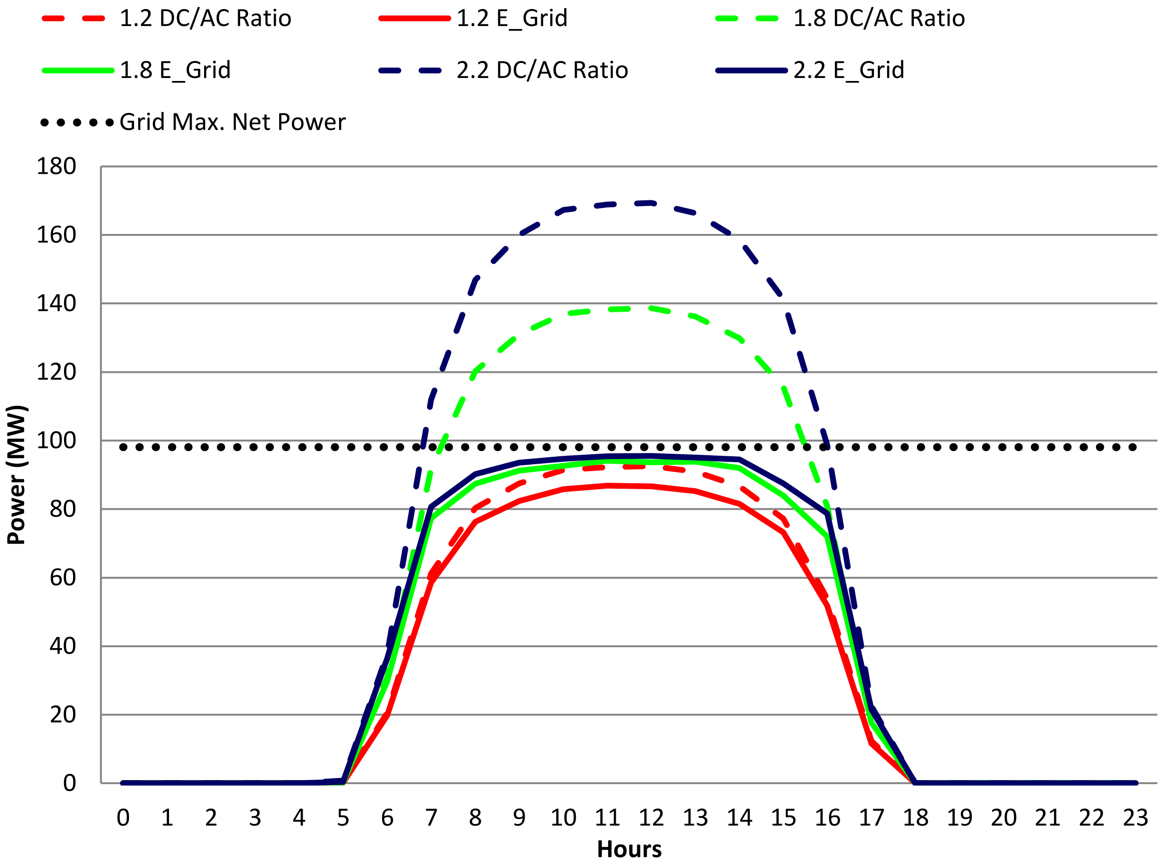


Figure 18 – Annual median DC and AC output of a PV system with various DC/AC Ratios

# 3 MATERIALS AND METHODS

In regards to the activities performed to achieve such goals, as explained in the section 1.3., this document will be divided in 2 parts: theoretical and practical aspect of BESS and PV plant. The theoretical part was covered in the literature review, that focused on gathering information about power production focused on solar generation, as well as storage systems, their technologies and services and benefits they can provide to the electric grids that they are connected to.

The practical part will cover the proposition of a method to analyze the technical benefits and financial returns of a Battery Energy System coupled to a PV system on its DC buss, with the battery being selected based on the amount of observed clipped energy. The system will be storing energy that would be clipped from the solar array and the net present evaluation will be calculated considering the extra revenues that the project can benefit from having a higher amount of energy to dispatch, granted by the energy stored on the battery.

Methodology does not cover substation costs, but the shared substation components (controls, area, grounding grid, breakers, switched, size of transformers, etc.) are also expected to increase overall project returns, since the components that the BESS system and the solar photovoltaic need those same components to be able to export power to the grid.

## 3.1. METHODOLOGY

This section provides a clear methodology for comparing the cost and performance of the most prominent, commercially available energy storage technologies for a selected subset of illustrative use cases.

Considering that topology discussed in section 2.3.1, the algorithmic approach is defined as follow:

1. Asses the amount of energy that the site would produce based on certain DC/AC ratio, using proven industry method.
2. Determine amount of energy that’s being clipped and potentially chargeable into the battery. This sizing strategy consists on averaging the PV power beyond a certain power limit (clipping level), hence hiding power dynamics to the sizing process.
3. Determine various different battery sizes based on clipped energy profile.
4. Determine charging and discharging curve based on the battery size.
5. Determine the new energy profile injected into the grid.
6. Determine revenue stream based on hourly load energy price cost

7. Proceed with Internal Rate of Return (IRR), Net Present Value (NPV) and payback of each solution assessment of each solution based on the cost related to the battery (wrapping up land and O&M cost, with initial solar set up cost remaining fixe).

The proposed methodology and analysis can be applied to determine, depending on the plant’s measurements and parameters, the size of a BESS to add to the PV plant for clipping energy storage. This information is necessary and required to perform an economic assessment, and how it can impact the IRR and NPV and assist in the decision-making process. For clarification of this study, the internal rate of return (IRR) is a metric used in capital budgeting to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. And NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

### 3.1.1. ENERGY ASSESMENT

PVsyst® is PC software package for the study, sizing and data analysis of complete PV systems. It includes modeling of system as grid-connected, stand-alone, pumping and DC-grid (public transportation) PV systems, and includes extensive meteorological and PV systems components databases, as well as general solar energy tools [52].

PVsyst is an industry stand method that is capable to determine a variety of parameters using to evaluate a solar system performance, given the necessary minimum inputs such as:

- A PV module model, chosen in the database or provided by manufacturer
- An inverter model, chosen in the database or provided by manufacturer
- The number of inverter inputs (either full inverters or number of MPPT inputs)
- The number of modules in series and the number of module strings.
- Project specific losses (ohmic wiring losses, thermal losses, soiling losses, etc.)
- Project specific meteorological data, factoring satellite and ground measure data.

The process of designing a project in PVSyst includes the following basic steps:

- Project – define the location and meteorological data
- Orientation – define module azimuth and tilt
- System – choose the system modules, inverters and electrical design
- Module Layout – create the electrical string connections
- Detailed Losses – mismatch.
- Simulation – view a summary of the system's energy output

This dissertation will focus on the following data:

- **E_Grid:** The total AC energy production [MWh], effectively injected into the grid ($E_G$), all of the ohmic losses as discounted.
- **EArr_MPP:** Array "virtual" energy, which determined the energy potentially available in the PV plant array, after all array losses and before clipping losses ($E_{AM}$).
- **EArray:** Effective energy at the array output, after clipping losses and readily available to be converted by the solar inverter ($E_A$).

The difference between EAM and EA determines the Clipped Energy (CE), therefore available to be storage into the battery system, described on the Equation (3):

$$CE \ = \ E_{AM} - E_A \tag{3}$$

Where $CE$ is the clipped average power in MW.

The Chargeable Energy (CHE), in MW, is the difference between the EAM and the EA, applied the DC/DC efficiency of the buck-boost converter (η), formulated below:

$$CH_E \ = (E_{AM} - E_A) \ \eta \tag{4}$$

## 3.1.2. ENERGY PROFILE DETERMINATION

Once the chargeable energy is defined, the charge and discharge profiles will be calculated. Three different battery sizes are considered for a given DC/AC ratio and will drive the energy profiles determination.

The reasoning behind the calculation is defined on the steps presented below:

1. The batteries will be fully discharged at the beginning of each day and will fully discharge, complementing energy profiles injected into the grid
2. The batteries will only be charged from the energy produced on the PV plant and using chargeable energy.
3. DC power (not clipped) to estimate the clipped energy resulting from clipping the power curve. The charging process is through the clipped power estimation which subtracts the measured DC power from the selected model predicted.
4. Batteries will start to discharge when the sun goes down, mostly the time represented by the moment in the afternoon when the clipping losses cease and no power is available.
5. Round trip efficiency will be considered just as the DC/DC efficiency. Typically the a single stage DC-DC converter has the efficiency around 97% efficiency and round trip efficiency of around 94.09%, some of the new commercially available batteries present around-trip efficiency of 95% and DC/AC inverter has a nominal efficiency of

97%. Therefore, the energy passing through the BESS (PV to BESS and BESS to Grid) would experience an efficiency of 86.70% [53].

6. Batteries and solar modules degradation have not been considered in this analysis and will be considered for the future work and extension of this work.

The steps as listed above, algorithm are preceded for the energy profile determination of BESS sizing which depends on charging and de-charging of the BESS based on availability if hourly energy profile is available. The decision making is based on the Chargeable Energy (CHE) of battery. When the chargeable energy is available then the BESS has resource to charge and use that energy. In a case of no chargeable energy then the status of the plant whether it is the maximum power producing or not will be checked and the actions will be taken thru obtaining hourly energy profile. The detail steps are represented on the flow chart presented on the Figure 19, as indicated, the assumption is that the batteries will be fully discharged at sunrise. The main objective of this algorithm is to provide the estimation of clipped power by obtaining the hourly energy profile, the BESS sizing strategy, the proposed BESS configuration enabling fully usage of a Battery ESS (BESS) and the proposal of a control strategy to harness such power.

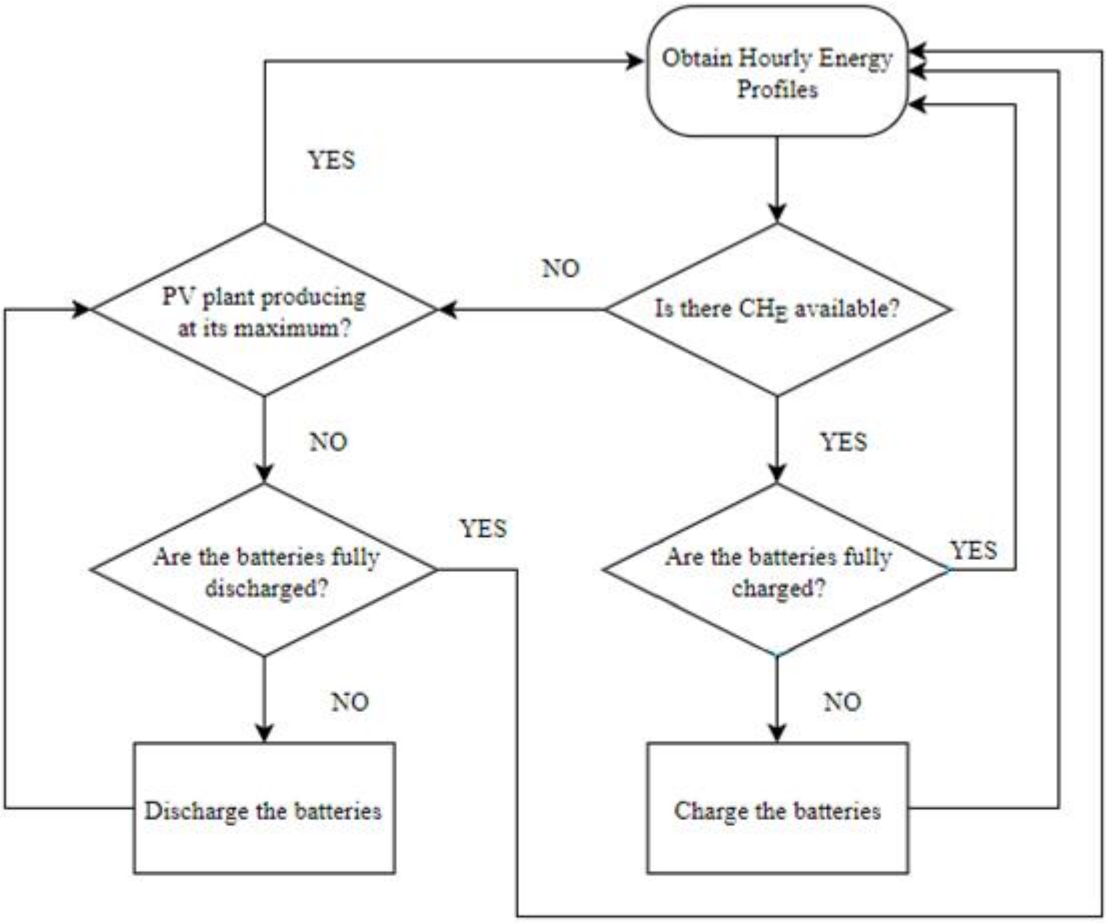


Figure 19 – Flow chart for energy profile determination

### 3.1.3. REVENUE STREAM CALCULATION AND FINANCIAL EVALUATION

The algorithm described on section 3.1.2 determines what will be the new energy profile. The hourly energy will be applied against the various revenues streams that a power plant that has the capability to de dispatched, such as firm capacity.

The net present value (NPV) of profits, internal rate of return (IRR) and payback of the combined PV solar and BESS are calculated for different scenarios of battery capacity for a given DC/AC ratio.

The NPV is the economical index that shows how much return the solar plant and BESS will make, accounting for the time value of money. Factors such as opportunity cost, inflation and risk are all accounted for in NPV to give the overall value of the project in today's time. A positive value for NPV for the PV project with BESS indicates that the project is set to make money or prove profitable to clients over the time period considered, which is typically around 30 years. Vice versa is the case for a negative NPV. Hence this means that a project with a positive NPV is considered to be a "good investment" and is a criteria for deciding whether to consider a particular project for investment. Hence NPV accounts for the “future value” of the investment made into an installation project.

As another economical index, IRR or Internal Rate of Return is the discount rate at which the sum of Net Present Value (NPV) of the current investment and all future cash-flow (positive or negative) is zero. It is an index of the growth of the project is expected to generate. The IRR index is a useful parameter for comparing the returns different investment opportunities in renewable energy market and choosing rightly between them. This also means that on obtaining accurate data of each investment, comparison between the IRR of investing in solar to the IRR of otherwise capital investment can shed light on the one with the highest return [54].

Variation of sizes for the storage capacity is tested against the economical indices for PV and BESS integration system. This range of sizes allows the model to explore whether an increase in size would be profitable for the whole plant.

# 4 CASE STUDY

The section will provide the application of the methodology proposed on the chapter 3.

## 4.1. POWER PLANT’S DESCRIPTION

The power plant considered is a typical utility scale solar PV plant, using single axis tracker, composed by several power conversion systems (including combiner boxes, inverters and 34.5 kV step-up transformers) daisy-chained by medium voltage cables, connecting to another step-up substation, with medium voltage feeder breakers and a main power transformer with a secondary voltage at transmission level. All losses considered, as all as other alternate current assumptions followed the typical industry best practices.

The power plant is located on the State of Texas, United States, at the western part of the state and has 100 MW of net injection at its point of interconnection as a requirement and power limitation.

As the focus of this dissertation is the storage and photovoltaic portion of the power plant, the step-up substation and the medium voltage collector feeders won’t be described.

### 4.1.1. POWER CONVERSION SYSTEM

The case study will consider a power system unit from SunGrow®, using the SC2500U Energy Storage Inverter. The SC2500U is a four quadrant inverter focused on energy storage application and the typical grid support capabilities required by most of the grid operators around the world.

The power plant has 41 numbers of inverters, rated at 2,500 kVA, adding up to 102,500 kW. The DC/AC ratio for the inverter is considered as 1.8. The power conversion units is completed with the addition of a LV-MV transformer that steps up the inverter voltage from its operating range of 495 - 605V to the medium voltage collector system voltage, usually 34.5 kV. The suffix MV on SC2500U-MV denotes the full conversion unit. Figure 20 shows a picture of the full mounted SC2500-MW skid, including the LV-MW transformer.

Figure 20 – SC2500U-MV Power Conversion System

Energy Storage Systems applications and features:

- Peak-shaving, frequency regulation, load-shifting, capacity firming, etc.
- Bidirectional power conversion system with four-quadrant operation
- Grid voltage and frequency support, black start function integrated

Other grid capabilities and certifications:

- Compliant with UL 1741, IEEE 1547, UL1741 SA, NEC standard
- Grid support including L/HVRT, L/HFRT, soft start/stop, specified power factor control and reactive power support.

The Figure 21 shows the P-Q capability of the inverter with charge and de-charge sections. The percentages of active power with respect to the nominal power are indicated with 110%, 110%, and 45.8% with associated reactive power.

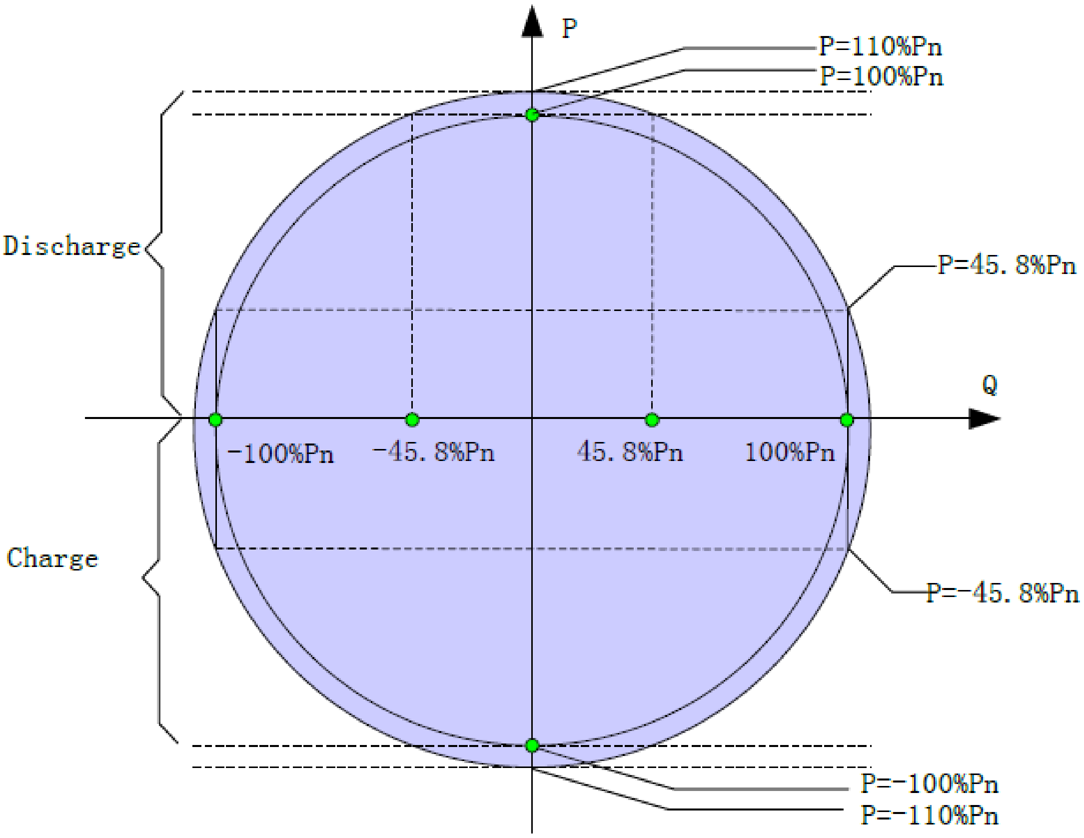


Figure 21 – SC2500U-MV P-Q Diagram

The main ratings of the SC2500U-MV are:

- Maximum DC Voltage: 1500 V
- Minimum DC Voltage: 800 V
- Nominal AC power (at 50°C): 2500 kW / 2750 kVA
- AC Voltage Range: 495 - 605V
- Grid frequency range (60 Hz): 55 – 65 Hz
- Max. discharge efficiency: 98.8 %

The Table 2 details inverter discharge efficiencies at various voltage levels.

Table 2 – Inverter discharge efficiency at various voltage levels

| P/Pn | 10% | 20% | 30% | 50% | 75% | 100% |
|---|---|---|---|---|---|---|
| **1300 V** | 97.51% | 98.19% | 98.34% | 98.28% | 98.17% | 97.99% |
| **1050 V** | 97.90% | 98.42% | 98.53% | 98.49% | 98.33% | 98.10% |
| **800 V** | 98.39% | 98.69% | 98.73% | 98.65% | 98.65% | 98.26% |

The Table 3 shows the inverter charge efficiency at various voltage levels:

Table 3 – Inverter charge efficiency at various voltage levels

| **P/Pn** | **10%** | **20%** | **30%** | **50%** | **75%** | **100%** |
|---|---|---|---|---|---|---|
| **1300 V** | 97.25% | 97.95% | 98.15% | 98.18% | 98.06% | 97.89% |
| **1050 V** | 97.56% | 98.20% | 98.33% | 98.31% | 98.17% | 98.00% |
| **800 V** | 98.04% | 98.47% | 98.56% | 98.47% | 98.32% | 98.13% |

According to manufacturer's feedback, the difference in cost of an inverter used for storage applications and a regular PV inverters is about 0.01 $/VA.

Another component that is added to the power conversion unit is the DC-DC converter that regulated the charging voltage at the batteries. This study considered SD250HV that is rated 275 kVA and has a 99% maximum efficiency.

The overall LV AC system single diagram is showed on the Figure 22 that shows the connectivity of energy storage system container with DC combiner box and the inverter connectivity to the medium voltage grid as shown in following. The Figure 23 shows the SD250HV communication diagram that shows the connectivity of AC cabinet with the battery unit, SD250HV, HVAC, etc.

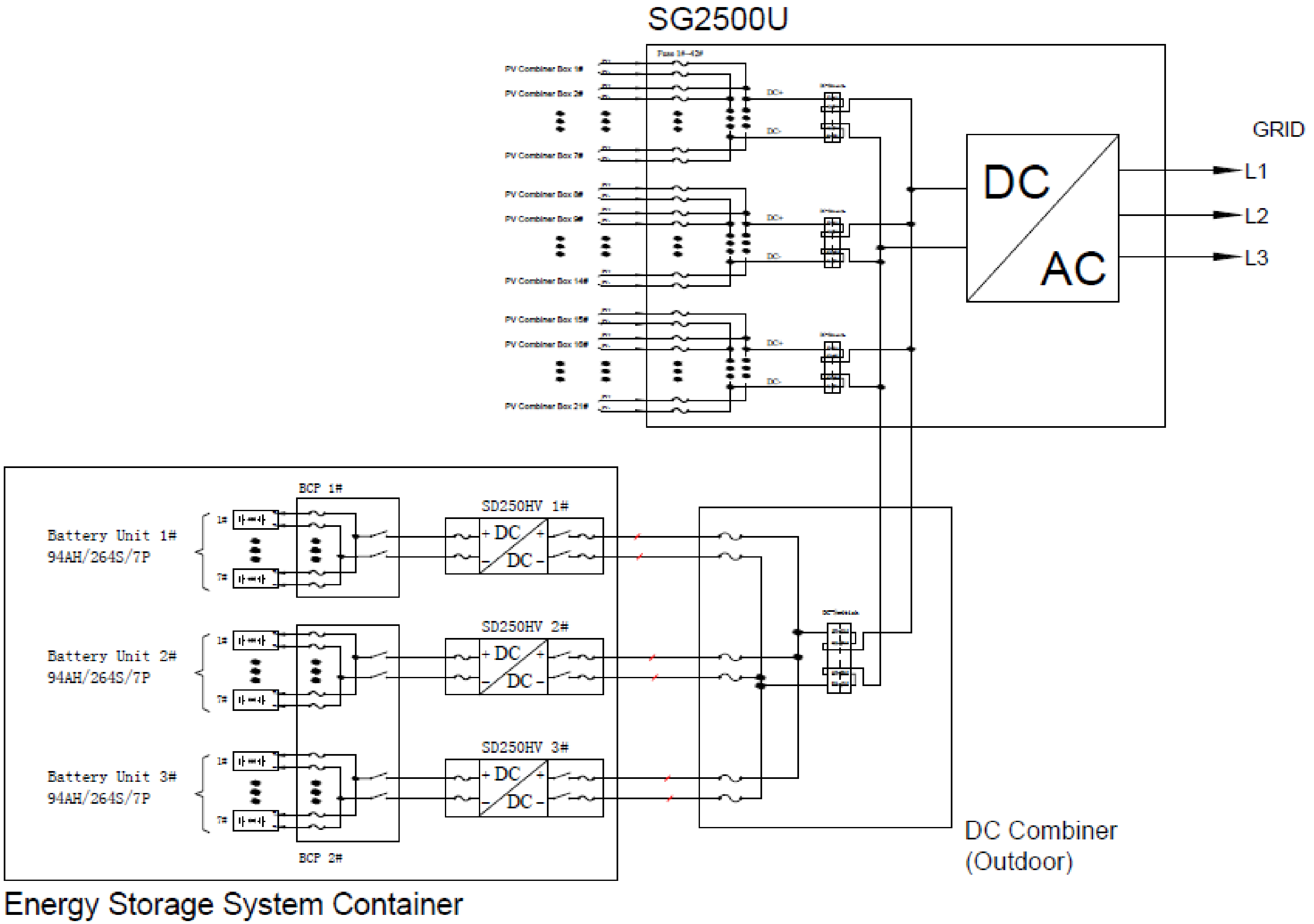


Figure 22 – SC2500U + SD250HV Single Line Diagram

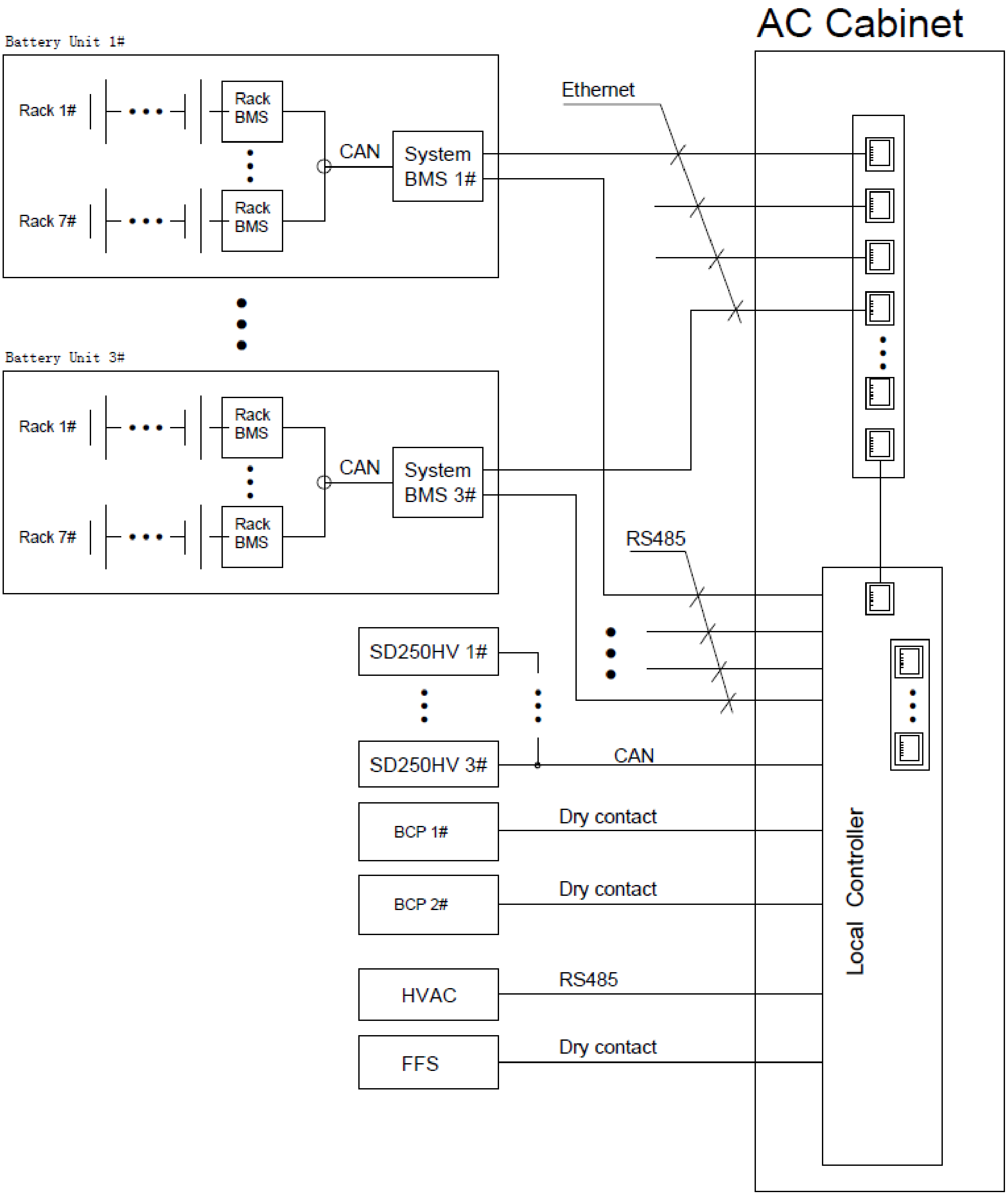


Figure 23: SD250HV Communication Diagram

### 4.1.2. SOLAR MODULES

Monocrystalline silicon high efficiency solar PV modules have been selected for this case study. Monocrystalline panels as the name suggests are created from a single continuous crystal structure. The panel can be identified from the solar cells which all appear as a single flat color. Monocrystalline solar panels have the highest efficiency rates since they are made out of the highest-grade silicon in compare to other technology. In addition, Monocrystalline silicon solar panels are space-efficient. Since these solar panels yield the highest power outputs, they also require the least amount of space compared to any other types. The unit nominal power is 380 W at STC. Table 4 shows the solar photovoltaic plant configuration.

Table 4 – Solar PV plant configuration

| # of Modules | Series | Parallel | Module Area ($m^2$) | Power STC (kWp) | DC/AC Ratio |
|---|---|---|---|---|---|
| 480,600 | 27 | 17,800 | 950,644 | 182,628 | 1.8 |

## 4.2. ENERGY ASSESMENT USING PVSYST®

Based on the power plant's configuration described on the previous sections, an energy assessment using PVSyst® has been prepared. The simulation used project specific meteorological data, factoring satellite and ground measure data, as explained in the methodology session. The Table 5 shows the summary of the insolation data, per month with GH Insolation (MWh/m2) and GI Insolation (MWh/m2):

Table 5 – Summary of the Monthly Insolation Data

| Month | GH Insolation (MWh/m2) | GI Insolation (MWh/m2) |
|---|---|---|
| **Jan** | 124.0 | 173.5 |
| **Feb** | 132.7 | 179.8 |
| **Mar** | 197.0 | 262.9 |
| **Apr** | 222.1 | 289.6 |
| **May** | 252.2 | 322.8 |
| **Jun** | 252.6 | 323.3 |

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| Continuation… | | |
|---|---|---|
| **Jul** | 251.1 | 321.9 |
| **Aug** | 236.5 | 307.2 |
| **Sep** | 188.5 | 246.3 |
| **Oct** | 161.6 | 220.1 |
| **Nov** | 126.0 | 175.3 |
| **Dec** | 110.6 | 152.3 |
| **Year Total** | 2254.8 | 2975.0 |

Where:

- GH Insolation (Global Horizontal Insolation): Total amount of insolation received by the solar modules, horizontal to the ground.
- GI Insolation (Global Inclined Insolation): Total amount of insolation received by the solar modules, horizontal to the modules surface.

Other meteorological inputs are necessary to calculate the energy yield of a given site, but they solely provide a rough estimate of the energy yield of a given site.

The losses assumed are the ones usually applied in the Solar PV industry. As indicated in Section 4.1.2 the DC/AC considered is 1.8.

A summary of the energy assessment is shown on the Table 6:

Table 6 – Summary of Energy Assessment

| | |
|---|---|
| **Max $E_G$ (kWh)** | 98,661 |
| **Energy Available AC-side (GWh)** | 333.3 |
| **Net Capacity Factor (%)** | 37.1% |
| **Energy Available DC-Side (GWh)** | 449.8 |

Where:

- **Max $E_G$ (MWh):** The maximum energy net injection into the electrical grid, on a given hour.
- **Energy Available (AC-side):** The yearly energy available at the plant's point of interconnection, the annual summation of $E_G$.
- **Energy Available (DC-side):** The annual summation of ($E_{AM}$)

- **Net Capacity Factor (NCF):** Net capacity factor which is the ratio between the energy produced during a certain and the maximum possible energy output over that period.

## 4.3. CALCULATION OF CHARGEABLE ENERGY

The Figure 24 shows the power plant $E_{AM}$'s 8760 hours annual profile, represented by the orange lines. The green horizontal line was included to show the maximum $E_A$ observed during the year and the EAM above that line roughly indicates the energy available for to charge the batteries.

Another line, the red one, was included in order to highlight the month's periods with the highest $E_{AM}$, starting on early April lasting till and end of June. This period coincides with the spring months in the north hemisphere, where the plant is located and it matches with the expected highest output of the solar arrays, since the modules output is also temperature. Spring months has a good insolation, with temperatures during the day that average 27.2 °C, while it tops 39 °C during the summer months.

The variability of the EAM represents the variability of the solar resource and it may indicate that working on storing the base of the energy curve would lead to a better charging usage of the battery.

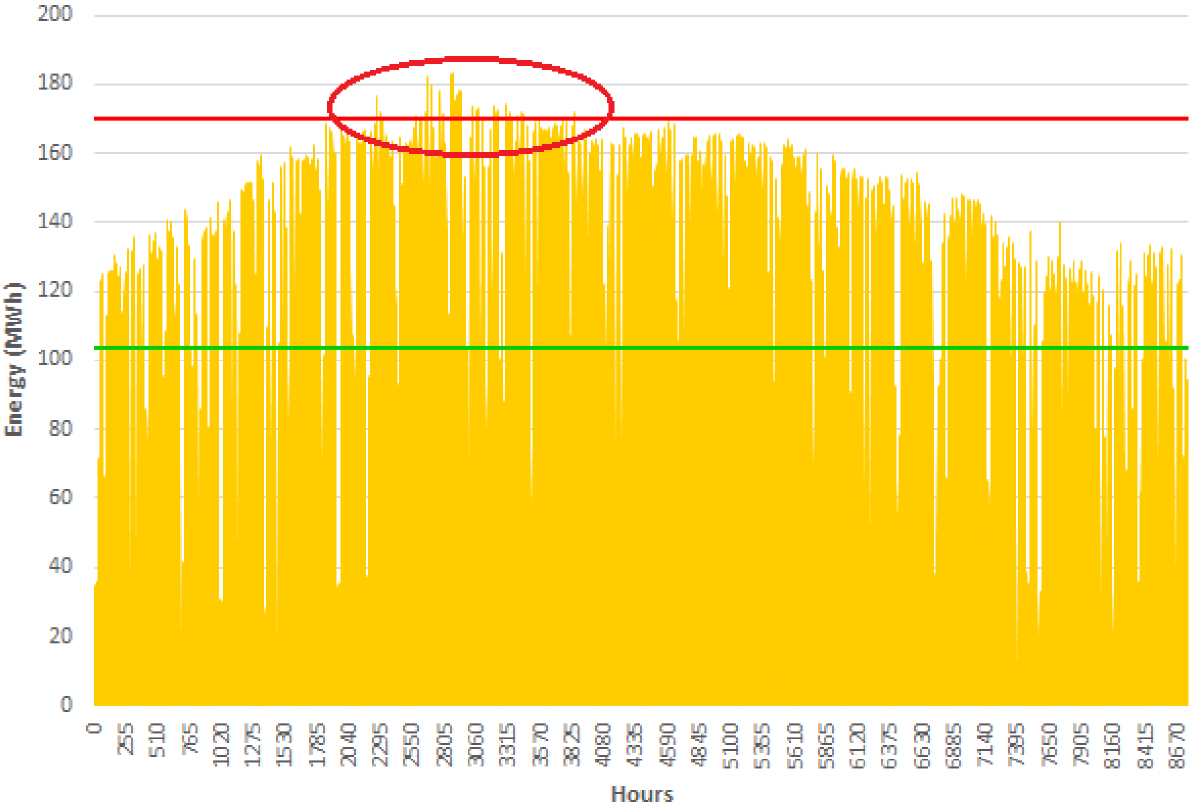

Figure 24: Power plant's 8760 hours $E_{AM}$

The Chargeable Energy ($CH_E$), in MW, is the difference between the $E_{AM}$ and the $E_A$, applied the DC/DC efficiency of the buck-boost converter (η), formulated on the equation 5.

$$CH_E = (E_{AM} - E_A)\,\eta \tag{5}$$

Table 7 shows the monthly summary of the energy produced in the power plant, in MWh.

Table 7 – Monthly summary of the energy produced in the power plant

| **Month / Day** | **$E_G$ (MWh)** | **$E_A$ (MWh)** | **$E_{AM}$ (MWh)** | **$CH_E$ (MWh)** |
|---|---|---|---|---|
| **Jan** | 23,097.6 | 24,155.7 | 28,013.1 | 3,833.5 |
| **Feb** | 22,100.4 | 23,135.7 | 28,631.7 | 5,441.1 |
| **Mar** | 28,842.9 | 30,180.4 | 40,422.4 | 10,139.6 |
| **Apr** | 29,674.6 | 31,060.3 | 43,612.0 | 12,426.2 |
| **May** | 32,727.4 | 34,252.3 | 47,289.1 | 12,906.5 |
| **Jun** | 33,125.0 | 34,656.2 | 47,167.9 | 12,386.5 |
| **Jul** | 33,462.3 | 35,023.0 | 46,935.4 | 11,793.3 |
| **Aug** | 31,813.3 | 33,305.4 | 44,774.1 | 11,354.0 |
| **Sep** | 27,684.2 | 28,968.0 | 36,848.3 | 7,801.4 |
| **Oct** | 25,874.9 | 27,068.1 | 33,711.4 | 6,576.9 |
| **Nov** | 23,271.1 | 24,366.2 | 27,551.9 | 3,153.8 |
| **Dec** | 21,591.5 | 22,571.8 | 24,842.8 | 2,248.3 |
| **Year Total** | 333,265,103.7 | 348,742,922.3 | 449,800,058.3 | 100,061,221.6 |

Table 8 and Table 9 show the main energy outputs of the system on the months of July and December, respectively.

Table 8 – Summary of July Daily Energy Amounts

| **Month / Day** | **$E_G$ (MWh)** | **$E_A$ (MWh)** | **$E_{AM}$ (MWh)** | **$CH_E$ (MWh)** |
|---|---|---|---|---|
| **Jul** | 33,462.3 | 35,023.0 | 46,935.4 | 11,793.3 |
| **1** | 916.5 | 958.2 | 1,293.0 | 331.5 |

| | | | | |
|---|---|---|---|---|
| **2** | 1,149.5 | 1,202.7 | 1,645.4 | 438.3 |
| **3** | 961.8 | 1,006.2 | 1,368.4 | 358.6 |
| **4** | 1,176.7 | 1,231.7 | 1,724.7 | 488.1 |
| **5** | 950.8 | 996.0 | 1,382.3 | 382.5 |
| **6** | 1,045.0 | 1,094.1 | 1,292.2 | 196.2 |
| **7** | 1,095.7 | 1,145.0 | 1,501.1 | 352.5 |
| **8** | 1,215.5 | 1,272.5 | 1,791.8 | 514.1 |
| **9** | 1,215.1 | 1,272.1 | 1,736.9 | 460.2 |
| **10** | 1,107.1 | 1,159.4 | 1,615.1 | 451.1 |
| **11** | 1,215.1 | 1,272.2 | 1,832.5 | 554.6 |
| **12** | 1,204.8 | 1,261.3 | 1,789.6 | 522.9 |
| **13** | 946.1 | 987.9 | 1,220.0 | 229.7 |
| **14** | 766.2 | 802.8 | 833.4 | 30.3 |
| **15** | 971.2 | 1,016.4 | 1,320.7 | 301.2 |
| **16** | 966.2 | 1,011.0 | 1,263.0 | 249.5 |
| **17** | 1,009.3 | 1,055.9 | 1,395.6 | 336.2 |
| **18** | 1,152.4 | 1,206.0 | 1,605.7 | 395.6 |
| **19** | 1,169.2 | 1,223.9 | 1,615.2 | 387.4 |
| **20** | 1,193.2 | 1,249.2 | 1,773.1 | 518.6 |
| **21** | 1,054.2 | 1,101.8 | 1,436.7 | 331.6 |
| **22** | 1,010.4 | 1,057.9 | 1,377.6 | 316.5 |
| **23** | 862.1 | 902.6 | 1,032.8 | 128.9 |
| **24** | 1,051.3 | 1,101.0 | 1,527.2 | 421.9 |
| **25** | 1,157.2 | 1,211.5 | 1,700.7 | 484.3 |
| **26** | 1,184.2 | 1,239.8 | 1,761.6 | 516.6 |
| **27** | 1,186.6 | 1,242.5 | 1,777.3 | 529.5 |
| **28** | 1,187.8 | 1,243.7 | 1,779.2 | 530.2 |
| **29** | 1,166.4 | 1,220.6 | 1,719.2 | 493.6 |
| **30** | 1,106.4 | 1,158.5 | 1,547.0 | 384.7 |
| **31** | 1,068.3 | 1,118.5 | 1,276.6 | 156.5 |

Continues…

Continuation…

Table 9 – Summary of December Daily Energy Amounts

| **Month / Day** | **$E_G$ (MWh)** | **$E_A$ (MWh)** | **$E_{AM}$ (MWh)** | **$CH_E$ (MWh)** |
|---|---|---|---|---|
| **Dec** | 21,591.5 | 22,571.8 | 24,842.8 | 2,248.3 |
| **1** | 681.1 | 711.9 | 726.5 | 14.5 |
| **2** | 819.9 | 859.4 | 956.6 | 96.3 |
| **3** | 651.3 | 681.2 | 730.1 | 48.4 |
| **4** | 408.8 | 424.4 | 424.4 | - |
| **5** | 765.5 | 802.6 | 862.6 | 59.4 |
| **6** | 593.5 | 620.1 | 623.9 | 3.8 |
| **7** | 621.9 | 649.0 | 649.0 | - |
| **8** | 836.9 | 876.2 | 1,017.2 | 139.6 |
| **9** | 847.8 | 887.4 | 1,020.8 | 132.0 |
| **10** | 747.9 | 781.6 | 831.7 | 49.6 |
| **11** | 437.1 | 452.8 | 452.8 | - |
| **12** | 821.8 | 860.6 | 977.1 | 115.3 |
| **13** | 387.6 | 402.6 | 402.6 | - |
| **14** | 837.9 | 877.2 | 994.4 | 116.1 |
| **15** | 243.5 | 252.9 | 252.9 | - |
| **16** | 446.1 | 464.1 | 464.1 | - |
| **17** | 844.5 | 884.1 | 1,025.5 | 139.9 |
| **18** | 846.0 | 885.6 | 1,027.3 | 140.3 |
| **19** | 847.6 | 887.4 | 1,040.0 | 151.1 |
| **20** | 846.1 | 885.7 | 1,026.1 | 139.0 |
| **21** | 839.6 | 878.9 | 999.7 | 119.6 |
| **22** | 845.4 | 885.1 | 1,023.0 | 136.5 |
| **23** | 848.4 | 888.3 | 1,040.2 | 150.4 |
| **24** | 671.4 | 700.8 | 704.7 | 3.8 |
| **25** | 837.3 | 876.6 | 1,005.1 | 127.2 |
| **26** | 847.1 | 887.0 | 1,037.2 | 148.7 |
| **27** | 447.3 | 464.2 | 464.2 | - |
| **28** | 814.9 | 852.7 | 950.0 | 96.3 |

Continues…

Continuation…

| | | | | |
|---|---|---|---|---|
| **29** | 832.3 | 871.8 | 993.6 | 120.6 |
| **30** | 405.9 | 421.0 | 421.0 | - |
| **31** | 669.0 | 698.4 | 698.4 | - |

July and December where presented because they have the months with the highest and lowest energy production, respectively. Those months also represent the extreme spreads between the total energy injected into the grid and the maximum energy available at the solar arrays. The Figure 25 represents graphically, Table 8 and Table 9.

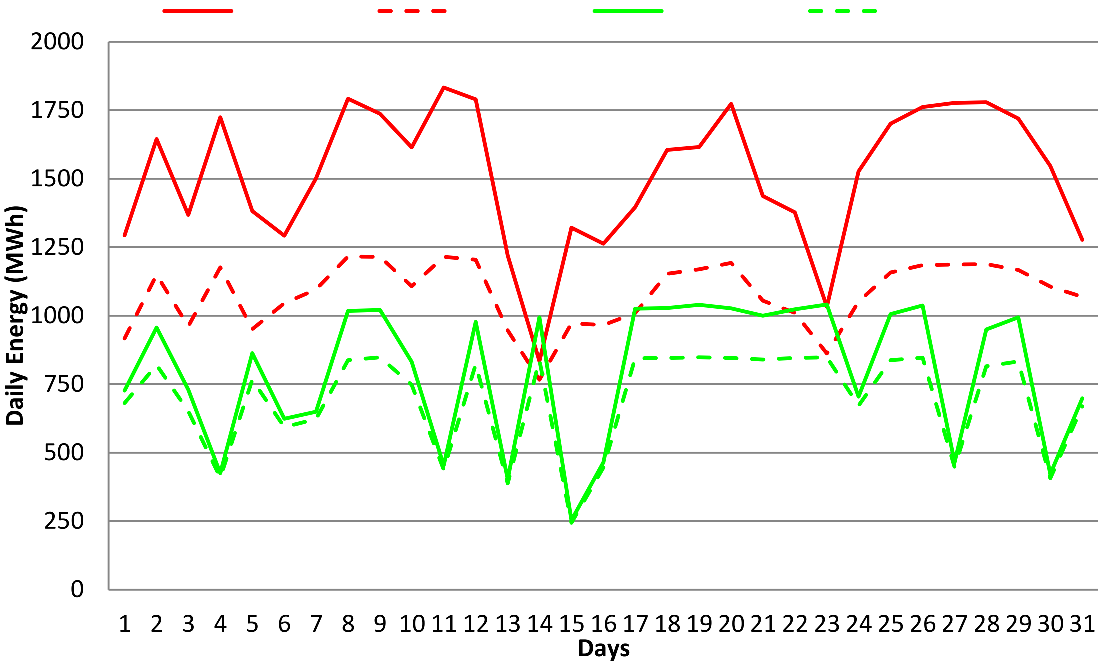

Figure 25: Daily energy available at the solar arrays and injected into the grid

## 4.4. NEW ENERGY PROFILE AND REVENUES

As mentioned in the previous chapters, 4 battery sizes will be considered for this case study. Since the DC/AC ratio has been intentionally boosted, the starting point of the analysis has the intent of storing the most of the energy available, therefore the base of the sizing was the 95% percentile of the daily Chargeable Energy.

The other 3 sizes where percentages of that number:

Table 10 – Case study battery sizes

| | |
|---|---|
| **Base Size (MWh)** | 570.0 |
| **75% (MWh)** | 427.5 |
| **50% (MWh)** | 285.0 |
| **25% (MWh)** | 142.5 |

Applying the algorithm discussed on Section 3.1.2, a new energy profile has been determined, for all 4 battery sizes. Below the summary of the New $E_G$:

Table 11 – Case study battery sizes

| | **MWh** | **$\Sigma E_G$** | **% Diff** |
|---|---|---|---|
| **$E_{100\%}$** | 570.0 | 427.23 | 0.00% |
| **$E_{75\%}$** | 427.5 | 420.12 | -1.66% |
| **$E_{50\%}$** | 285.0 | 402.22 | -5.85% |
| **$E_{25\%}$** | 142.5 | 373.63 | -12.55% |

A quick simulation was also done using a battery that would provide the maximum regularization possible, represented by a battery that would be able to store the maximum value of daily $CH_E$, equivalent to 717.7 MWh. This size of battery would represent a new amount of energy injected into the grid of 427.90 MWh, and addition of just 0.16% compared the base size, which is 570 MWh.

To illustrate the concept of the new energy profile injected into the grid, May 6th has been selected and presented on the

Table 12, where $E_{0\%}$ represents the configuration cannot store any amount of clipping losses.

Table 12 – Hourly energy profile for May 6th

| **Hour** | **$E_G$ (MWh) $E_{0\%}$** | **$E_G$ (MWh) $E_{100\%}$** | **$E_G$ (MWh) $E_{75\%}$** | **$E_G$ (MWh) $E_{50\%}$** | **$E_G$ (MWh) $E_{25\%}$** |
|---|---|---|---|---|---|
| **0** | - | - | - | - | - |
| **1** | - | - | - | - | - |
| **2** | - | - | - | - | - |
| **3** | - | - | - | - | - |
| **4** | - | - | - | - | - |
| **5** | 38.54 | 38.54 | 38.54 | 38.54 | 38.54 |
| **6** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **7** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **8** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **9** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **10** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **11** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **12** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **13** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **14** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **15** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **16** | 98.66 | 98.66 | 98.66 | 98.66 | 98.66 |
| **17** | 86.48 | 98.75 | 98.75 | 98.75 | 98.75 |
| **18** | 13.51 | 98.02 | 98.02 | 98.02 | 98.02 |
| **19** | - | 97.88 | 97.88 | 97.88 | 38.01 |
| **20** | - | 97.88 | 97.88 | 75.02 | - |
| **21** | - | 97.88 | 97.88 | - | - |
| **222** | - | 97.88 | 14.15 | - | - |
|  | - | 51.17 | - | - | - |
| **Total** | 1,223.78 | 1,763.26 | 1,628.36 | 1,493.47 | 1,358.57 |

Figure 26 represents the

Table 12 graphically.

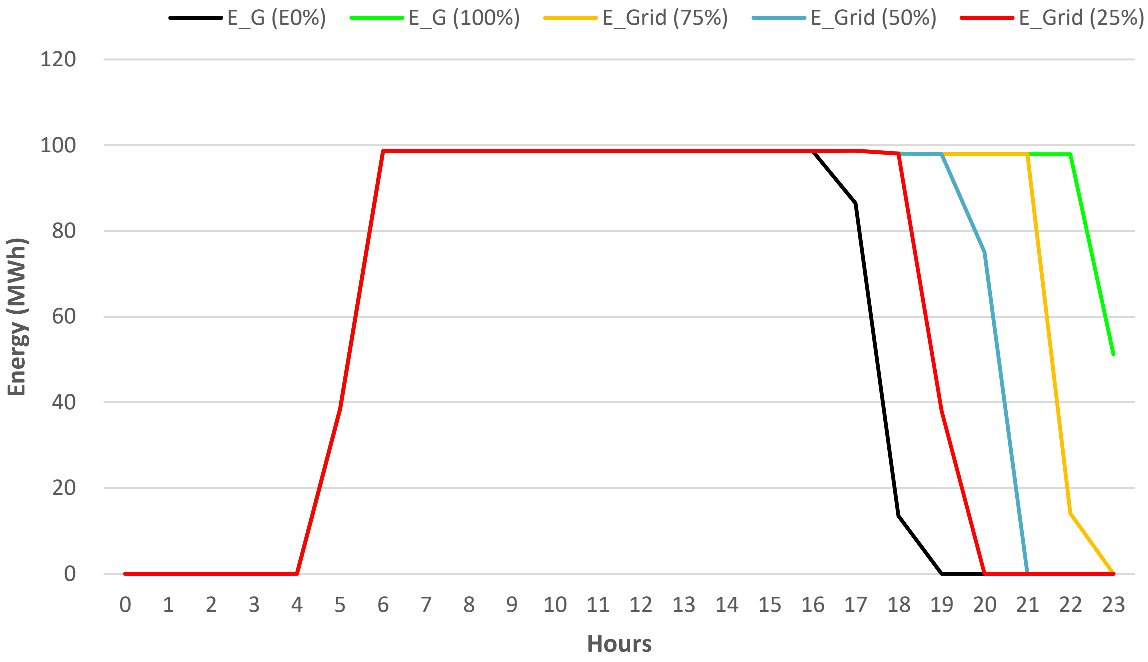

Figure 26: Hourly energy profile for May 6th

Figure 27 shows the yearly median normalized power, showing how much the solar production would be firmed, considering the addition of the battery energy system, in terms of power.

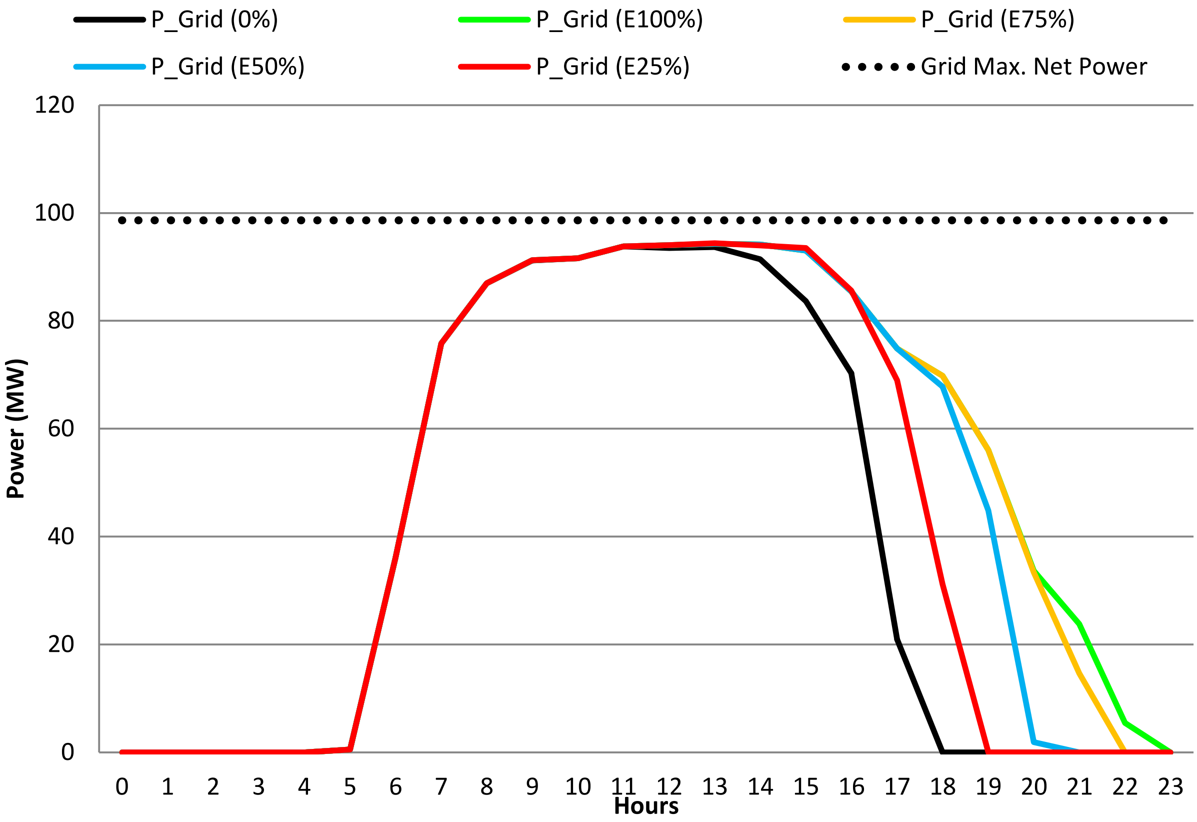

Figure 27: Yearly median normalized power

## 4.5. REVENUE CALCULATION AND FINANCIAL EVALUATION

The new energy profile will be then applied against a PPA value that varies depending on the hour of the day. The PPA table is a modified version of a RFP (Request for Proposals) previously issued by an Electric Power Utility located in the United States of America. The modification has been done to guarantee confidentially of the information and also to denote more clearly the goal of this dissertation. Numbers are presented on the Table 13:

Table 13 – PPA values per hour

| Hour | USD/MWh | Hour | USD/MWh |
|---|---|---|---|
| **0** | 30.00 | **12** | 30.00 |
| **1** | 30.00 | **13** | 30.00 |
| **2** | 30.00 | **14** | 30.00 |
| **3** | 30.00 | **15** | 73.85 |
| **4** | 30.00 | **16** | 221.56 |

Continues…

Continues…

| | | | |
|---|---|---|---|
| **5** | 30.00 | **17** | 221.56 |
| **6** | 30.00 | **18** | 221.56 |
| **7** | 30.00 | **19** | 221.56 |
| **8** | 30.00 | **20** | 221.56 |
| **9** | 30.00 | **21** | 221.56 |
| **10** | 30.00 | **22** | 73.85 |
| **11** | 30.00 | **23** | 30.00 |

The yearly revenues are calculated, considering the base case that has not batteries installed to it, as well as the 4 battery sizes selected.

Table 14 shows the increase in production and revenues, compared to the base case. For instance, the Base Size (570 MWh of batteries) show an increase in revenues of 110.39% while only it has only an increase in production of 28.20%. This is due to the fact that the energy firmed by the battery and the increase in price, of seven times, of the energy in hours where a solar PV plant could not produce power.

Table 14 – Revenue Summary

| | **MWh** | **$\Sigma E_G$ MWh)** | **% Diff Production** | **Revenues (MUSD)** | **% Diff Revenues** |
|---|---|---|---|---|---|
| $E_{0\%}$ | 0.00 | 333.27 | 0.00% | 17.23 | 0.00% |
| $E_{100\%}$ | 570.0 | 427.23 | 28.20% | 36.25 | 110.39% |
| $E_{75\%}$ | 427.5 | 420.12 | 26.06% | 35.47 | 105.88% |
| $E_{50\%}$ | 285.0 | 402.22 | 20.69% | 31.54 | 83.05% |
| $E_{25\%}$ | 142.5 | 373.63 | 12.11% | 25.21 | 46.31% |

## 4.5.1. FINANCIAL EVALUATION

The CAPEX for each solution is calculated, the investment numbers for the PV plant don't change, since the configuration remains the same for each battery proposed solution. The PV plant has an installed DC capacity of 182,628 kW, therefore:

Table 15 – PV CAPEX figures

| | **MUSD** | **USD/Wp** |
|---|---|---|
| **Solar Modules** | 67.57 | 0.37 |
| **BOP** | 58.44 | 0.32 |
| **Other BOP Costs** | 18.26 | 0.10 |
| **Other Costs** | 12.78 | 0.07 |
| **Total** | 157.06 | 0.86 |

Table 15 are based on market inquiries answered with non-binding offers, where the BOP costs bundle from the solar module installation until the substation. Other costs are considered a little bit lower than the market, since the boost on DC numbers doesn't influence these numbers and the total CAPEX is comparable to a regularly optimized PV plant, with 1.25 DC/AC ratio.

The all-in CAPEX numbers for the battery portion of the project will be considered linear and won't factor delivery schedule and economy scale, typical of orders of this size. The all-in CAPEX for the battery portion will be considered as 0.35 $/Wh. The Table 16 shows the investment numbers for all the solutions:

Table 16 – PV + BESS all-in CAPEX

| | **MWh** | **PV Portion (MUSD)** | **Battery Portion (MUSD)** | **Total (MUSD)** |
|---|---|---|---|---|
| **$E_{0\%}$** | 0.00 | 157.06 | 0.00 | 157.06 |
| **$E_{100\%}$** | 570.0 | 157.06 | 171.00 | 328.06 |
| **$E_{75\%}$** | 427.5 | 157.06 | 128.25 | 285.31 |
| **$E_{50\%}$** | 285.0 | 157.06 | 85.50 | 242.56 |
| **$E_{25\%}$** | 142.5 | 157.06 | 42.75 | 199.81 |

Based on the investment numbers displayed on Table 16, the Net Present Value (NPV), Payback and Internal Rate of Return (IRR) have been calculated, considering:

- 30 years useful life of the project
- No degradation of batteries and solar modules
- Year 1 on the cash-flow will bear all the investment, with the revenues starting at the year after
- Discount rate of 5.5%

Table 17 – Economical Evaluation

| **Battery Size (MWh)** | **0.0** | **570.0** | **427.5** | **285** | **142.5** |
|---|---|---|---|---|---|
| NPV (MUSD) | 88.49 | 188.42 | 218.20 | 204.58 | 157.90 |
| IRR (%) | 10.41% | 10.50% | 12.02% | 12.64% | 12.22% |
| Payback (years) | 9.12 | 9.05 | 8.04 | 7.69 | 7.93 |

All the battery scenarios presented gains of all of the financial indexes considered, while a significant boost has been observed on the battery sizes from 427.5 to 142.5. That is due to the fact that the smaller battery sizes have a more continuous usage of the battery, suggesting that a better ratio between $CH_E$ and battery capacity improves the system financial returns.

# 5 CONCLUSION

It can be concluded, based on the data analyzed, that boosting the DC/AC ratio of a PV plant and integrating batteries on the DC buss of the power conversion systems, the project will be boosted. This is possible due to the extra sources of revenues that the PV + BESS hybrid systems starts to be able to tap, once it can be dispatched and produce power during the night, which is not an option for PV plants. The higher returns are observed where the ratio between the battery capacity and the new energy grid are higher.

It is also concluded that even though there are many storage technologies available, their stage of development, costs and performance, the integration with BESS can help on unleashing the potential of the power production based on renewable sources.

The use of battery systems solely to reducing clipping losses is not accretive to the project returns, since the clipping losses are already kept at a level inferior to the round trip efficiency of the battery and the advantage of the system is observed only in situations where the DC/AC ratio is high. The results of this dissertation show that the seasonal variability of the renewable source would be better controlled using batteries, basing on the economic figures considered.

The charging mechanism should be better investigated, since the variability of the solar resource over the year could lead to a battery size that is not optimal to the project returns or lead to elevated clipping losses during spring and summer times. As showed on 4.3 and integrated approach between clipping losses optimization and battery size could lead the set to better performance and returns.

The proposed algorithm to verify chargeable energy, charge the battery and discharge it back during evening time, while with some simplifications, worked as proposed and helped on calculating the new net energy profile.

It is suggested as future works:

- Detail augmentation strategy and include it in the evaluations.
- Inclusion of the detailed degradation of the solar modules, losses of a BESS, deepening the impact of the battery types on the system behavior and how it battery type would function on a certain type of grid service.

- Include the DC/AC ratio and the calculated energy profiles as part of the question to be answered, by means of proposing and integrated approach to optimize the system as a whole.

DC coupled BESS systems are starting to be made available for battery and inverter manufacturers, but given the lack of project footprint and clear regulatory framework to treat DC couples systems, it’s considered that the dissertation achieved its intended goal.

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