MSc Program
Renewable Energy Systems

Analysis of the feasibility of PV plus battery storage in utility-scale plants in Spain

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Dr. DI Amela Ajanovic

José Manuel Alonso Huerta, MSc

11728344

Vienna, 02.11.2019

Affidavit

I, **JOSÉ MANUEL ALONSO HUERTA, MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ANALYSIS OF THE FEASIBILITY OF PV PLUS BATTERY STORAGE IN UTILITY-SCALE PLANTS IN SPAIN", 148 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Thanks to my whole family for their support and the colleagues of this Master, who have been like another family

Abstract

The photovoltaic (PV) technology is a mature technology in Spain, a country with high sun resource. The implementation of storage solutions in the PV plants provides an opportunity to improve the performance of the PV plants, resulting in higher incomes compared to the projects without storage. Will the prices of storage solutions drop to make them economically feasible to be implemented in PV plants? What are the trends? When will prices be attractive and make the investment feasible?

Lithium-ion batteries are an attractive option for electricity storage, not only for PV projects but for wind projects too. PV plants can benefit from these new opportunities and/or the technical and economic improvement of the lithium-ion battery technology, triggered by the competition of other storage technologies.

PV is a mature technology in the Spanish market. For the current PV investment costs and electricity market prices, it is possible to invest without big risks as it has been proven with the latest renewable energy auction, when 1,037 MW of PV projects were awarded to different developers.

On the other hand, lithium-ion battery storage systems investment needs still a huge economic effort and, though prices are expected to decrease significantly during the next years, they will still remain high. Considering only the battery system cost reduction, the levelized costs of energy (LCOE) of PV plants with lithium-ion batteries are expected to be above the electricity market price still by the year 2030. Only the combined reduction of PV plant and battery storage costs will bring the total costs to LCOE values below the electricity market price. This occurrence is expected to happen during the next decade depending on different technical and economic scenarios.

INDEX

1 Introduction

As a former consultant of renewable energy projects, most of them developed in Spain and focused on wind and PV, I remember the first time I visited a concentrated solar power (CSP) plant. I lacked of previous knowledge on this technology and became immediately attracted, like a magnet, by the huge molten-salt tanks that could provide the CSP plant with 3 hours of additional generation at full load. Since that very first experience, I see with great interest the possibility that storage systems can provide to improve the performance of other renewable energy projects like in wind and PV plants.

One of the advantages of storing energy is to improve the fluctuating nature of the supply of the solar and wind energy sources. These two sources could behave in a very intermittent way, either providing large amounts of energy or none, in different years, for the same period of time of the year. Storage systems may also help improving the economic performance of the projects, provide more stable output power or supply electricity when the demand overcomes electricity generation .

The development of energy storage devices provides an opportunity for its implementation in wind and PV plants. Storage may be a larger challenge if we take into account a future scenario where the revenues of the wind and PV plants, and most of the renewable energy projects, are based on market prices, without FIT, premium prices or other subsidies. Therefore, I see with high interest the challenge to analyze a PV plant with lithium- (Li-ion) batteries and to estimate when and under which conditions would they be attractive from the economic point of view.

Is it feasible to implement energy storage facilities in utility-scale PV plants in Spain in the near future? For that purpose, the current PV market is to be analyzed as well as the current situation of storage possibilities in Spain, focusing in lithium-ion battery storage. Using the results of this analysis as a start, the objective is to assess different future scenarios with which to estimate under which circumstances the implementation of storage in utility-scale PV projects would be attractive for developers.

The method of approach in this master thesis is therefore summarized as follows:

- overview of the PV market in Spain from the technical, legal and economic point of view, showing the first steps of development of the technology, the golden years and the current situation
- selection of two PV project location. The size of the PV plant is 1 MW

- estimation of the radiation, generation and revenues of the chosen projects, with and without storage, with irradiance hourly data from SIAR (June 2018-May 2019) and hourly market prices
- estimation of the scenario and expected year when lithium-ion storage systems would be economically attractive (LCOE below electricity market prices)

2 Storage technological overview

2.1 Storage overview

The past century saw a large development of numerous energy storage technologies in the world of which the largest systems were typically based on physical or thermal principles (Fu et al (2018)). An example of the first storage systems is a pumped hydro storage system, where the water is pumped into a reservoir situated above the conversion center. The stored water is released downhill, whenever the demand needs energy, and passes through hydroelectric turbines to convert the stored potential energy into electricity. The first large-scale pumped hydro system in the USA was built in 1929 near New Milford, Connecticut, and the largest one was built in 1985 with a generation capacity of 3 GW. The efficiency of this technology is typically around 70%–80%, but costs are a major problem. Cost-effective sites must have characteristics that permit damming to create a reservoir, and usually the required areas are very large in size and situated far from the populated areas, where the demand of energy is high. Additionally, environmental and landownership considerations may lead to lack of project approvals.

An example of pumped hydro storage system in Spain is the Hydroelectric plant of Aguayo, in the autonomous community of Cantabria. This plant is on service since 1982 and has an installed power of 360 MW with a flow of 30 m^3/s and a height of 328,5 meters between the upper and lower reservoir. It supplies up to 38% the electricity generation of the region (EN (2015)).

Nowadays the number of types of storage system have increase and can be summarized in mechanical, thermal, electrochemical and electromagnetic systems, which are subdivided into the following subcategories (IDAE (2011)):

- Mechanical systems:
    - Compressed air
    - Pumped hydro
    - Flywheels
- Thermal systems:
    - Molten salts
    - Phase-changing materials
- Electromagnetic systems:
    - Supercondensators
    - Superconductor magnets

- Electrochemical systems:
    - Hydrogen
    - Flow batteries
    - Stationary batteries

The different storage technologies are currently in different stages of development. The ideal storage technology for all-purposes does not exist. However, each of these technologies have advantages, disadvantages and associated costs which make them the suitable alternative depending on various circumstances and generation demand.

Figure 1 shows the characteristics of storage technologies for systems built between 1958 and 2017 worldwide, categorized by storage type: electrochemical, electromechanical, thermal, and hydrogen. Pumped hydro is not shown because its global capacity is much larger than the capacity of the other technologies.

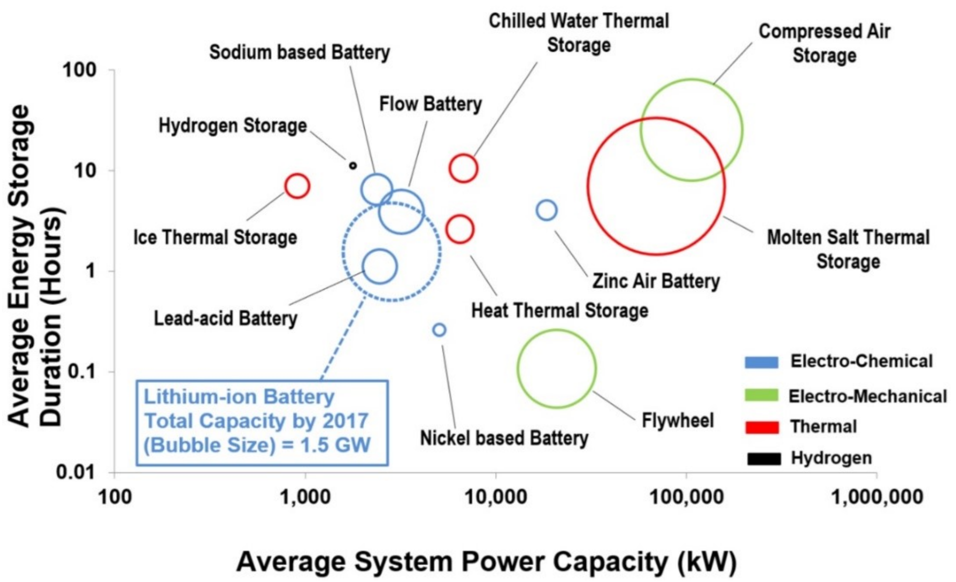


Figure 1 .- Average characteristics of storage systems built worldwide between 1958 and 2017 (Fu et al (2018))

Figure 2 shows the annual capacities of storage systems built worldwide between 2005 and 2017. It can be seen, especially during the year 2015, the rapid growth of Li-ion storage worldwide during the recent years. Between 2008 and 2015, Li-ion capacity grew at a compound annual growth rate of 173% in terms of cumulative capacity, and Li-ion capacity accounted for 89% of annual storage capacity in 2015 (Fu et al (2018)). Like in Figure 1, pumped hydro is not shown because its global capacity is much larger than the capacity of the other technologies.

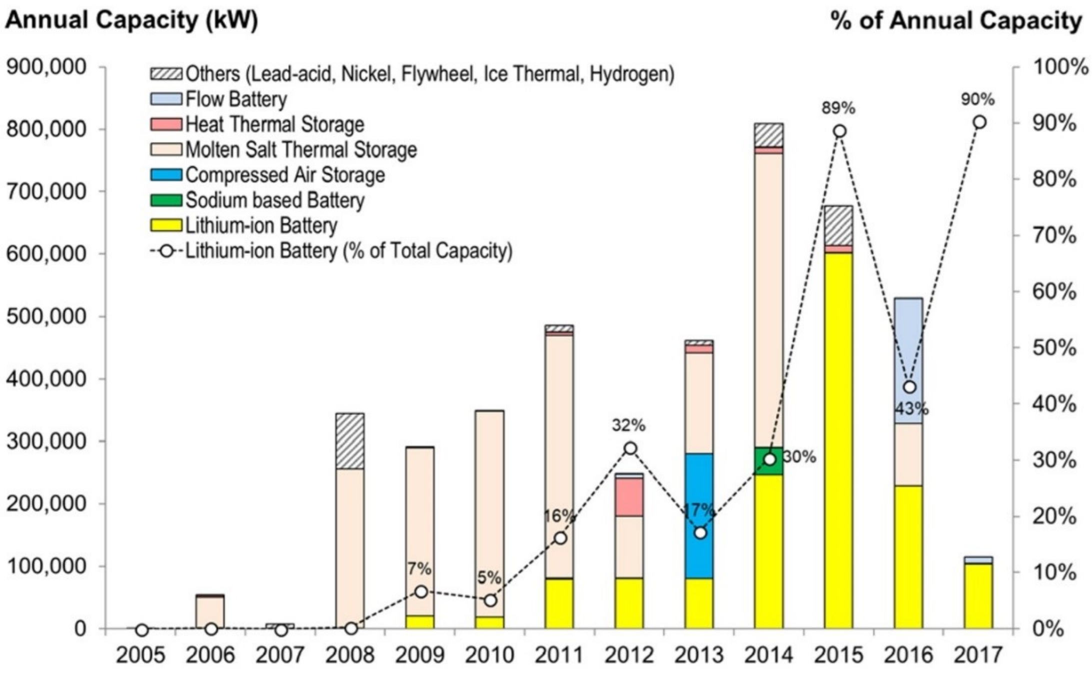


Figure 2 .- Annual capacities of energy storage systems built worldwide between 2005 and 2017 (Fu et al (2018))

The following chapters present a description of some of the storage technologies according to IDAE (2011). On the other hand, the batteries used for the calculations of this thesis, lithium-ion batteries, are later presented in the separated chapter 2.2 Main PV plant components.

2.1.1 Compressed air

Compressed air technologies involve system which may be suitable to level the charge at large scale. These systems are based on the use of pumps for the storage of compressed air in tanks or sitting, that means, the energy is stored as mechanical energy in the form of pressurized air or heat, which is later discharged on turbines to generate electricity. The advantages of this technology are the scalability of the energetic capacity and its potential as an economic solution for the short-term storage. However, its cycle efficiency is lower than expected (down to 40%, maximum of approx. 70%), leading to the necessity to improve the heat compression and the storage of the pressurized heat (IDAE (2011)).

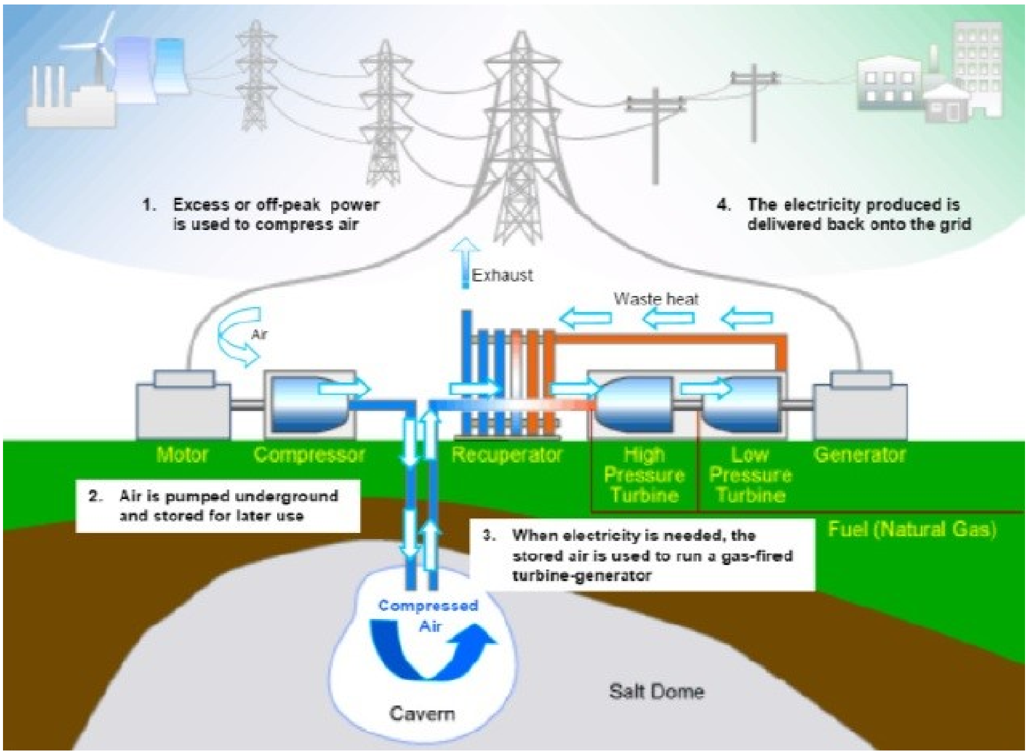


Figure 3 .- Description of compressed air energy storage process (Cheng et al (2013))

2.1.2 *Flux batteries*

Flux batteries involve a large variety of solutions and have been mainly developed towards two technologies (IDAE (2011)):

- Vanadium redox batteries: this solution is considered the future option for large-scale storage. Its performance is based on the chemical storage of different ionic forms of vanadium inside sulfuric acid electrolytes. The electrolytes are oxidized and reduced creating a current which is transported via electrodes with a reversible reaction that permits the battery to be charged, discharged and recharged. This technology presents high energetic scalability potential and efficiency (75-85%). On the other hand, the need of large amounts of acid chemicals increases its costs. The technology is considered as almost mature and is a consistent option for medium-scale projects.
- Sodium-Sulphur batteries: this technology is well implemented in large-scale projects with satisfactory results. They are based on the chemical storage of different sodium and sulphur ionic forms as liquid electrodes, forming reversible reactions that permit the battery to be charged, discharged and recharged. Of great advantage is the availability of raw material for its construction and that they are not toxic and have a high efficiency (75-85%).

A disadvantage of this technology is the need for isolation for the high temperature accumulator and that the warm-excess requires of energy, i.e., 15-30 kW/MW of the capacity of the battery. It is a promising technology relatively mature with various reference projects in service, with capacities of up to 34 MW.

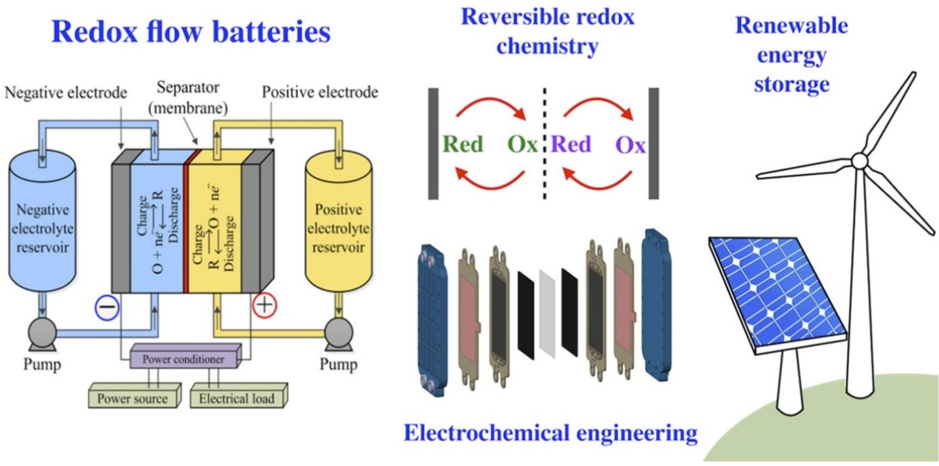


Figure 4 .- Description of flux battery storage (Arenas et al (2017))

2.1.3 *Pumped hydro*

Pumped hydro is the most widely storage technology used in the world (IDAE (2011)). It works in a very simple way: the usage of pumps to transport water from a base level to a higher level where the water is stored as potential energy. When the demand requires it, the water is driven down to the base through turbines that generate electricity. The advantages of this technology are the total scalability and a high efficiency (~80%).

On the other hand, this technology depends much on the availability of suitable land and social/political acceptance due to the large extensions required for its construction.

It is a mature and reliable technology but limited to new projects and with performance difficulties in warm climates due to the evaporation of the stored water in the long term.

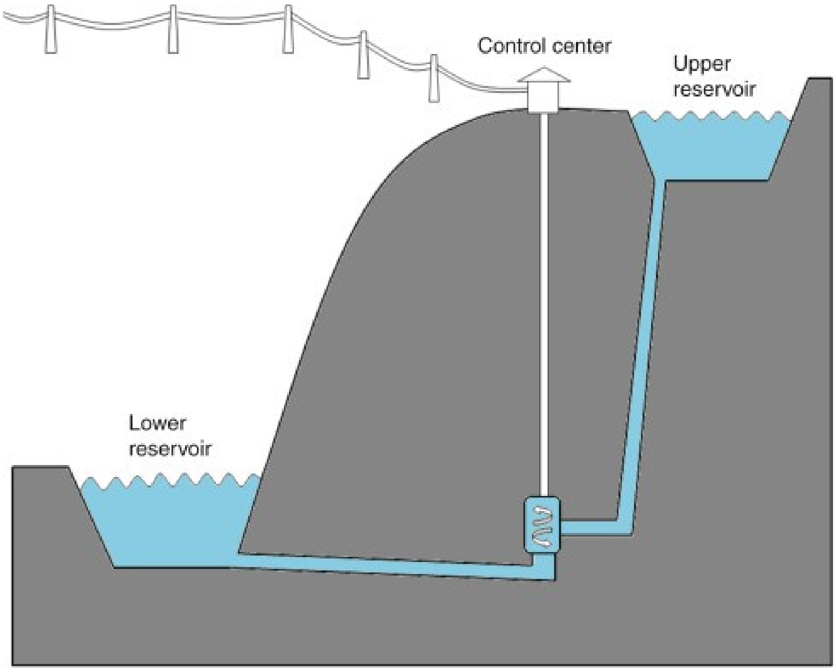


Figure 5 .- Description of pumped hydro storage (Yang (2016))

2.1.4 Hydrogen

Hydrogen siting is considered as a suitable solution for the long-term storage. The technology is based on the electrolysis for H_2 (and O_2) generation and subsequent H_2 storage. It is store on siting or tanks that permits the later generation of electricity with turbines or fuel cells (IDAE (2011)).

The advantages of this technology are the highest energetic density among the large-scale storage solutions and that it is the most economical solution on the large-term. However, it lacks of aa suitable efficiency with a poor 40% and requires large construction sites.

This solution is considered as a not yet well-proven technology but could provide a potential solution for large-scale wind parks though it still needs development, since it is still on a conceptual stage and for which only partial solutions have been proved.

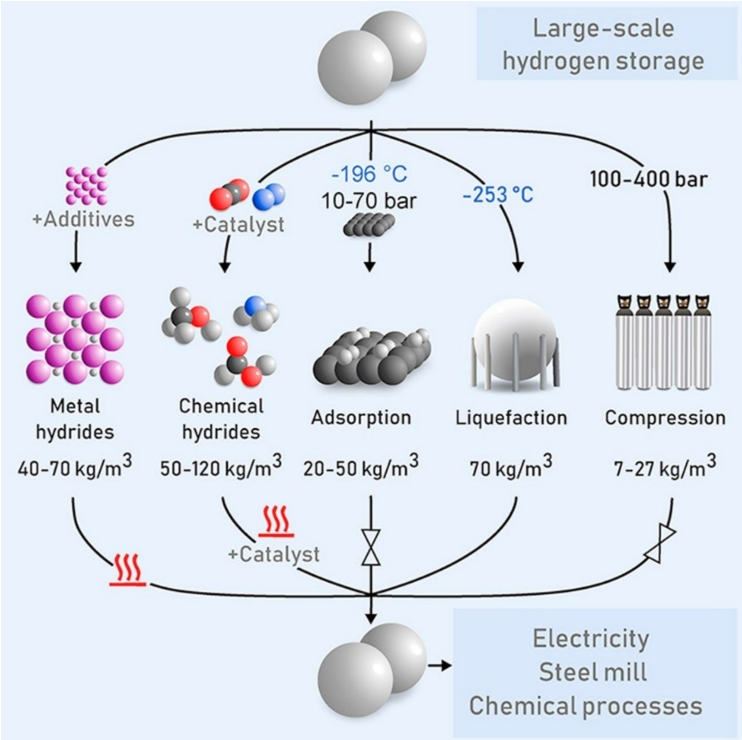


Figure 6 .- Description of hydrogen storage (Andersson and Grönkvist (2019))

2.1.5 Flywheels

Flywheels are considered a good technological option to store electricity on the short term. When the system is in charging mode, an electric motor spins a wheel of steel or compound material, normally supported on magnetic bearings, up to speeds of 20,000 RPM (100,000 RPM in vacuum). Then the wheel keeps on spinning permanently (IDAE (2011)).

When the system is in discharge mode, the wheel pushes a generator which produces electric energy.

An advantage of this technology is that they can be frequently used without or with few effects on the lifespan of the wheel. Furthermore, it is a fast recharging method with relatively high electric power. On the other hand, the discharge times are very short, meaning low storage capacity.

This mature technology is therefore considered an uninterrupted power systems in substitution of large batteries and could be, in the future, a solution to balance the peaks in the grid on the short-term.

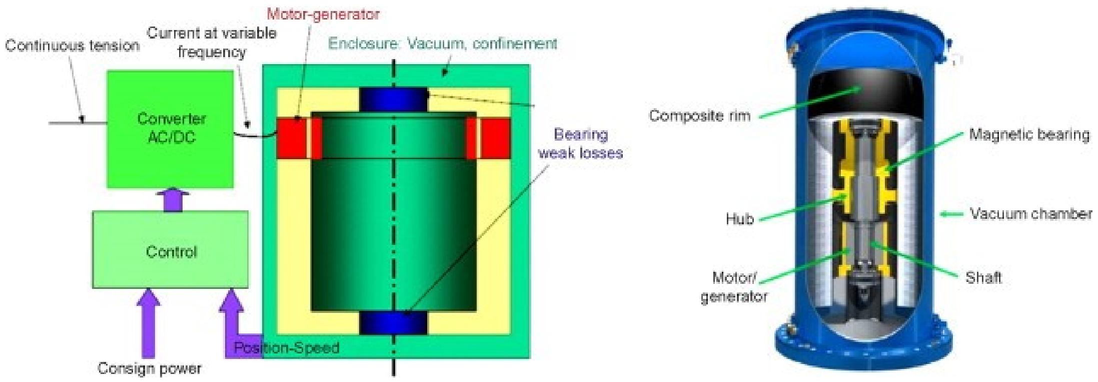


Figure 7 .- Description of flywheel storage (Kavadias (2010))

2.1.6 *Molten salts*

These thermal storage systems are based on the usage of the solar concentrated energy to warm molten salts, either indirectly by means of the oil in CSP of parabolic through technology or directly (tower technology). When the demand requires it, the stored heat is discharged to the system and heats the water whose steam moves the turbines that generate electricity (IDAE (2011)).

The typical solution is the so called two-tank solution, where one of the tanks contains “cold” salts which are heated and pumped to the “warm” tank.

The main advantage of this technology is that there is no energy conversion to electric energy before the storage takes place, what improves the efficiency of the cycle.

However, it is not suitable for decentralized solutions, since the molten salts can freeze under low radiation conditions. Therefore, this technology is considered as mature with undergoing research and development (R&D) but mainly limited to CSP plants, while its use in other type of projects has not been yet evaluated.

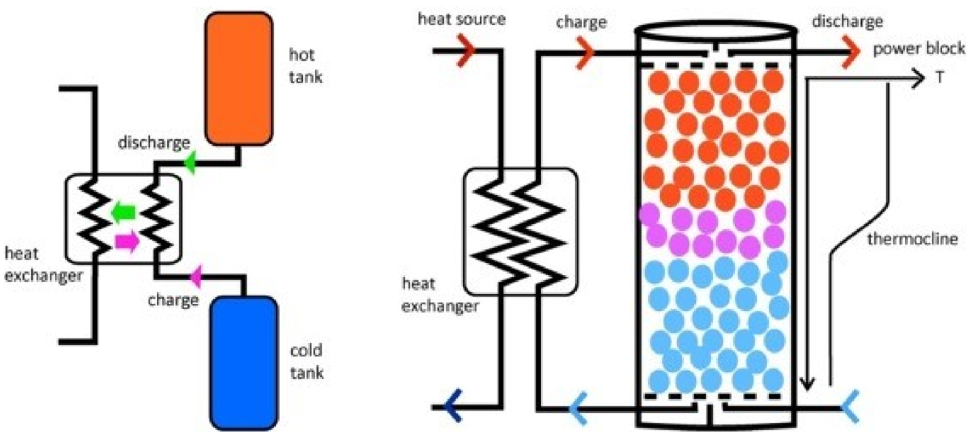


Figure 8 .- Description of molten salts storage (Stutz et al (2017))

2.2 Main PV plant components

2.2.1 Introduction

PV plants with lithium-ion storage have a number of components whose complexity and quality influence the performance/efficiency of the plant in a higher degree than other components. These components are the PV panels, the inverters, the transformers and the lithium-ion batteries themselves. The following sections provide an overview of them.

2.2.2 PV panels

The direct conversion of solar radiation into electricity is the base of the PV plants. Solar modules are the main element of these PV plants. The solar radiation provides energy to the electrons of the semiconductor material in the solar modules. When this energy is enough, the electrons are freed after overcoming the bandgap of the semiconductor in a process known as the photovoltaic effect (Cepeda and Sierra (2017)). This process creates a difference in electrical potential which can be increased when the modules are connected in series. The simplicity of this technology permits the creation of large projects in remote areas or small installations suitable for individual residences.

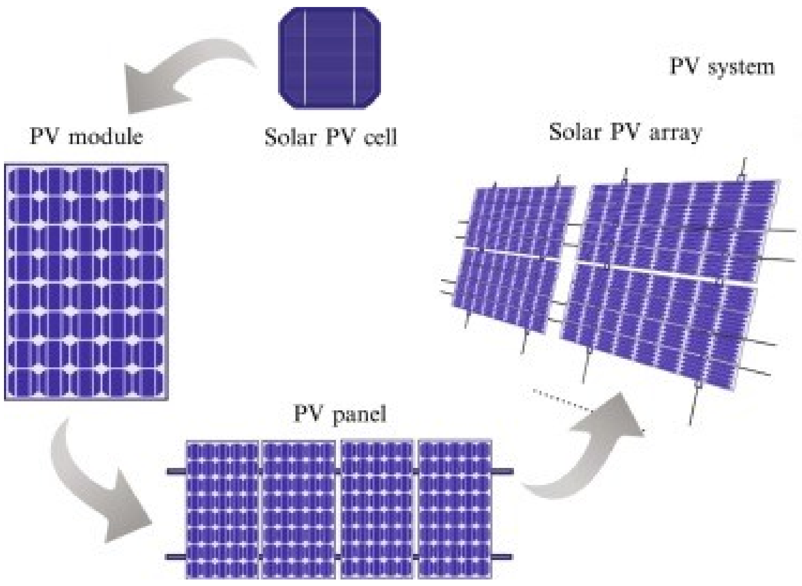


Figure 9 .- PV panels (Yang et al (2018))

The main element of the PV panel is the solar cell, which is where the conversion of solar radiation into electricity takes pace. Most of the solar cells for big commercial PV plants are made of silicon, either mono or polycrystalline.

Monocrystalline cells are usually made of silicon wafers of about 350 µm of thickness. They are of very high purity and perfect crystalline structure and have a characteristic blue uniform color, though they can also be black. These wafers are cut in squares of about 10 cm side. On the other side, polycrystalline wafers are made on a similar way as monocrystalline wafers. The difference in its construction is that the silicon is melted and poured in a mould and the wafer can be cut in a square shape. The temperature of the silicon then decreases and crystalizes itself in an imperfect way, which gives the wafer a color characterized by many different tones. Monocrystalline cells have a manufacturing process which is more complicated and expensive than the process of the polycrystalline cells, but the former usually have better efficiencies.

Film cells, also known as amorphous cells are also often used, though their efficiency is lower than the previous ones and have a much cheaper production. These consist of a solid surface, usually a glass, over which one or a combination of photovoltaic material is deposited. This photovoltaic material can be silicon or other materials like cadmium telluride, gallium arsenide or Copper Indium Selenide. Photovoltaic modules made of amorphous cells can lack of a metallic frame, like the ones used by crystalline modules, and have a dark black look.

Following is a summary of the types of cells according to Cepeda and Sierra (2017).

Table 1 .- Efficiency of Monocrystalline, Polycrystalline and Amorphous cells (Cepeda and Sierra (2017))

Type of cell	Efficiency	
	Lab	Direct
Monocrystaline	24%	14-17%
Polycrystaline	19-20%	11-14%
Amorphous	16%	<10%

The efficiency of the PV panels depends on the maximum power point/peak power (MPP). The MPP is the product of the maximum voltage (V_M) by the maximum current (I_M). This is the point at which the solar cell is more efficient. Therefore, the efficiency of a cell/module is defined as follows (Chikate et al (2015)):

$$\eta = \frac{P_M}{P_L} = \frac{I_M \cdot V_M}{P_L} \quad (1)$$

where P_L is the energy input from the sun. These parameters are obtained in standard conditions according to norm EN61215:

- solar radiation: 1000 W/m^2 (1 KW/m^2)
- spectral distribution of the incident radiation: AM1.5 (air mass)
- normal incidence
- cell temperature: 25ºC

Another important parameter is the so called NOCT (nominal operational cell temperature), which is described as the temperature that the cell reaches when operating under the following conditions:

- irradiance: 800 W/m^2
- spectral distribution of the incident radiation: AM1.5 (air mass)
- normal incidence
- cell temperature: 20ºC
- wind speed: 1 m/s

Different factors affect the temperature of the photovoltaic module when it is in service. These factors can be both external and internal and should be reduced in order to maximize the performance of the module. These and other factors together with the performance ratio are later explained in section 4.3.2.

2.2.3 Inverters

An inverter is a device which can convert electrical energy from DC form to AC form.

In a PV plant the inverter converts the direct current generated in the PV panels to alternating current, which is the type of current that is used by the grid and supplied to the final consumers. Furthermore, the inverter converts the direct current into a three-phase alternating current with an offset of 120°. Therefore, the inverter is not only the device responsible to convert the type of current but also to synchronize the wave to make it compatible the grid. Moreover, the inverter has security features to guarantee the quality of the wave supplied to the grid and the safety of the PV plant itself and the people working on it.

The inverters are the devices that set the nominal power of the PV plant, that means that they set the upper limit at which the PV plant can produce.

For a good performance of the PV plant, it is desired that the inverter provides the PV plant with the following (Diaz and Carmona (2010)):

- High efficiency and readiness to perform on a high range of power values

- Low no-load consumption
- High reliability, resistant to start-up peaks
- Protection against short-circuit
- Security
- Good regulation of the supplied voltage and frequency, which have to be compatible with the electric grid

The parameters that determine the characteristics and performance of an inverter are the following:

- Power: like before stated, the inverter set the maximum power at which the PV plant can supply electricity to the grid. The market provides inverters with a large range of available power, from 50W of the mini-inverters that are installed on each PV panel to 400W for small PV plans and up to kW values. Many of these inverters can be connected in parallel to increase the power of the PV plant.
  Inverters with a power below 5kW are usually mono-phase devices while above 15kW they are usually three-phase devices
- Efficiency: the efficiency of a inverter should be high in the whole range of power for which it is designed. The average efficiency of the current inverters is 90%, being higher when the inverter works at its nominal power. To have a good performance of the PV plant, it is important that the peak power of the PV plant is higher that the nominal power of the inverter
- Protections: in order to guarantee the protection of the inverter, and therefore the PV plant, it is recommended that the device has:
    - Automatic switch
    - Protection against islanding operation
    - Maximum and minimum voltage limiter
    - Maximum and minimum frequency limiter (2% range)
    - Overload protection
    - Short-circuit protection

The inverter can be considered as the second most important device of the PV plant and it is a critical point in the design of the plant: should the PV plant have many small inverters or fewer but bigger?

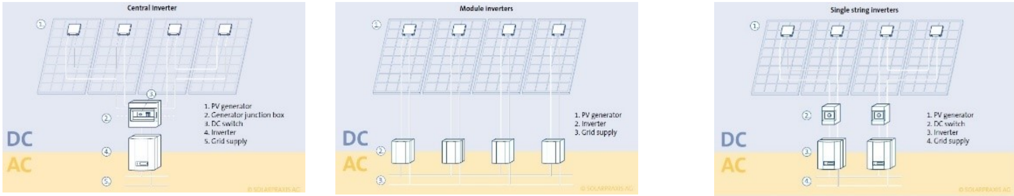


Figure 10 .- Solar inverters in different possible configurations for a PV plant (Solarpraxis (2011))

2.2.4 *Transformer*

The transformer is an alternating current device that converts the value of the current and voltage between two or more circuits. The conversion of the transformer maintains the frequency of the electric wave and the output power of the inverter.

The transformer in a PV plant converts the voltage supplied by the inverter so it matches the voltage in the electric grid. It can be considered a critical element of the PV plant together with the PV panels and inverters.

Transformers have high efficiency rates and require of few maintenance tasks. Similar to inverters, the closer to the nominal power the transformer works the higher its efficiency is.

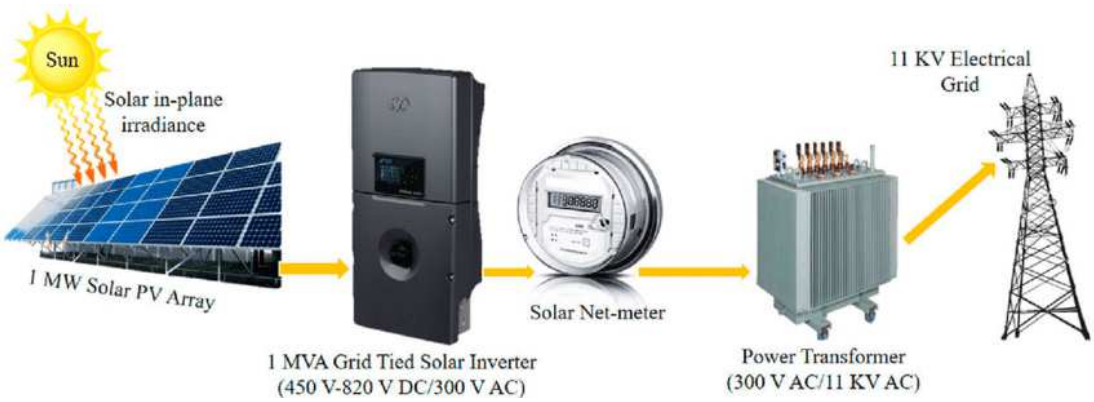


Figure 11 .- Transformer together with main components of a PV plant (Kumar (2017))

2.2.5 *Lithium-ion batteries*

Morante (2014) presents lithium as an element with very favorable energetic properties, due to its lightness (Pm = 6,939 g/mol) and high standard potential reduction (-3,04 V), what make lithium an optimal element to be used as an electrode in electrochemical batteries. To improve these batteries and avoid short-circuit problems, one lithium metallic electrode is replaced with an electrode that inserts lithium into the crystalline network of the material used as the electrode. Hence lithium-ion batteries are created.

The evolution of lithium-ion batteries implies the coexistence of different materials for both the cathode and anode and electrolytes. These materials operate in a similar way aiming to search for the maximum efficiency in the lithium intercalation/deintercalation process and to minimize the degradation caused by these processes.

Material usually used for the cathodes are:

- LCO Lithium cobalt oxide. It currently covers 50% of the lithium battery market
- LMO Lithium manganese oxide. Covers 10% of the market
- NMC Cobalt manganese oxide lithium nickel. Covers 25% of the market
- NCA Aluminum oxide cobalt nickel lithium. Covers 10% of the market
- LFP Lithium iron phosphate. Covers 5% of the market, although it has a strong growth forecast

Material usually used for the anodes are:

- Graphite
- Carbon derivatives such as graphite, active carbons, etc.
- Tin alloys
- Materials based on nanostructured silicon
- LTO Lithium Titanites

Electrolytes are usually mixtures of different carbonates (DMC dimethyl, EC ethylene, EMC ethyl methyl) with different lithium salts (LiPF6 hexafluorophosphate, LiBF6 tetrafluoroborate, LiBOB di-oxalate borate).

Figure 12 shows the basic lithium-ion battery system. Li-ion batteries are based on an electrochemical reaction between interleaving and de-interleaving lithium ions between the layers of the material constituting the cathode and anode electrodes.

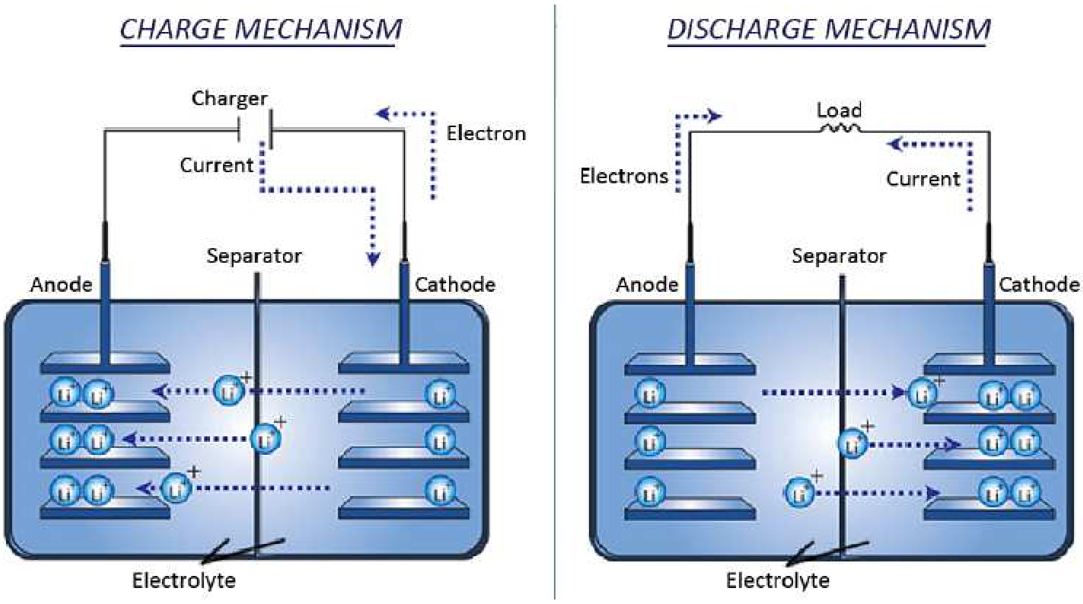


Figure 12 .- Schematic diagram of the charge-discharge process of a Li-ion cell (Noshin et al (2012))

The reactions occurring in the battery are as follows:

$$LiCoO_2 + C \rightarrow Li_{1-x}\,CoO_2 + Li_xC$$

Later, the discharge reaction occurs through the migration of lithium ions from the anode to the cathode. In the reaction below, the arrow pointing to the left represents the discharging process while the arrow pointing to the right indicates charging process.

$$Li_{1-x}\,CoO_2 + LixC \leftrightarrows Li_{1-x}{+}d_xCoO_2 + Li_{x-dx}C$$

With a fully charged battery, lithium is stored in an interleaved mode in the anode material. During the discharge process, lithium migrates from the anode to the cathode through the electrolyte in the form of positive ions. At the same time, electrons flow from the anode through an external circuit and into the cathode. During the first cycle of the battery, a thin layer, known as solid electrolyte interface (SEI), forms on the surface of the electrodes in a spontaneous way as a result of electrolyte decomposition. This layer is generally insulating but ionically conductive. Generally, this layer is formed at the graphite anode and operates at potentials at which the electrolyte is thermodynamically unstable (less than 600 mV vs. Li/Li+), creating a complex heterogeneous phase with many secondary interfaces. The composition, behavior and properties of the SEI vary with different electrode/electrolyte systems and operating conditions. The electrolyte is usually a non-aqueous organic liquid, such as ethylene carbonate containing dissolved lithium salts such as LiPF6.

The reaction for the intercalation of lithium in different materials has been widely studied and constitutes the differentiation between different companies. Some examples are shown in Figure 13.

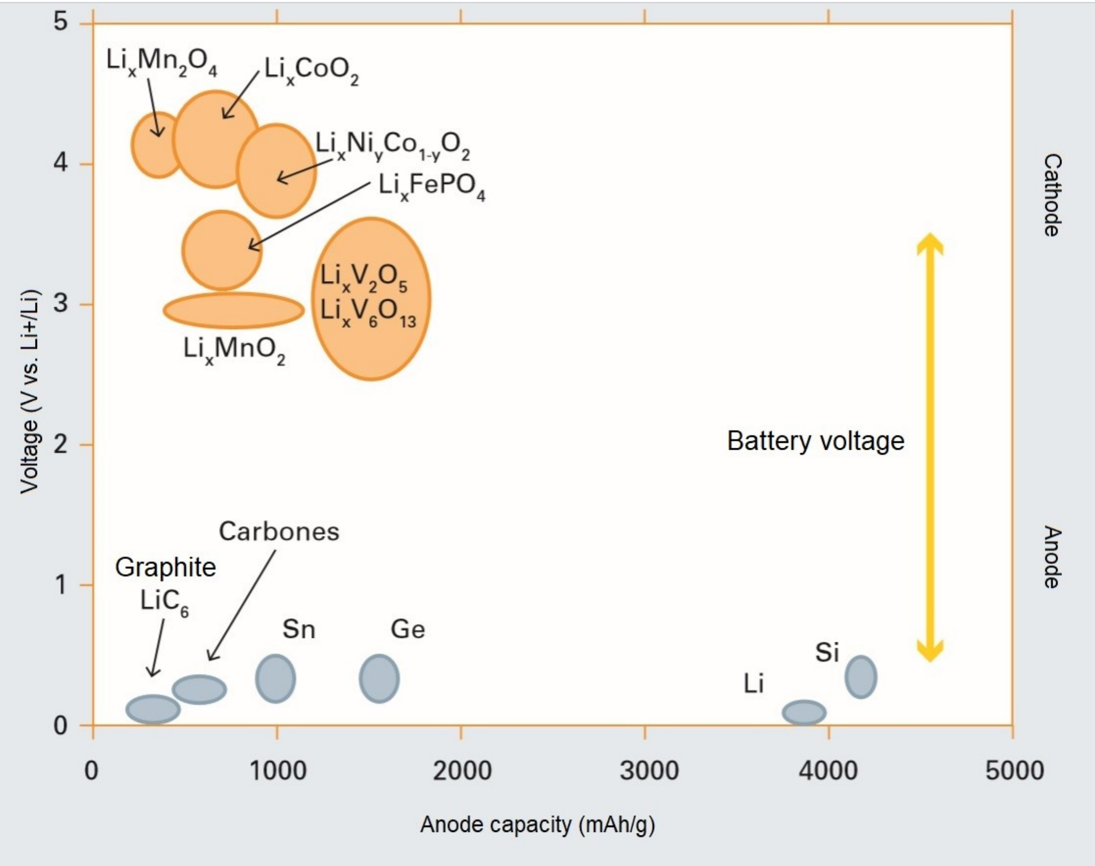


Figure 13 .- Potential interval of the different lithium interleaving electrode materials with respect to the potential of metallic lithium (Morante (2014))

With the anode and cathode materials used in these batteries, high energy densities and energy densities per unit weight can be achieved, with values of approximately 170-300 Wh/L and 75-160 Wh/kg respectively. The voltages are high too, with values on the average operating voltage of 3.6 V - 3.7 V for graphite anode batteries. These voltages are approximately three times the cut-off voltage characteristic of Ni-Cd and Ni-MH batteries.

Lithium-ion batteries attract the interest in the field of materials, technology and other fields, in order to obtain high-power devices for applications of electric vehicles and stationary energy storage, where new materials can provide large improvements of performance.

On the other hand, their dynamic characteristics are also outstanding. The time it takes to reach 90% of the nominal power of the battery is around 200 ms, with an efficiency of 78% in 3,500 cycles. This makes these batteries very good candidates for applications where the response time is important, presenting a minimum self-discharge of only 1-5%, without any memory effect as occurs with other batteries like Ni-Cd and Ni-MH batteries.

The major driver of the Lithium-ion technology is at the moment the automotive industry. However, it has also extended its use in the direction of the wider market that constitutes the electrical network. An example of a large-scale lithium-ion battery system is the Tehachapi project in California, United States. This project is located in the wind power production area of Tehachapi, one of the largest in the world if considering wind energy production potential (4,500 MW of wind power before 2015). The storage system of this project consists of a lithium-ion battery based on phosphate cathodes, of 8 MW with 4 h of autonomy (32 MWh of storage capacity). This battery and the rest of the storage unit equipment are housed in a 585 m^2 building that is remotely controlled.

Several companies are testing systems of about 25-50 kW as Distributed Electric Energy Storage (DESS) elements, and some companies have already implemented them. In Europe, companies such as EDF Energy Networks, together with ABB, have implemented experimental systems (200 kW for one hour) on wind and photovoltaic farms to help with issues like voltage control, frequency regulation, power factor correction, compensation within the battery capacity of the intermittence, support for the connection ramp and others. Siemens has been also developing, together with battery manufacturers, a modular storage system especially aimed for smart grids and with expansion possibilities in the range of 2 MWh with output powers of up to 8 MW.

The main advantages of the lithium-ion batteries are:

- High energy density
- Low weight and small volume
- High efficiency per cycle: values in the range between 85 and 98%, depending on the technological variant.
- Low required maintenance
- The low level of self-discharge: 0.1% per day
- The high voltage of the redox reaction per cell

- They provide large amounts of power in short periods of time, as well as lower power levels in longer periods of time (hours), with a response time of seconds

One of the disadvantages of the lithium-ion batteries is that they need to maintain a safety voltage and operating temperature ranges due to their complex internal fragility, requiring protection circuits. On the other hand, its main advantage is related to the phenomenon of lithium intercalation, but this is also responsible for its gradual degradation, as the crystallographic structure of the electrodes degrades due to its intercalation and generates a growing internal impedance in the battery.

Innovations should consolidate the battery characteristics based on the use of new cathode, anode and electrolyte materials and should ideally be:

- The increase of the number of cycles and/or lifespan; a cycle number greater than 10,000 is desired
- Cost reduction
- Safety increase
- Improving the working temperature range
- The definition of a complete recycling chain, with its methodology and control
- The implementation of new tools for battery control and diagnostic adapted to its functions in electrical networks, controlling temperature, voltage and current per cell and battery module without increasing costs

Being placed in a currently high competitive market and with the perspectives for the coming years, lithium-ion batteries will have to compete in costs and effective lifespan with other new technologies with similar response times or power and energy requirements, which in turn offer advantageous options and features, and very probably without presenting the expected cost increase of lithium in the future. Therefore, an improvement of this technology is necessary if lithium-ion batteries don’t want to lose their market in electrical networks compared to other technologies with performance in the same range but with only a fraction of their cost.

In a PV plant, the components of a battery storage system are basically (Fu et al (2018)):

- Storage devices, consisting of the battery cells, the battery, the packs and the racking system
- Storage container, which is provided with a HVAC system, thermal management, monitors and controls, fire suppression, switchgear and energy management system
- Power conversion system

- Transformer for voltage conversion

Figure 14 shows the components of a battery system, starting from the battery cell, which make up the modules. Modules are installed in battery racks which, in turn, are placed inside containers in the PV plant.

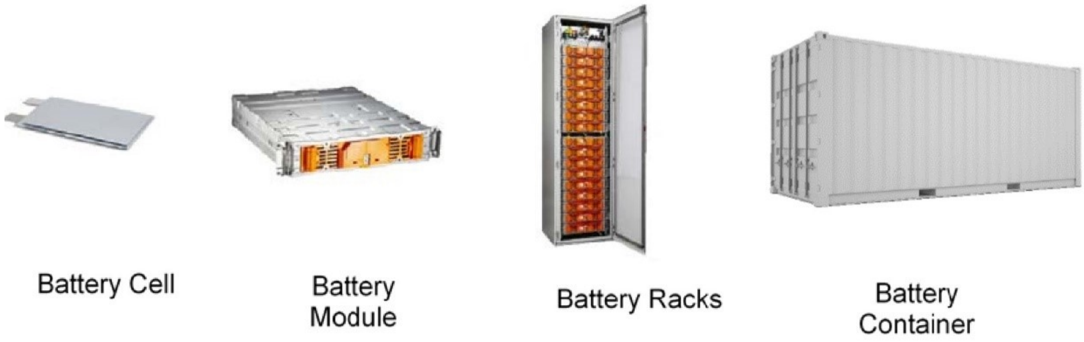


Figure 14 .- Battery system components (Fu et al (2018))

3 The PV sector in Spain. Past and current situation

3.1 Technical aspects

3.1.1 Historical

It is considered that the PV installed power in Spain started to be significant by the middle of the decade of 2000 (ANPIER (2018)). As shown in Figure 15, by 1998, among the cumulated power installed in Spain, only 9 MW belonged to PV plants. This number increased up to 512 MW in the year 2007 before the boom of the PV sector in the country. This boom led the country to witness the installation of more than 2,718 MW of PV power in one single year. However, this fast and sudden evolution resulted in poorer developments in the following years mainly due to law restrictions (see section 3.2).

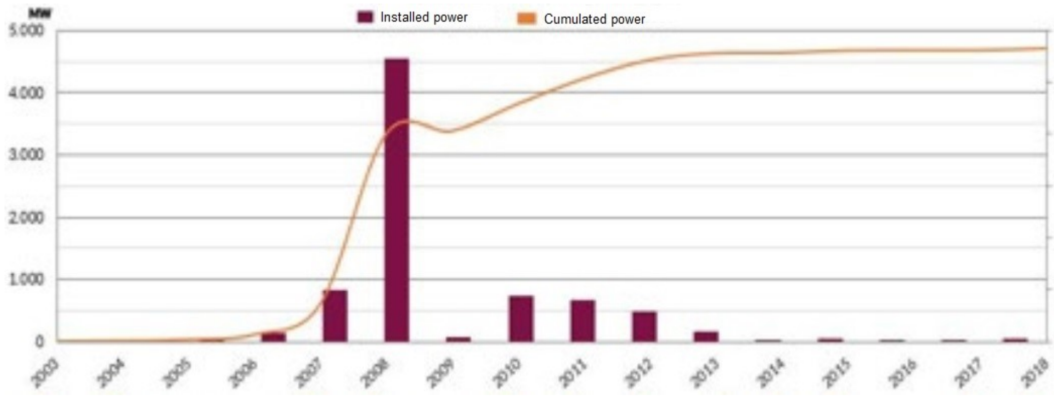


Figure 15 .- Evolution of the installed PV in Spain (ANPIER (2018))

The majority of the installed PV power in the country is found in the southern autonomous communities, more specifically Andalucía and Castilla-La Mancha, with 878 MW and 925 MW installed respectively. Though with lower installed power, Extremadura, Castilla y León y Murcia contribute together with the former two autonomous communities to share the 70% of the total installed capacity of the country. Regarding electricity generation, Castilla-La Mancha y Andalucía are the bigger PV producers with 1.742 GWh and 1.579 GWh respectively. Extremadura, though with lower installed power, follows nearly with a generation of 1.118 GWh in 2017. Again, the aforementioned five autonomous communities sum up to approximately the 73% of the total PV electricity generation (UNEF (2018)).

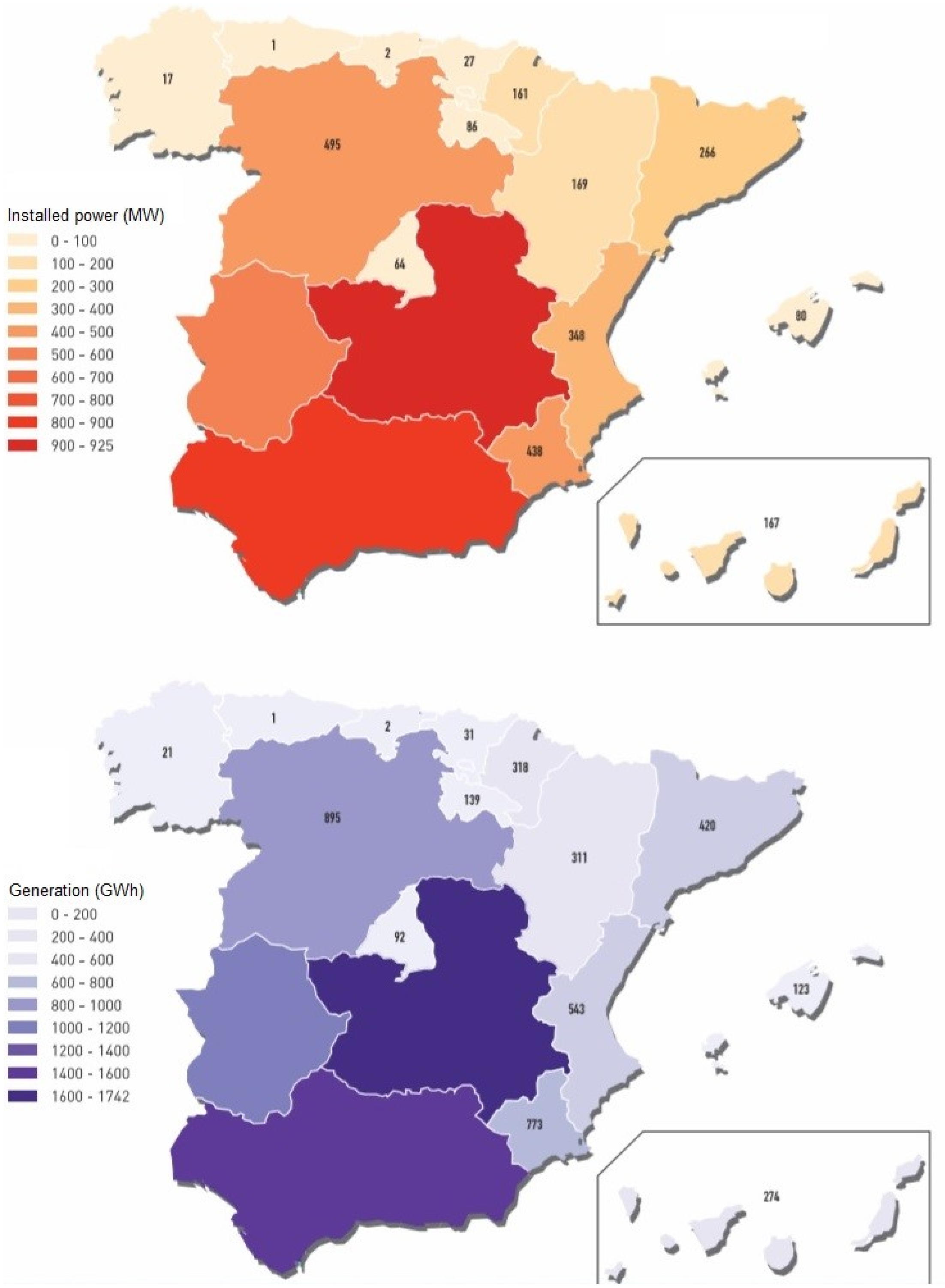


Figure 16 .- Installed power and PV electricity generation per autonomous community (UNEF (2018))

The PV electricity generation has been increasing throughout the years in line with the increase of installed power. From year 2012 until 2017, after the installed PV power peak was reached, the yearly PV electricity generation has been constantly around 8,000 GWh with a variability of approximately 400 GWH, as shown in Figure

17. This electricity generation confirms that the share of the PV plants to the total electricity generation of Spain is around 3% in the period 2012-2017 (UNEF (2018)). This is a significative fact taking into consideration that during these years the share of renewable energy in the Spanish mix changed from 40.6% to 32.1%, showing the high stability that the PV sector represents in the Spanish electricity market.

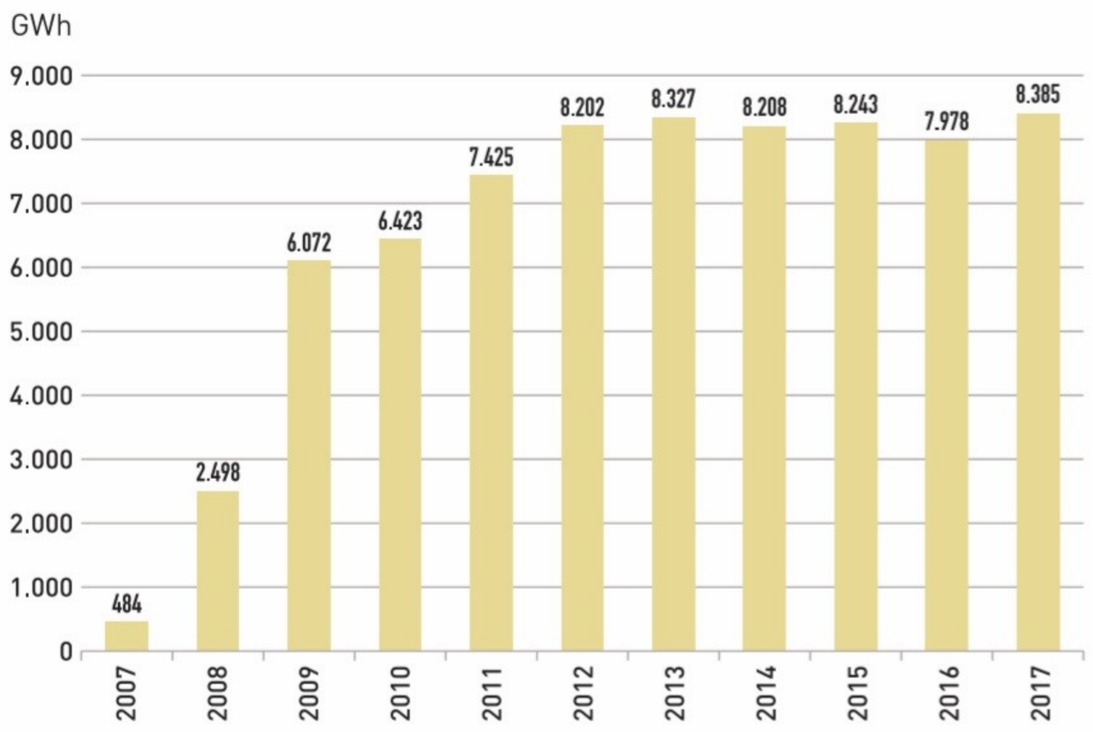


Figure 17 .- Electricity produced by PV in Spain in the period 2007-2017 (UNEF (2018))

3.1.2 Recent years

The electric energy generation in Spanish mainland, which represents approximately the 95% of the total national generation , was of 246,893 GWh during the year 2018, what means a reduction of 0.5% with respect to 2017 (REE (2018)). The main variations are the increase in hydropower generation (+84.9%) and decrease of combined cycle and coal (21.5% and 17.8% respectively).

Regarding the island territories, the electricity generation decreased approximately a 0.7% (14,081 GWh), with a decrease of 7.9% in coil generation and 4.5% in fuel/gas. However, the wind energy generation was a 56.6% higher than the previous year.

It is to be highlighted that the generation quota of the renewable energy sector has significantly increased, from a 33.7% in 2017 up to 40.1% in 2018, bringing them back to a leading position.

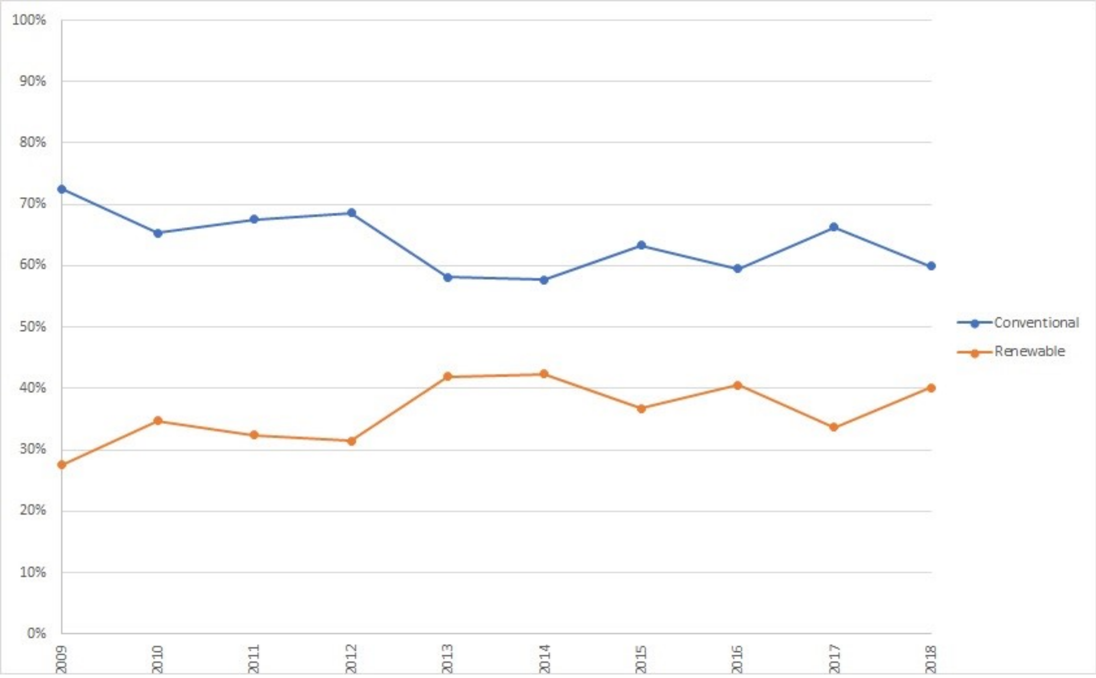


Figure 18 .- Evolution of the generation of conventional and renewable energy sources (own figure from data of REE (2018))

Regarding PV plants, quantitative values show a decrease of the generation in approximately a 7.8%. This tendency was followed by almost all sources of renewable energy with the exception of wind technology, whose generation increased a 3% with respect to 2017. Regarding the installed power, 2018 showed an increase on PV plants of 0.6%, similar to the 0.7% increase of wind technology.

Table 2 .- Electricity generation in 2018 and evolution of electricity generation of conventional and renewable energy sources 2017/2018 (REE (2018))

	Mainland		**Islands**		**Total**	
	GWh	**% 2018/2017**	**GWh**	**% 2018/2017**	**GWh**	**% 2018/2017**
Hydraulic	34,103	84.9	3	0.1	34,106	84.9
Pumping turbines	2,009	-10.7	-	-	2,009	-10.7
Nuclear	53,198	-4.2	-	-	53,198	-4.2
Coil	34,882	-17.8	2,392	-7.9	37,274	-17.2
Fuel/gas	-	-	6,683	-4.5	6,683	-4.5
Combine cycle	26,403	-21.5	3,642	6.5	30,044	-18.9
Hydroelectric	-	-	24	16.9	24	16.9
Wind	48,946	3	625	56.6	49,570	3.5
PV	7,374	-7.8	385	-3.1	7,759	-7.6
Solar thermal	4,424	-17.3	-	-	4,424	-17.3
Other renewables	3,547	-1.5	10	-8.3	3,557	-1.5
Cogeneration	28,981	2.9	35	-3.5	29,016	2.8
Nonrenewable waste	2,294	-6.7	141	-5.2	2,435	-6.6
Renewable waste	733	0.7	141	-5.2	874	-0.3
Generation	246,893	-0.5	14,081	-0.7	260,974	-0.5
Pumping consumption	-3,198	-11.3	-	-	-3,198	-11.3
Link mainland-Balearic Islands	-1,233	4.6	1,233	4.6	0	
Physical international interchanges balance	11,102	21.1	-	-	11,102	21.1
Demand	253,563	0.4	15,314	-0.3	268,877	0.4

Table 3 .- Installed power in 2018 and evolution of the installed power of conventional and renewable energy sources 2017/2018 (REE (2018))

	Mainland		**Islands**		**Total**	
	MW	**% 2018/2017**	**MW**	**% 2018/2017**	**MW**	**% 2018/2017**
Hydraulic	17,047	0.1	2	0	17,049	0.1
Pumping turbines	3,329	0	-	-	3,329	0
Nuclear	7,117	0	-	-	7,117	0
Coil	9,562	0.3	468	0	10,030	0.3
Fuel/gas	0	-	2,490	0	2,490	0
Combine cycle	24,562	-1.5	1,722	0	26,284	-1.4
Hydroelectric	-	-	11	0	11	0
Wind	23,091	0.7	416	97.7	23,507	1.6
PV	4,466	0.6	248	0.2	4,714	0.5
Solar thermal	2,304	0	-	-	2,304	0
Other renewables	859	0.6	6	0	865	0.6
Cogeneration	5,730	-1.3	10	0	5,741	-1.3
Nonrenewable waste	452	-1.4	38	0	491	-1.3
Renewable waste	123	0	38	0	162	0
Generation	98,643	-0.2	5,452	3.9	104,094	0

In total, the installed generating power has decreased a 0.2% with respect to 2017. It is to be highlighted that the share of the renewable energy sector in Spanish mainland becomes larger with the years, increasing a 0.5% from 2017 while conventional technologies reduced their installed power quota a 0.9%. In total, the installed power remains the same with a share of 46.7% in renewable energies and 53.3% in conventional technologies.

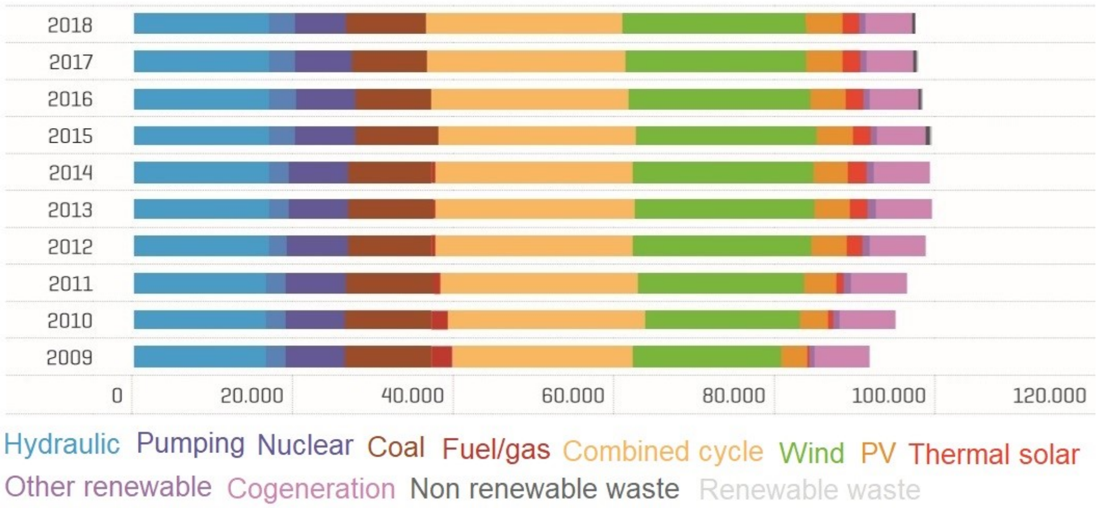


Figure 19 .- Evolution of the installed power (MW) of conventional and renewable energy sources (REE (2018))

The contribution of the renewable energy projects to the electricity generation in the mainland in 2018 is found to be the fourth highest contribution in history, after increasing its share form 33.7% in 2017 to 40.1% in 2018. One of the reasons of this increase is the highest share of the hydraulic generation, after the year 2017 when the country suffered from a drought period, consolidating the renewable energy share against conventional technologies, specially combined cycle and coil plants.

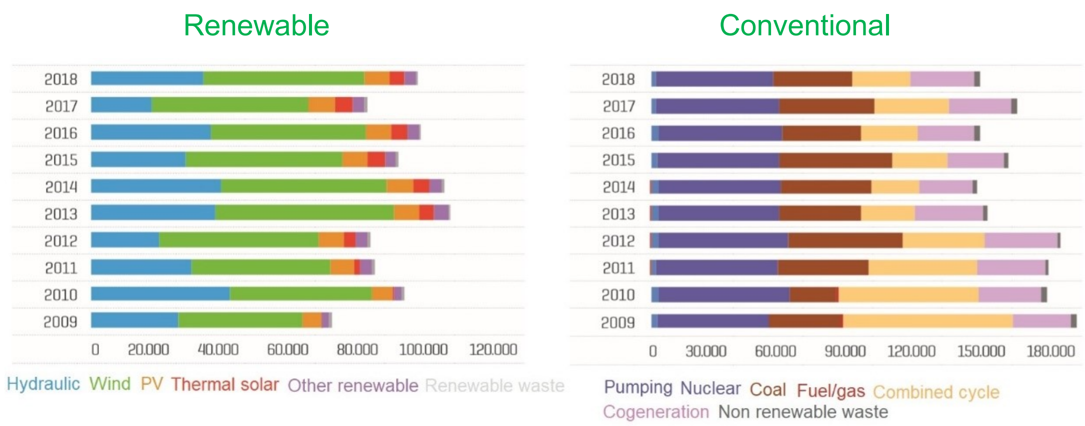


Figure 20 .- Evolution of the renewable and conventional electricity generation in mainland – solar PV in cream color (REE (2018))

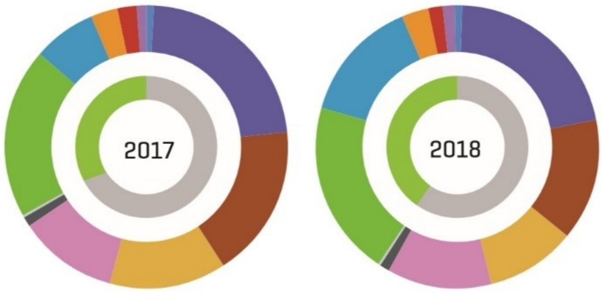
The renewable energy generation increased in the mainland in a 18.5% in 2018 with respect to 2017. The main increase took place during the first half of the year, especially during March, when the renewable generation was a 51.1% higher with respect to the same month of the previous year, reaching a historical monthly peak of

13,201 GWh. Furthermore, on 20th March 2018 a new daily renewable generation record was set with 530 GWh, a 63.0% of the total generation in mainland that day.

Among all the renewable energy technologies, the wind sector had the highest share in generation in 2018 with 49.4%, followed by the hydroelectric (34.4%) and PV (7.4%).

The PV plants in mainland produced during 2018 a total of 7,374 GWh, representing a decrease of 7.8% with respect to the previous year, when a new generation record of the technology was set at 8,001 GWh. This decreased in generation is mainly due to the lack of solar resource, especially during spring and summer months. In this year 2018, the share of the PV technology in the Spanish market has changed with respect to 2017, reducing its value from 3.2% to 3.0%.

	2017	2018
TURBINACIÓN BOMBEO	0,9	0,8
NUCLEAR	22,4	21,5
CARBÓN	17,1	14,1
CICLO COMBINADO	13,6	10,7
COGENERACIÓN	11,3	11,9
RESIDUOS NO RENOVABLES	1,0	0,9
RESIDUOS RENOVABLES	0,3	0,3
EÓLICA	19,1	19,8
HIDRÁULICA	7,4	13,8
SOLAR FOTOVOLTAICA	3,2	3,0
SOLAR TÉRMICA	2,2	1,8
OTRAS RENOVABLES	1,5	1,4



	2017	2018
RENOVABLES	33,7	40,1
NO RENOVABLES	66,3	59,9

Figure 21 .- Structure of electricity generation in mainland in 2017 and 2018 (%) (REE (2018))

Regarding the islands, the electricity generation has decreased after three years of an increasing tendency, being a 0.7% lower in 2018 with respect to 2017. However, in the case of Canary Islands, the wind installed power increased in 2018 a 99.5% to a total of 413 MW. Also, the renewable energy generation increased a 32.2% despite the total decrease in electricity generation. It is important to highlight the case of El Hierro island, which was able to cover the 100% of the demand continuously with renewable energy during 18 days and 9 hours, starting on 15th July and finishing the morning of the 2nd of August.

3.2 Regulatory developments

The history and evolution of the renewable energy market, and thus the PV market, his linked to the different norms that came into force throughout the years under different regulatory systems. The following chapters present an overview of the past regulations and the presentation of the current year (ANPIER (2019)).

3.2.1 Until 2014

The generation of the different renewable energy technologies was ruled at the beginning of XXI century by three norms: the law 54/1997 of the electric sector, the royal decree RD 2818/1998 regarding renewable energy generation and the royal decree RD 1663/2000 regarding the connection of PV plants to the low voltage grid.

These norms, though not very adequate for the renewable energy market, showed some interests in its development and implementation. This interest was backed by the *Plan de Fomento de Energías Renovables en España*[1] from 1999, with an aim to increase the total installed power of renewable energies in the period 1998-2010 from 18,857 MW to 30,356 MW (Spanish government (1999)). More specifically, the plan was expecting a change from 9 MW to 144 MW of the installed PV power during this period.

During these first years, ICO-IDAE helped the development of the PV sector providing loans under advantageous conditions, though the slow bureaucracy involving these loans relegated them to only special cases (ANPIER (2019)).

3.2.2 2004-2007

This period of time can be considered as the beginning of the PV expansion in Spain. The royal decree RD 436/2004 came into force, providing the sector with a stable retributive legislation with which the developers and investors had higher legal security.

The royal decree included the Tarifa Media de Referencia (TMR), Reference Average Tariff in its Spanish acronym, that was the base for two retributive options:

- Regulated tariff: the incomes are based on a percentage of the TMR
- Market sale: the incomes were a sum of the market sales, a percentage of the TMR and an incentive

The TMR was defined by the royal decree RD 1432/2002, were the methodology for its approval or modification was established. The TMR was annually set via ministerial

[1] Plan for the promotion of renewable energies

decree with the following values: 7,2072 c€/kWh (2004), 7,3304 c€/kWh (2005) and 7,6588 c€/kWh (2006). On the other hand, the tariff amount was dependent on the size of the PV plant.

As a result, the PV market increased the number of projects and the size of them, reducing the amount of private funds too. However, the costs of the PV technology were still high and there was a lack of investors (ANPIER (2019)). But problems also arouse in the PV market due to the great number of requests to be granted with a connecting point to the grid. Many of these requirements came from developers who were not planning to construct the PV plant in the short or medium term, what created delays on other PV projects that were really planned to be immediately developed.

The first Plan de Energías Renovables (PER, Plan for Renewable Energies in its Spanish acronym) was published in 2005 substituting the Plan de Fomento de Energías Renovables en España. This plan set the growing and implementation targets for the renewable energy technologies accordingly to the European decisions. The plan expected the installed renewable energy power in Spain to increase from 27,033 MW in 2004 up to 42,495 MW in 2010, more than 12,000 MW than the expected installed power according to the Plan de Fomento de Energías Renovables en España from 1999. On the other hand, the PER expected the installed PV power to change from 37 MW in 2004 to 400 MW in 2010. That means 266 MW as previously planned with the Plan de Fomento de Energías Renovables en España. This can be seen as a sign of the importance of PV in the energy mix in Spain as an electricity generator source.

3.2.3 2007-2010

The period of time between 2007 and 2010 saw a big development of the renewable energy sector, and more specifically of PV projects, in Spain.

With the aim to comply with the targeted installed power by 2010 and to promote some renewable energy technologies that were not as much developed as expected, the new royal decree RD 661/2006 came into force as a substitute of the previous RD 436/2004. The new royal decree set a new incentive system with the aim, among others, to be the definitive boost for the PV technology. The new tariffs under the new royal decree are shown in Table 4.

Table 4 .- Regulated tariffs for PV plants (source: Spanish Royal Decree RD 661/2007)

Project size	Tariff (€/MWh)	
	< 25 years	> 25 years
P < 100 kW	440	352
100 kW < P < 10 MW	418	334
10 MW < P < 50 MW	230	184

Other changes by the RD 661/2007 were:

- The remuneration system is now based on the Consumers Price Index (CPI) instead the TMR, providing the sector with higher stability
- PV plants would be granted with the regulated tariff throughout its lifespan, though reduced a 20% after year 20
- Enforceability to provide an endorsement of 500 €/kW for PV plants

The conditions under the RD 661/2007 would be kept until a 371 MW limit for PV plants, which was exceeded only three months after the norm was published and when there was already a huge number of PV projects under construction that had to be finished.

However, the RD 661/2007 anticipated this situation and consequently the RD 1578/2008 arouse, aiming to provide a stable regulatory frame until 2011. After the experience of previous years, the new royal decree sets periodic short-time revisions to adjust the tariffs according to the evolution of international markets. Thus, a system of trimestral quota of installed power and decreasing tariffs were established.

Table 5 .- Regulated tariffs for PV plants (source: Spanish Royal Decree RD 1578/2008)

Project type		Tariff (€/MWh)
		< 25 years
Roof mounted	P < 20 kW	440
	P > 20kW	418
Ground mounted		230

The tariff reduction under this new royal decree was of a 29%, decreasing between a 5% and a 11% yearly, depending on the fulfillment of the installed power quota (planned quota of 100 MW/year with maximum plant size of 10MW). In 2009 the installed power was not the expected but in 2010 the quota for every trimester was fulfilled, resulting in a tariff reduction for 2011 of 13.9%

3.2.4 2010

From the year 2009 the Spanish government started to legislate in such a way that the renewable energy sector started to be severely punished under the new norms. Thus, the new royal decree RD 1565/2010 modified the retribution period of time and the later royal decree law RD-Ley 14/2010 limited the number of hours of generation for the PV plants (1,250 hours for fix ground-mounted plants), after them the PV plants would not be granted with any kind of special remuneration but receive only the market price.

After an average reduction of 25% in incomes for the PV plants in 2011 and 2012 (ANPIER (2019)), the royal decree 1544/2011 set a toll of 0,5€/MWh for all producers to grant their access to the distribution and transport net.

The new royal decree law RD-L 1/2012 cancelled all previous tariffs for the projects under special regime except for those already in implementation stage, effectively meaning the stoppage of the development of new ground-mounted PV plants until mid-2017.

This moratorium clashed with the already approved second PER in 2011. This plan expected the installed power of renewable energy projects to increase from 39,214 MW in 2010 to 50,996 MW in 2015 and 63,761 MW in 2020. Regarding PV plants, the expected change was from 3,787 MW in 2010 to 5,416 MW in 2015 and 7,250 MW in 2020. This improvement on installed power was however quite impossible to fulfill, due to the new RD-L 1/2012 and the legal uncertainty that it provided.

Furthermore, and as an example that if something goes wrong it can still get worst, the Spanish government brought a new law into force, the Ley 15/2012 that set a new levy to tax the PV producers with a 7% of the gross incomes. In addition to that, soon a new royal decree law came into force, the RD-L 2/2013, which change the mechanism to update the tariffs: the CPI was substituted by the IPC-IC, a specific index applied to the electric sector. The practical implications of this royal decree law were the update of the tariff with negative indexes.

3.2.5 From 2013 to 2016

With the aim to approved a new legal and economic frame, the new royal decree law RD-L 9/2013 came into force, were the tariffs under the RD 661/2007 were substituted too. Later the law 24/2013 developed the norms in the RD-L 9/2013, which introduced the Reasonable Return concept. Thus, the new regulatory frame established that the PV plants would have incomes based on the sum of:

- Market price
- Specific remuneration
  - Installed power term: investment retribution price in €/MW to cover, where applicable, the investment costs not covered after the electricity sale
  - Operation term: operation retribution in €/MWh to cover the difference between the operational costs and the incomes after market sales

The Reasonable Return concept for PV plants, of around a 7.39%, is a term calculated by the government as the value of the Tasa Interna de Retorno (TIR), Internal Rate of Return in its Spanish acronym, deducting the cash flows during the lifespan of the project so the Valor Neto Actual (VAN), Net Current Value in its Spanish acronym, including the initial investment costs, is zero. However, the methodology used by the government was not proven and far from reality, especially for PV plants owned by small investors like families or small enterprises. This resulted in the need of refinancing for many small developers, meaning that they would receive a return of the investment after 18 years instead of 10 years as originally planned. Needless to say, the reality shows that the reasonable return values for PV plants have not only never been achieved, neither been ever close to be achieved (ANPIER (2019)).

3.2.6 2017

In 2017 Spain had two important problems in the electricity market: the lack of investors, who fled to countries with a more stable market, and the possibility to fail complying with the commitments undertaken with Europe in regards of renewable energy installed power.

In order to mitigate these problems and taking advantage of the cost reduction of the renewable technologies, the Spanish government started a system of auctions to improve the number of new renewable energy projects.

The auctions are based on the investment starting value, which is a critical factor to define the investment retribution. The investment starting value is set by the government for each auctioned power unit. The potential investors bid then a reduced value, the result of the auction being a reduced percentage of the investment starting value, what also influences the investment retribution price during the lifespan of the project. So far there has been three auctions and the allotted projects must be in operation before the end of 2020. At the moment, the fourth auction is to be announce and expected for the year 2019 with an expected minimum auction of 3,000 MW.

Table 6 .- Allotted power (MW) in the renewable energy auctions in 2016 and 2017[2]

	1st auction - 2016	2nd auction - 2017	3rd auction - 2017	Total
Wind	500	2,979	1,128	4,607
Biomass	200	20	-	220
PV	-	1	3,903	3,904
Total	700	3,000	5,031	8,731

3.3 Economic aspects

Similar to all other renewable energy technologies, PV projects have to face very high investment costs while the operation and maintenance (O&M) costs are very low in comparison. There are also many other aspects that influence the decision of whether to invest or not in a PV project. Among them, the price of the modules is one of the main factors and which can account up to approximately half of the investment.

Like above said, the highest share of the investment lies on the modules, taking about half of the costs to start a PV project. Other costs like the inverters, installation materials or the electrical labor account, each of them, for around a 10% of the investment costs, while the remaining costs (permitting, taxes, land acquisition…) have a lower share. (Figure 22, Goodrich et at (2012)).

[2] Sources: Spanish Official State Gazettes

- number 18 section III page 5617 of 21st January 2016
- number 125 section III page 42787/42788 of 26th May 2017
- number 179 section III page 70288 of 28th July 2017

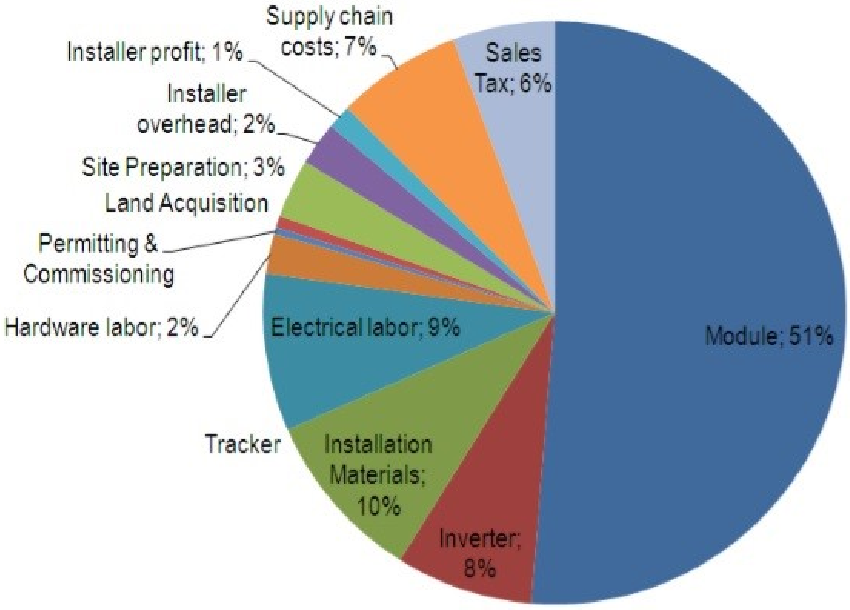


Figure 22 .- Benchmark 2010 fixed-axis utility-scale PV system price: breakdown by element (Goodrich et at (2012))

The PV technology has experienced a large evolution during the last decades. As a result, the number of installed PV power has increased enormously in the world. One of the consequences of this large deployment of PV plants in the world is the change of price of the PV panels, which shows a decreasing pattern during the last three decades.

In the second half of the decade of the 70's, the price of the PV panels was slightly below 100 $/Wp. This price was drastically reduced in a short period of time, as it decreased by more than half only three years later. By the late 80s the price of the PV panels was already fluctuating around 10$/Wp to continue dropping below this barrier. There have been periods of slight increase of the PV panels price due to shortage in silicon availability. This historical price evolution is shown in Figure 23.

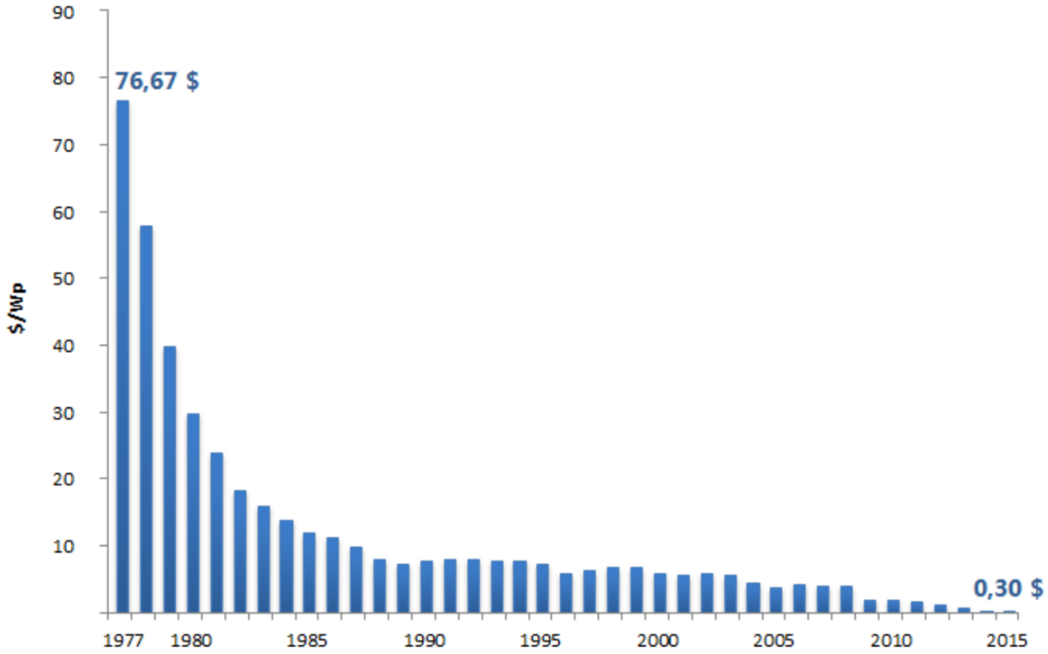


Figure 23 .- Evolution of the price of the PV panels 1977-2015 (source: BNEF (2016))

Focusing in the 2010-2018 period, the prices of PV panels were between 2.0-3.5 $/Wp at the beginning of the decade and depending on the technology used. Then the prices dropped again drastically to the range of 1.0 $/Wp during 2012/2013 and continue decreasing but in a smoother and much regular way. Current prices for all PV module technologies are now below 0.5 $/Wp, what means a reduction of around 85% since the beginning of the decade (Anuta et al (2019)).

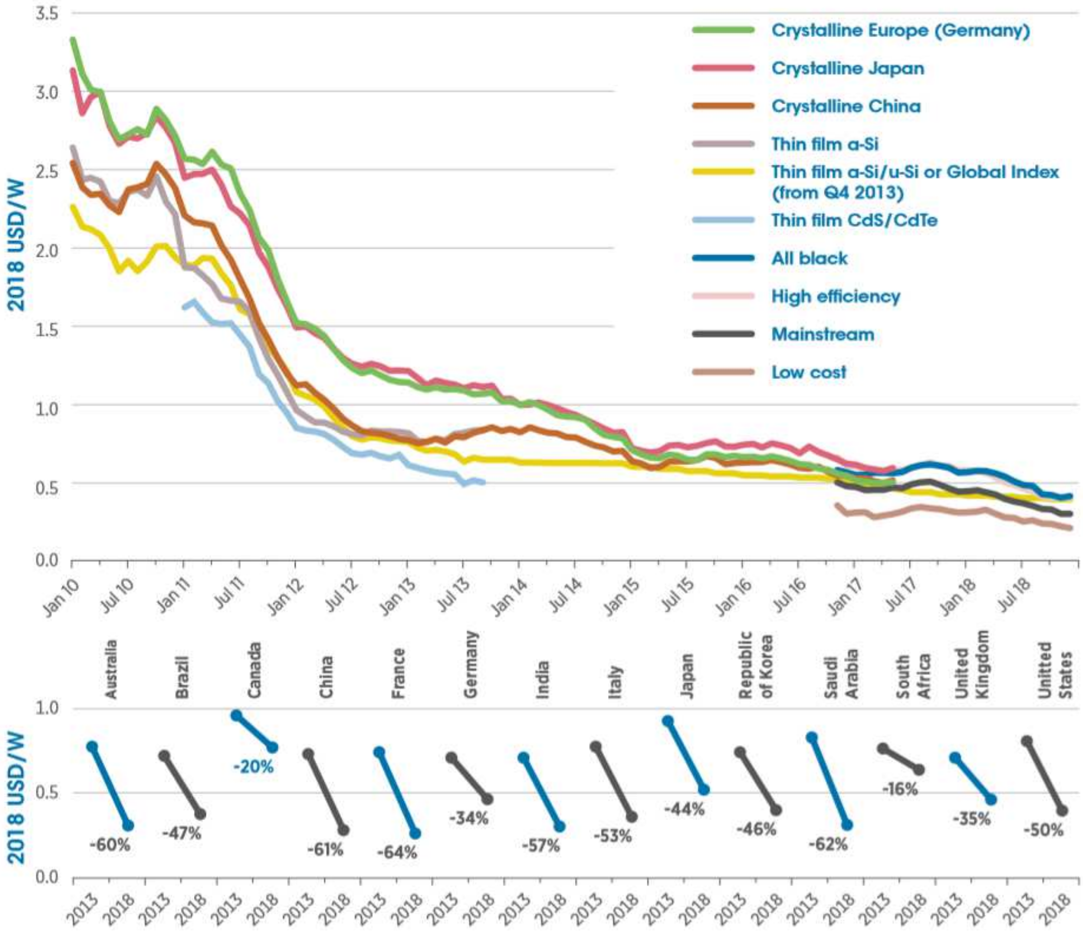


Figure 24 .- Average monthly solar PV panel prices in Europe (top) and average yearly module prices by market (bottom) (Anuta et al (2019))

Parallel to the price reduction of PV panels, the investment costs trends show a drastic decrease worldwide during the last decade and in the different PV markets. Anuta et al (2019) provides an analysis of some of these markets. At the beginning of the decade the total installed costs were around 5,000 $/kW in many PV markets from Europe, Asia and America, though the costs in China were about 20% lower. Eight years later the trend of the markets shows the same decreasing behavior as the price of PV panels. In the markets under analysis, they all reached total installed costs of around 1,000 $/kW. Only Japan has still larger costs, doubling those of the other markets. The cost reduction for most of the markets in 2018 lies in the range of 74% to 84% compared to the costs at the beginning of the decade. This trend is reflected in the global weighted-average LCOE of utility-scale solar PV, whose reduction of 77% led to values of 0.085 $/kWh at the end of the decade.

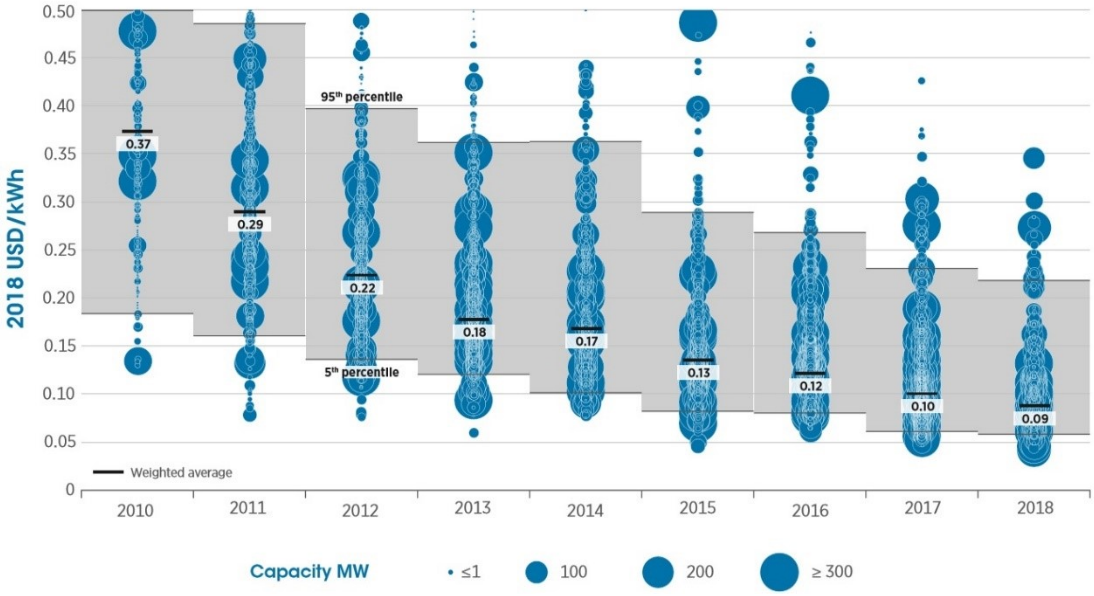


Figure 25 .- LCOE values of utility-scale solar PV projects, 2010–2018 (Anuta et al (2019))

With respect to the Spanish market, the trends are like the international market. Donoso (2019) presents a recent analysis of the current economic situation of the PV technology in the country. From the data presented in the analysis, it can be considered that the PV panel prices have been halved within the years 2014-2018.

Table 7 .- Module prices (€/W) excluding transport to the site, VAT/TVA and sales commission (Donoso (2019))

Year	Lowest price of a standard module crystalline silicon	Highest price of a standard module crystalline silicon	Typical price of a standard module crystalline silicon
2014	0.50	0.60	
2015	0.50	1.05	0.60
2016	0.45	0.64	0.55
2017	0.45	0.64	0.55
2018	0.23	0.34	0.31

The analysis of Donoso (2019) presents a current cost breakdown for different PV systems MW. The total installed costs for ground mounted systems of 10-20 MW are of 0.72 €/W in average, with almost a 40% of them (0.27 €/W) corresponding to the PV panels. The average cost of the inverters (0.10 €/W) is almost a third of the cost of the modules, while the analysis considers 0.20 €/W for the so-called soft-costs, which are the installation labor, permitting, contracting,…and 0.10 €/W for hardware costs (wiring, frames,…). For smaller PV plants, the costs are 0.88 €/W for grid-connected roof-mounted PV plants of 100-250 kW and increasing for smaller roof-mounted grid connected plants. The analysis does not include PV plants with installed power similar to the values used in this thesis.

Vartainen et al (2015) analyses the operational expenditures (OPEX) of PV plants, which is mainly constituted by the O&M prices. The analysis brings obvious differences between rooftop and ground-mounted PV plants. For these last, the economy of scale is a factor that reduces these costs, since the manpower can be shared with other tasks or even other PV projects. The OPEX prices have been significantly high during the past years. The reason for this was mainly the existence of FITs, which gave the PV projects high margins to invest in areas like O&M. However, the reduction or even cancellation of these FITs in many countries led to a higher competitivity within O&M companies and thus the reduction of the related prices. For instance, from 2011 and in only two years, the average O&M price in Italy was reduced by 40%. Of interest for this thesis, Vartainen et al (2015) sets an average OPEX price of 20 €/MWp/year for 1 MWp ground-mounted systems in 2014. However, prices of around 5-10 €/MWp/year were reported in some countries like Germany, but these prices depend much on the country and service required. The analysis concludes that 50% of the value of the OPEX depends on the country/area where the PV plans is erected and is also reduced in parallel to the better performance of the PV panels. Each of these factors can lead to a 15% reduction of the OPEX and for a total 30% reduction by the year 2030 (14 €/kWp/year).

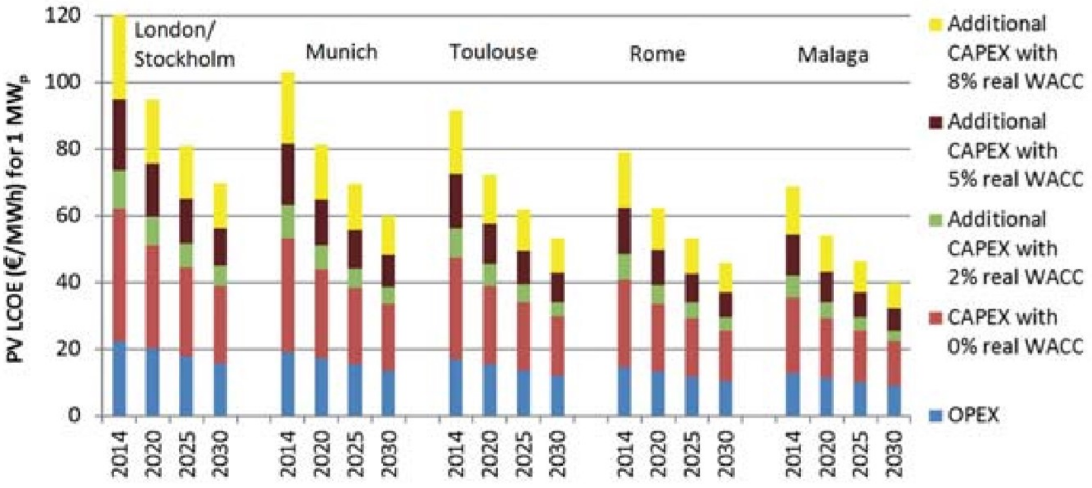


Figure 26 .- LCOE for ground-mounted 1 MWp in 6 different locations (Vartainen et al (2015))

Figure 26 above shows current and expected OPEX values in Malaga, Spain, what is a good example for the sites selected in this thesis. As it can be seen, OPEX values drop from above 15 €/MWh in 2014 to values under 10 €/MWh by the year 2030. As a result, the LCOE (CAPEX+OPEX) in Malaga in 2030 are expected to be around 40 €/kWh.

Vartainen et al (2017) analyzed the competitiveness of PV in Europe a couple of years after their previous analysis. This time, the location in Spain was Madrid instead of Malaga and the forecast until the year 2050 is longer than previous analysis. For this location, the LCOE forecast for the year 2020 is similar as in Vartainen et al (2015). The tendency of the LCOE is to decrease around a 20% by 2026. Eight years later a 75% reduction is expected and by the year 2050 the LCOE is expected to halve the value of 2020.

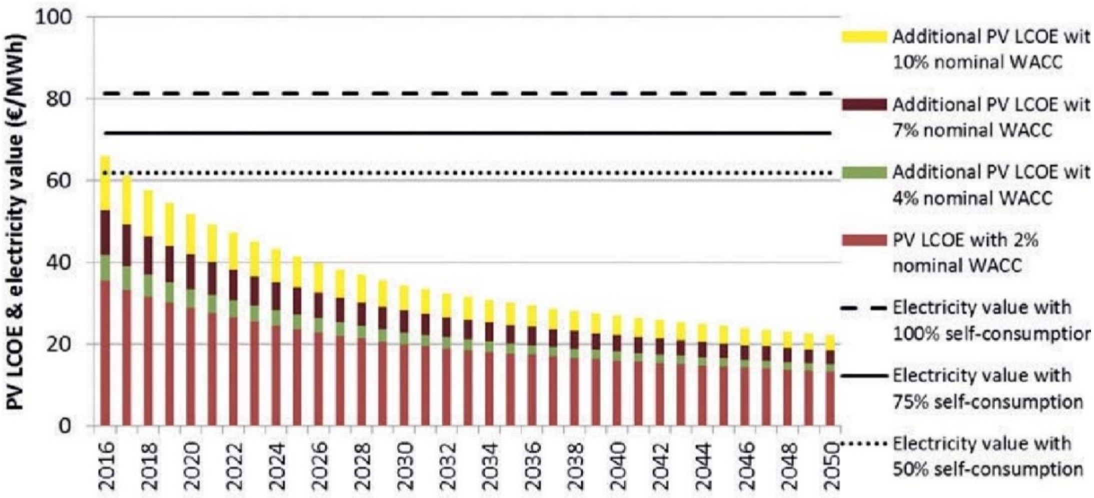


Figure 27 .- LCOE of a PV plant of 1 MWp in Madrid, Spain (Vartainen et al (2017))

Very recently BNEF (2019) has analyzed the past and future tendencies of different technologies in the coming years. The analysis is based on public and proprietary data from more than 7,000 projects all over the world. The LCOE prices shown are of 57 $/MWh for PV plants whose construction started as early as 2019. The interest of this analysis is that it shows current prices for lithium-ion batteries, with LCOE of 187 $/MWh. The LCEO of both PV plants and lithium-ion batteries have experienced a short and quick decrease since the first half of 2019. Therefore, the LCOE reduction is of 18% and 35% for PV plants and lithium-ion batteries respectively. With respect to the lithium-ion batteries, its LCOE has been reduced a 74% since 2012 and has reached the point that makes them competitive, in many markets, with other technologies like gas or coal generation, even though the projects are no longer under

FIT or subsidies. Like those last technologies, PV combined with storage is a suitable way to provide electricity when the demand requires it, substituting the more polluting technologies.

Figure 27 shows the country weighted-average LCOE values. The values related to lithium-ion battery storage system corresponds to utility-scale systems at a daily cycle including charging costs assumed to be 60% of the whole sale base power in each country. LCOE values has been lowered from 800 $/MWh in 2013 down 300 $/KWh in 2018.

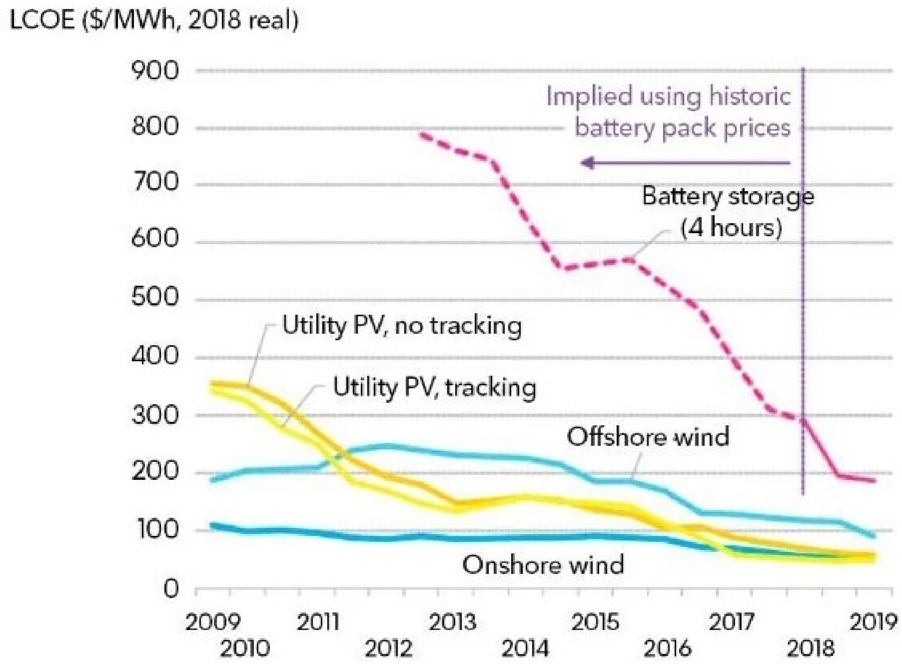


Figure 28 .- Global benchmarks – PV, wind and batteries (BNEF (2019))

However, this decrease of price of the lithium-ion batteries, triggered by the improvements of the technology and the market scale, faces the problem related to the high raw material demand in the future, something which could cause a bottleneck in its actual development and to favored other uprising storage technologies (BNEF (2019)).

Curry (2017) provides lithium-ion battery costs from real values and projections to 2030 too. The observed values in 2010 were of the range of 1,000 $/kWh and halved only four years later. The observed prices for 2016/2017 are however lower than those provided by BNEF (2019). The projection shows that the current lithium-ion battery prices are around 200 $/kWh and will drop down to 100 $/kWh by 2025 with a further reduction of 10-15% by the year 2030.

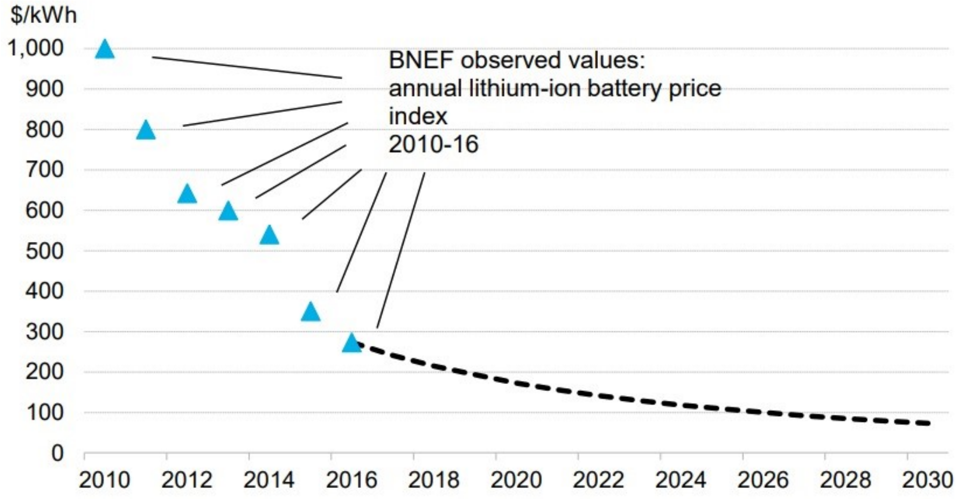


Figure 29 .- Lithium-Ion Battery Cost Projections to 2030 (Curry (2017))

More recently, Ran et al (2018) analyzed the cost benchmark of utility-scale PV plants with storage in the US. Figure 30 shows the results of the model with PV systems of 60 MW and different battery durations. The difference in price is significant, being the 4h duration battery system more than 50% cheaper (380 $/kWh) than the 0.5h duration batteries (895 $/kWh). It is to be noted that the battery system accounts for more that the half (55%) of the total costs of the storage system for the 4h duration batteries. On the other hand, for the lower duration systems, the weight of the remaining costs (balance of system (BoS), EPC, developing,…) are higher in comparison to the batteries themselves (23%).

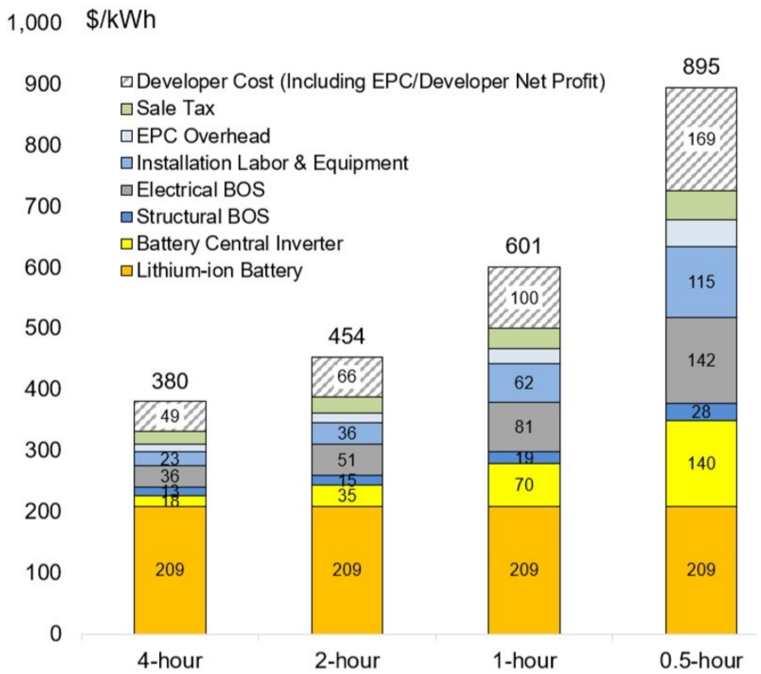


Figure 30 .- 2018 U.S. utility-scale lithium-ion standalone storage costs for durations of 0.5–4 hours (60 MWDC) – Ran et al (2018)

Table 8 below presents the details of the figure above for the 60 MW PV plant with 1h duration battery system.

Table 8 .- Detailed Cost Breakdown for a 60-MW U.S. Li-ion Standalone Storage System with Durations of 1 Hour (Ran et al (2018))

Item	**60-MW, 1-hour Duration, 60-MWh**		
Model Component	Total Cost ($)	$/kWh	$/W
Li-ion battery	12,540,000	209	0.21
Battery central invert	4,200,000	70	0.07
Structural BoS	1,159,612	19	0.02
Electrical BoS	4,877,337	81	0.08
Installation labor & equipment	3,743,838	62	0.06
EPC overhead	1,535,075	26	0.03
Sales tax	1,978,209	33	0.03
∑ EPC cost	30,034,071	501	0.50
Land acquisition	250	4	0.00
Permitting fee	295,289	5	0.00
Interconnection fee	1,802,363	30	0.03
Contingency	975,887	16	0.02
Developer overhead	975,887	16	0.02
EPC/developer net profit	1,716,675	29	0.03
∑ Developer cost	6,016,101	100	0.10
∑ Total storage system cost	36,050,172	601	0.60

4 Methodical approach

4.1 Irradiance data

The irradiance data used for this analysis is obtained from SIAR[3] (Sistema de Información Agroclimática para el Regadío), an entity belonging to the Ministry of Agriculture, Fisheries and Food of the Spanish government. The information below relates to the SIAR project and is available in the SIAR web page (siar.es).

SIAR is a net of stations that measure, record and share agroclimatic data, useful to calculate the hydrological demand in the irrigated areas. It gives useful, rigorous and quality information and contributes to a better planning, managing, operation and control of the irrigating lands.

SIAR has been developed and updated for more than 13 years now and comprises:

- 468 agroclimatic stations scattered all over the country, which measure and transmit the collected data to the Zone Center, where they are recorded.
- 12 Zone Centers, one per each Autonomous Community that collaborates with the net. Each of these centers is provided with a hardware and software which permits the acquisition, storage and use of the measured data.
- 1 National Center, located at the headquarters of the ministry and provided with technical means to receive, use and spread all the information which has been daily collected at each of the zone centers

The configuration and location of each of the agroclimatic stations is chosen after the recommendations of the WMO, INM, FAO and ASAE. Among others, the location of the station must comply with the following requirements:

- It should be located in an open space
- The wind should blow free without significant obstacles, avoiding tress, buildings,etc near them.
- If there are obstacles in the near, they should be located at a distance of 8-10 times its height (big obstacles) or 2-3 times (small obstacles like bushes).
- The station must be free of shadows, which are only permitted during sunrise and sundown.

[3] Siar.es

- The location should not be affected by sudden changes, like marshes, mountains or steep hillsides.
- Roads or dirt roads are to be avoided, due to high dust transport and are susceptible to vandalism or looting.
- Locations to be avoided are valleys, gorges, old stream channels, areas with frequent dew or floods.
- Good GSM signal and low electromagnetic radiation, avoiding high voltage lines.
- Good access for its maintenance, especially during winter or rainy seasons.

The stations are designed to automatically measure the following parameters:

- Air temperature
- Air humidity
- Wind speed and direction
- Radiation
- Rainfall

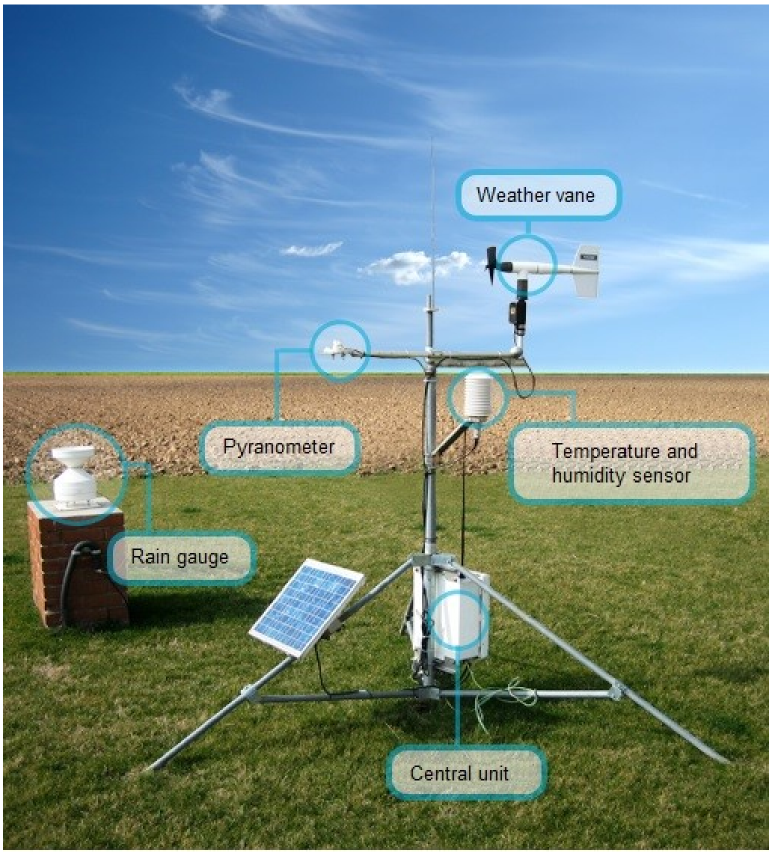


Figure 31 .- Agroclimatic station configuration (www.siar.es)

The measurement devices installed in the agroclimatic stations, shown in Figure 31, are:

- Central unit – the central unit has a datalogger, a modem and a charge controller. The central unit controls the correct operation of the systems of measurement and data transfer and controls the power supply of the whole system.
- Solar panel – amorphous module of 12 Wp and 12 V connected to the power supply regulator in the central unit.
- Tripod – structure of galvanized steel with a height of 2m. The structure is anchored with buried stakes and has fixing brackets to hold the temperature and humidity sensors, the wind sensor and the radiation sensor.
- Sensors – the sensors installed in the stations can measure the following parameters:
    - Temperature and humidity
    - Radiation (pyranometer)
    - Wind speed and direction
    - Rainfall (rain gauge)
    - Ground temperature (only a few stations)

The stations have a pyranometer in order to measure the irradiance. A pyranometer is a device which measures the intensity of the solar energy, both arriving directly (beam radiation) or from the sky (diffuse radiation). The model used is a SKYE SP1110, consisting on a silicon photocell, sensible to radiation in the range of 350 nm to 1100 nm and south oriented. Table 9 below presents the main technical characteristics of the pyranometer.

Table 9 .- Characteristics of the pyranometer SKYE SP1110 (www.siar.es)

Signal range	**Sensitivity range**	**Accuracy**
1mV / 100Wm^2	350 - 1100nm	± 5%

The agroclimatic undergo the following maintenance tasks:

- Preventive maintenance with a biannual frequency, where a main revision of the station is performed.
- Calibration with an annual frequency, where all devices are calibrated in a laboratory.

* Corrective maintenance when needed.

For the purpose of the study two stations have been chosen. These are located in the mainland Spain and represent locations with low and high horizontal irradiance values.

Figure 32 shows the location of each site of analysis in the Spanish territory on a global horizontal irradiation map from SOLARGIS[4] while Table 10 shows the coordinates of these places.

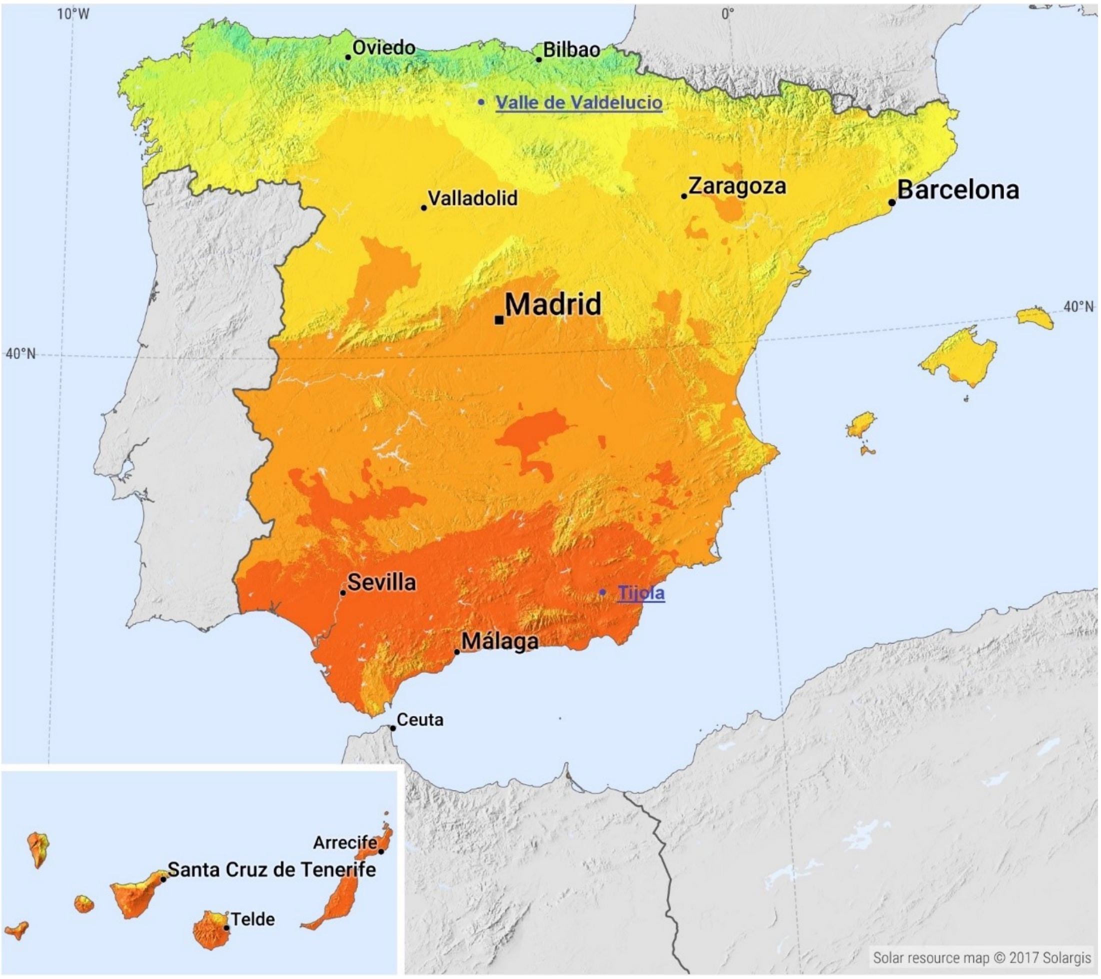


Figure 32 .- Global Horizontal Irradiation in Spain (SOLARGIS, 2017)

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4 https://solargis.com/maps-and-gis-data/download/spain

Table 10 .- Coordinates of the chosen locations (own table)

Location	Province	Latitude	Longitude
Valle de Valdelucio	Burgos	42°43′05″N	4°05′32″W
Tíjola	Almeria	37°24′05″N	2°29′53″W

The reason to choose the locations in the table above is that there is a SIAR station with available irradiance data at each of them, therefore a comparison of different places with different irradiance values for the same day and under the same hourly market price is possible.

A first estimation of the available irradiance in the selected places is done with the help of three different irradiance sources that can be found in internet:

- Photovoltaic Geographical Information System[5] (PVGYS). PVGIS has been developed for more than 10 years at the European Commission Joint Research Centre, focusing on the research in solar resource assessment, photovoltaic (PV) performance studies, and the dissemination of knowledge and data about solar radiation and PV performance. PVGIS provides solar radiation data as monthly and yearly long-term averages, based on data with hourly time resolution from satellite.
- Global Solar Atlas[6] (GSA). The World Bank Group provides the Global Solar Atlas in addition to a series of global, regional and country GIS data layers and poster maps. The work is funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank and supported by 13 official bilateral donors. The Atlas provides long-term averages of solar resource.
- SOLARGIS[7]. This private company provides reliable and accurate solar and weather data that are used in the whole lifecycle of solar power plants. Since 2010 SOLARGIS develops and operates a platform for fast access to historical, recent, and forecast data for almost any location on the Earth.

[5] PVGIS, European Commission, https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html
[6] GSA, World Bank Group, https://globalsolaratlas.info
[7] Solargis.com

The SIAR station of Valle de Valdelucio is in a range of 1,400-1,510 kWh of yearly horizontal irradiance. This value is above of the average in the whole Europe. In the northern coastal region of Spain there are areas of much lower irradiance, like the Basque country, Cantabria and Asturias, which are dominated by cloudy and humid weather, where very few PV projects are developed in comparison with the rest of the country, due to its poor sun resource. These regions have been therefore dismissed from this study and Valle de Valdelucio has been considered as a low irradiance area.

On the other hand, Tíjola is located in what it can be considered an area of high horizontal irradiance. The irradiance data provided by the aforementioned sources show values which are 21%-25% higher than the ones from Valle de Valdelucio.

Table 11 summarizes the yearly horizontal irradiance information obtained from the three different sources: Photovoltaic Geographical Information System, the Global Solar Atlas and SOLARGIS.

Table 11 .- Irradiance values (own table after data from PVGIS, Global solar atlas (GSA) and SOLARGIS)

Location	Irradiance area	Yearly horizontal irradiance (kWh/m^2)			Difference		
		PVGIS	GSA	SOLARGIS	PVGIS	GSA	SOLARGIS
Valle de Valdelucio	Low	1,400	1,510	1,494	0%	0%	0%
Tíjola	High	1,690	1,880	1,844	21%	25%	23%

4.2 Economic data

The investment values and running costs used in this thesis are taken from the data presented in section 3.3 Economic aspects of this thesis.

On the other hand, the hourly prices of the electricity market with which to calculate the revenues of the PV plants are obtained from OMIE[8]. Market agents trade the electric energy (MWh) with OMIE, the company that manages the wholesale electricity

[8] Omie.es/reports/

market in Spain. More precisely, the data used is the day-ahead traded electric energy.

Bids for electricity transactions are managed in the day-ahead market. In this market, distributors, retailers and some consumers make offers and bids for the electric energy of each of the 24 hours of the following day. Once the offers are received, the matching price for every hour is established by starting with the cheapest offer, adding electric energy until reaching the value that matches the demand. The offer corresponding to the last bid that makes generation to match the demand sets the hourly price.

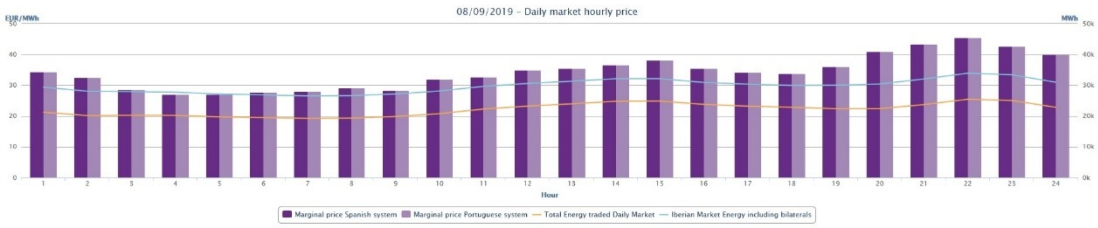

Figure 33 .- Example of daily market hourly price – 5th April 2019 (omie.es/reports/)

During the period of time of analysis in this thesis (June 2018-May 2019) the average market price is of 59.05 €/MWh.

Aleasoft (2019) analyzed the tendency of the electricity market prices from the year 1998 onwards. Until the year 2007 the average yearly price showed a clear upward trend and the hourly prices of the same day presented a large dispersion. However, from 2009 the average yearly prices still grow but at a lower rate. Additionally, the price dispersion during the same day was reduced too. Among the reasons for this smoother tendency are the increase of market traders, what makes the market more stable. Another reason are the international interconnections, which trigger a generation shootdown and the import of electricity when the market prices increased a lot compared to the neighbor markets. Likewise, when the market price is significantly lower than in neighbor markets, the generation is increased to be exported, avoiding the electricity market price to be reduced.

On regards of the investment and operating assumptions considered in this thesis, the following was considered:

- 7,5% discount rate has been chosen (Freyman and Tran (2018))
- Investment costs considered are based on the values presented in section 3.3

- PV plant: 0.75 €/W. Taking into account the cost trends and the installed power of the PV plants (1 MW), this investment cost is considered as an average value in Spain between grid-connected ground-mounted PV systems of 10-20 MW and grid-connected roof-mounted PV systems of 100-250 kW, in accordance to Donoso (2019)
- Battery system: the costs of the battery system considered are 0.50 €/W, which are the costs shown Ran et al (2018) for a 1h-duration battery system shown in Figure 30 using the dollar/euro exchange of 8th September 2019 and estimating a price decrease due to the battery cost trends

- Running costs considered are based on Vartainen et al (2015) and set to 35,000 €/year, considering it a conservative value. These costs are considered to increase a 2% every year, the same amount as the revenues will increase yearly
- The lifespan and investment horizon of the PV projects are 20 years, at the end of which the PV plant will be sold for a price of 1% of the investment costs

Table 12 .- Figures for investment and running costs (own table)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0.50	MW
Investment Costs (PV plant)	0.75	€/W
Investment Costs (Battery system)	0.50	€/W
Total Investment Costs	1.39	€/W
Running costs (OPEX)	35,000	€/year
Incomes	59.05[9]	€/MWh
Real escalation of OPEX costs	2.00%	%/year
Selling the PV plant	1.00%	% of investment costs
Investment horizon	20	year

4.3 Modeling

The model used to perform the calculations in this thesis uses the hourly irradiation from the selected SIAR stations as an input. Then, the hourly radiation components

[9] Average day-ahead hourly market price in the period June 2018-May 2019

are calculated to obtain the global radiation in the plane of the PV panels. The model calculates the hourly generation of the PV plant and obtains, with the help of the hourly electricity market price, the revenues of the PV plants.

Following sections describe how the model calculates the radiation, the generation and the storage strategy used to improve the economic performance of the PV plants.

4.3.1 Radiation

The model used in this thesis aims to use the global horizonal irradiance data to obtain the direct (B), diffuse (D) and reflected (R) radiation on the surface of the PV panels.

$$G = B + D + R \tag{2}$$

The model uses, as an input, the measured hourly horizontal irradiance data from the selected SIAR stations, described in section 4.1, together with the following data:

- Latitude and longitude of the selected SIAR station
- Collector tilt angle
- Reflectance of surface
- Installed power
- Power of the inverter
- Battery capacity
- Performance ratio (PR) of the installation

The global irradiance is divided in two components, direct beam and diffuse irradiation.

$$G(0) = B(0) + D(0) \tag{3}$$

The model then calculates the irradiance on the surface of the PV panels, which is divided in three components: direct, diffuse and reflected.

The model first calculates the solar declination (δ) of the chosen location for every day with the following formula:

$$\delta = 23.45 * SIN\left(\frac{360}{365} * (n - 81)\right) \tag{4}$$

where *n* is the Julian day, being 1 the first of January and 365 the 31st of December.

Following it calculates the solar altitude (βn), which is defined as the sun angle from horizon at noon. This value is related to the solar declination and the latitude of the selected location with the following formula:

$$\beta n = 90 - \phi + \delta \tag{5}$$

The diffuse component of the horizontal irradiance has been calculated with the model from Threlkeld and Jordan (1958). This model suggests that the diffuse irradiation in a horizontal surface is proportional to the direct beam radiation by means of the so-called sky diffuse factor. This factor is calculated with the help of the Julian day *n* with the following formula:

$$\mathrm{C} = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right] \tag{6}$$

Therefore, the horizontal diffuse radiation is as follows.

$$\mathrm{D} = \mathrm{G}(0) \cdot \left[0.095 + 0.04 \sin\left(\frac{360}{365}(n - 100)\right)\right] \tag{7}$$

On the other hand, the horizontal direct beam radiation is calculated as the global horizontal radiation minus the horizontal diffuse radiation.

$$B(0) = G(0) - D(0) \tag{8}$$

In order to calculate the direct beam radiation on the PV panels the following formula has been used:

$$B = B(0) \cdot (cos\beta_n \cdot cos\Phi_c \cdot sin\beta + sin\beta_n \cdot cos\beta) \tag{9}$$

Where β_n is the solar altitude, ϕ_c is the collector azimuth angle and β the collector tilt angle. For this analysis the collector azimuth angle is set to zero, while in all the cases it is assumed that the PV panels are facing the south. On the other hand, the collector tilt angle has been considered as 35° in all cases, being this a typical tilt angle in projects in Spain. Finally, the solar altitude is a value that changes daily.

Finally, the model calculates the reflected radiation on the surface of the PV panels. For this purpose, it is assumed that both the direct and diffuse radiation are isotropically reflected on the ground and the reflected solar radiation can be, therefore, calculated by means of the albedo and the PV panel tilt angle.

$$R = G(0) \cdot \rho \cdot \frac{(1 - cos\beta)}{2} \tag{10}$$

where ρ is the albedo of the ground and β the collector tilt angle.

The albedo coefficient is defined like the fraction of global incident irradiation reflected by the ground in front of a tilted plane. This effect takes place during the transposition computation of the horizontal irradiation onto a tilted plane. The albedo is zero for horizontal surfaces and increases subsequently with tilt.

The value of the ground albedo varies though the day due to several factors, like the change in the law of isotropy or the variations in ground properties (e.g., snow cover or soil water content). Another characteristic of the albedo is that the morning and afternoon values are not symmetrical, since there exists the chance of partial shading or azimuthal inhomogeneities in the ground cover. For this study the albedo has not been calculated but estimated as constant with a value of 0.2 as it is often estimated (Gueymard (2009)), and which represents urban environments and grass and is used as a default value in renowned PV software like PVSYST.

The model then calculates, for every hour of the period between June 2018 and May 2019, the radiation on the tilted surface of the PV panels according to the following formula.

$$B = B(0) \cdot (cos\beta_n \cdot cos\Phi_c \cdot sin\beta + sin\beta_n \cdot cos\beta) + \mathrm{G}(0) \cdot \left[0.095 + 0.04 \sin\left(\frac{360}{365}(n - 100)\right)\right] + G(0) \cdot \rho \cdot \frac{(1 - cos\beta)}{2} \tag{11}$$

4.3.2 Generation of the PV plant

4.3.2.1 Gross generation

After the radiation is calculated for every hour in the PV plant, the hourly generation of the different cases is calculated without considering the batteries, that's it, the gross generation of the PV panels alone. Since the generation of the PV plants is used as one of the sensible factors in this study, its calculation has been simplified.

In order to properly calculate the generation of a PV plant, the power characteristics of the PV panels have to be known as well as its efficiency. On the other hand, the different losses occurring in a PV plant will decrease the output that reaches the electric grid and will therefore decrease the generation of the system.

Modern silicon modules have efficiencies of around 20% and higher. On the other hand, the losses in a PV plant vary depending in its design, but are in general the following[10]:

- Shading losses due to obstacles in front of the PV panels.
- Incidence angle modifier (IAM), is the optical effect corresponding to the weakening of the irradiation really reaching the PV cells surface, with respect to irradiation under normal incidence.
- Irradiance Loss, which is the decrease of the nominal efficiency, specified for the standard test conditions (STC) of 1000 W/m², with irradiance according to the PV standard model.
- Thermal behavior of the PV array due to the working temperature of the PV panel, usually higher than the standard test conditions specified for a cell temperature (25°C), but the modules are usually working at much higher temperatures. For crystalline silicon cells, the loss is about -0.4 %/°C at MPP.
- Real module performances of the module with respect to the manufacturer specifications.
- Mismatch losses, which are caused when cells or modules with different properties or which experience different conditions from one another are connected together.
- Dirt on the PV-modules.
- MPP loss, as the difference between the effective operation conditions and the maximum available power point.
- Ohmic wiring losses, as thermal effects, resulting in a voltage drop of the I/V-array characteristics.
- Regulation loss, which is the energy that could be potentially used from the PV array but cannot be used by the system.
- Performance losses of the inverter and transformer.

[10] Pvsyst.com/help/array_losses.htm

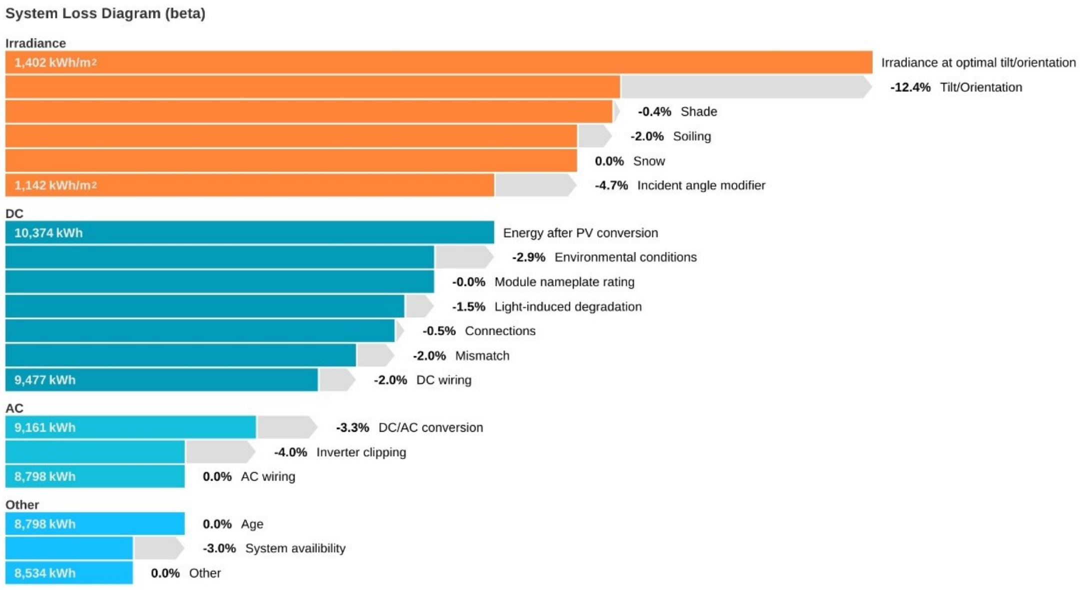

Figure 34 .- Example of losses in a PV plant (AURORASOLAR[11])

However, for the purpose of this study, the generation is calculated after the assumption of different PR values for the different cases. The PR is independent of the location of the system and it is a measure to compare the performance of different PV plants in relative terms. A higher PR means a better performance of the system.

The Performance Ratio, which includes optical losses, array losses and system losses, is defined in the norm IEC EN 61724 as the ratio of the energy effectively produced in a PV plant with respect to the energy which would have been continuously producing under its nominal STC efficiency.

$$PR = \frac{E_{real,output}}{E_{theo,output}\ x\ \frac{\mathrm{I}}{1000}} \qquad (12)$$

where

- $E_{real,output}$ is the real yearly electricity generation of the PV plant in kWh/year
- $E_{theo,output}$ is the theoretical (expected) yearly electricity generation of the PV plant in kWh/year, dependent on the yearly radiation and the technical characteristics of the PV plant
- I is the radiation in the plane of the PV modules in W·m^2

[11] aurorasolar.com//hc/en-us/articles/235994088-System-Loss-Diagram

- The value of 1,000 W/m^2 refers to the radiation in standard test conditions (STC), which are the conditions with which the theoretical energy output is calculated.

The electric output performance crystalline silicon and thin film PV panels are generally measured under STC, what permits to compare different PV panels and evaluate its output. The STC conditions correspond to the irradiance and spectrum of sunlight incident on a clear day upon a sun-facing 37°-tilted surface with the sun at an angle of 41.81° above the horizon and are:

- irradiance of 1000 W/m2
- cell temperature of 25°C
- air mass 1.5 (AM1.5) spectrum
- sunlight hitting the positioned solar cells perpendicularly

Leloux et al (2015), analyzed PV plants installed and distributed between 2006 and 2014 over 9 different countries, including multi-megawatt PV plants installed on a static structures in Spain. The results of the study found significant performance differences as a function of the inverter manufacturer, and the PV panel manufacturer and technology. Also, an improvement of the state-of-the-art, in the form of an increase in performance in the yearly integrated PR of around 3 to 4% over the last seven years was found, which represents an increase of about 0.5% per year. The study also finds possible for the PV sector to reach PR of values over 0.84 for most of the PV plants to be installed in the future, representing an improvement in performance around 10%, and a corresponding reduction in LCOE of the same order of magnitude. More specifically and related to Spain, the study found a typical PR value in Spain of 0.81.

Figure 35 below shows the distribution of the PR in Spain, where the average values are above 80% and around a 10% of the plants have PR values of around 85%. Around a 2% of the PV plants in Spain have PR values of 90%.

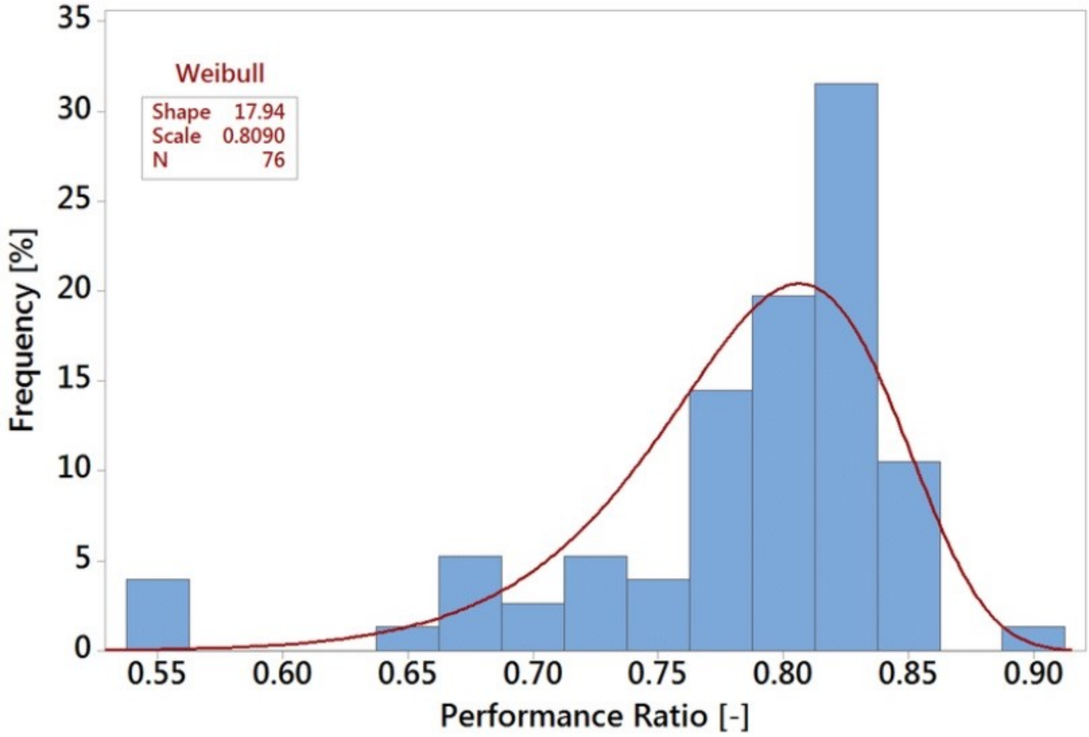

Figure 35 .- Distribution of the yearly PR for PV plants in Spain (Leloux et al (2015))

The high PR values of 90% should not be seen as a estrange phenomenon. Reich et al (2012) investigated in 2011 the performance of about 100 German photovoltaic system installations and they were of the believe that PR values above 90% were realistic considering the commercially available components at that time. They concluded that these values should be expected more frequently in the future. Therefore, the use of PR values of 90% in this study, though optimistic, are realistic too.

It has to be pointed out that the PR value is not constant throughout the year but it varies. Varo and Menendez (2017) studied the performance of a 10 MW PV plant and analyzed the daily and monthly variations of this parameter. The data used from this 10 MW PV plant, located in the Spanish province of Córdoba, were obtained from its transformation center during the year 2013.

Figure 36 below shows on of the finding of this study. Differences up to approximately 10% can be appreciated in daily PR values for the same month of 2013, like in May.

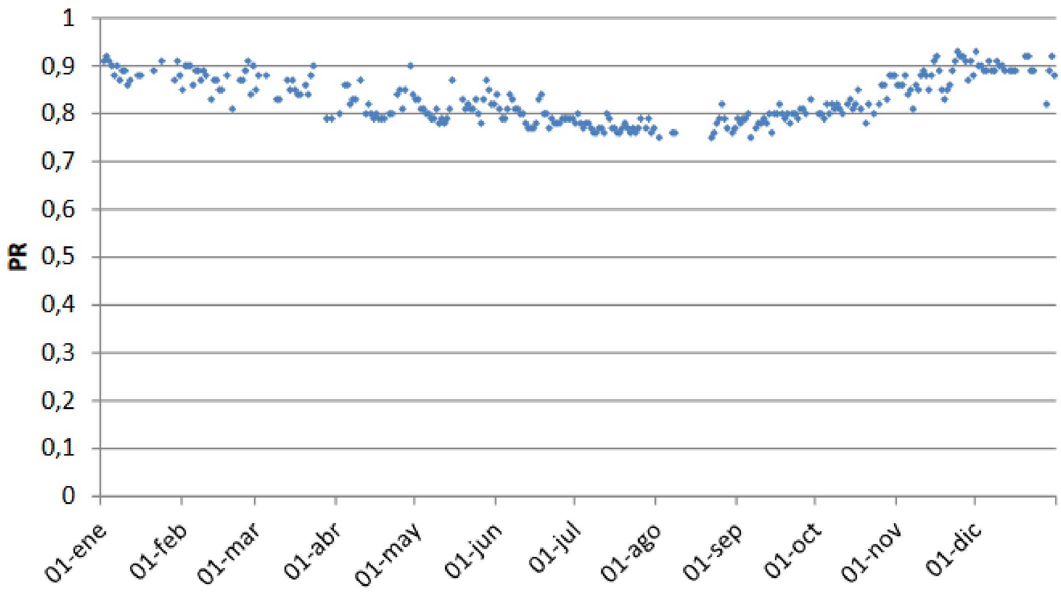

Figure 36 .- Daily variation of the PR during 2013 (Varo and Menendez (2017))

Varo and Menendez (2017) observed the influence of temperature on the PR values. Thus, during 2013 the PR values were diminishing from January until reaching the lower values during summer to increase once again towards the end of the year. Therefore, the temperature during the warmest days of the year is of great influence on the PR values. Figure 37 shows the monthly variation of the PR for this PV plant, ranging from 75% during summer to 88% in winter, resulting in a 13% difference between the warmest and coldest months.

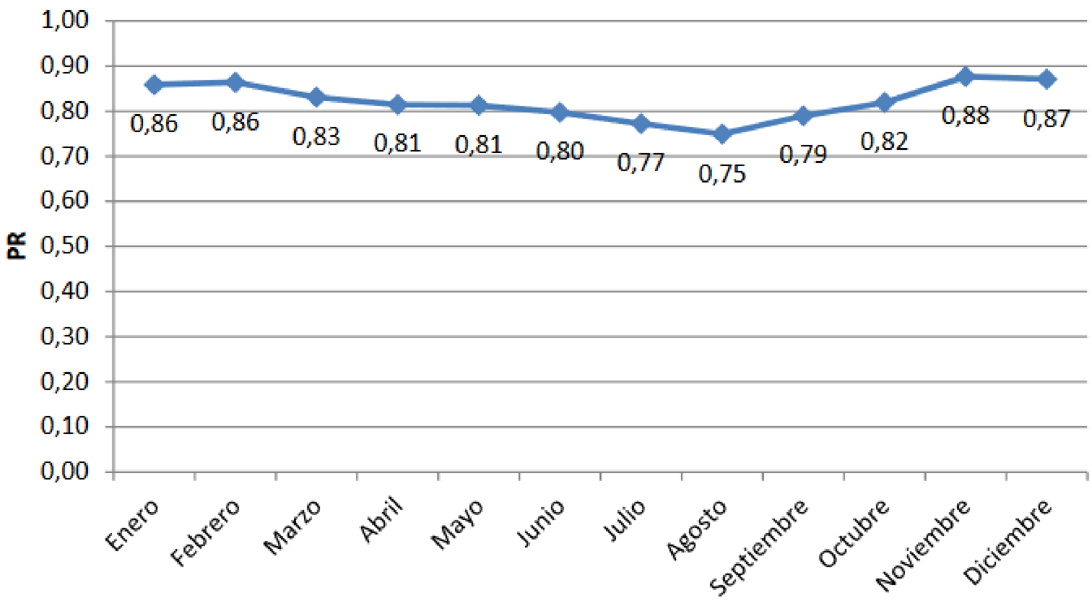

Figure 37 .- Monthly variation of the PR during 2013 (Varo and Menendez (2017))

The theoretical electric energy output considered in the study is the installed peak power of the PV plant. At this point it should be to differentiate between the peak power (kWp) and the nominal power (kW) of a PV plant.

The peak power of a PV plant refers to the total amount of kW installed, resulting from the sum of the Wp of each of the PV panels that make up the PV plant. The Wp of each PV panel that is constructed is register under the STC previously defined.

The peak power is specific for every PV plant, wherever the field where it was tested and permits to compare different PV panels under the same conditions, meaning that PV panels with the same kWp value are the same, independently of its location on Earth.

The peak power should be differentiated from the nominal power. This term refers to the power of the inverter, which is the device that transforms the electricity generated in the PV panels to be supplied to the grid. It is the nominal power of a PV plant what limits its performance, since it is not possible to supply more electricity than the limit that the inverter provides. However, the peak power is always higher than the nominal power in an attempt to cover the maximum capacity of the inverter for as much time as possible during the year, in order to improve the performance of the PV plant and make it economically feasible.

For instance, the generation of a PV plants is affected by shades, the tilt angle of the PV panels,,…and a higher peak power permits to increase the generation on the hours of the day like at dawn and dusk, when the PV plant is affected by the scattered radiation. However, PV plant developers must not install as much peak power as possible, since this increases the costs of the installation, but to find a compromise between cost and efficiency.

Therefore, for each hour, the electric energy output of the different systems has been calculated under the following formula:

$$E_{output,h} = PR \cdot E_{theo,output,h} \cdot \frac{I}{1000} \tag{13}$$

where

- $E_{output,h}$ is the hourly electricity output of the PV plant in kWh
- PR is the performance ratio
- $E_{theo,output,h}$ is the hourly theoretical electricity output of the PV plant in kWh
- I is the radiation in the plane of the PV modules in W·m^2

- The value of 1,000 W/m^2 refers to the radiation in standard test conditions (STC

It has to be noted that, since this calculation is done in an hourly basis, the theoretical electric energy output corresponds to the installed peak power of the PV installations.

4.3.2.2 Generation of the PV plant with batteries and charging/discharging strategy

There exist a number of different strategies to charge and discharge the batteries for utility-scale PV plants.

- Strategy to smooth short-term power fluctuations: variations in irradiance produced by changes in cloud cover can cause rapid fluctuations in the power generated by large PV plants, what may adversely affect the power quality and reliability of the power grid. Thus, batteries are necessary in order to smooth power fluctuations below the maximum allowable (Marcos et al. (2014)).
- Strategy to only store the electric energy excess: the batteries only store the excess of electric energy that cannot be supplied to the grid due to the limitations of the inverter.
- Strategy to store losses plus discharge transfer: the system stores the excess generation like in the strategy above and additionally the generation during the hours of lower prices to discharge in accordance to two sub-strategies:
    - Secure the electricity supply: the PV plant discharges its batteries at the end of the day, when the demand is usually higher compared with the rest of the day.
    - Improve the economic performance of the PV plant: the PV plant discharges the electricity stored in its batteries when the prices are higher to obtain higher economic revenues.

The strategy considered in this study focuses in obtaining the highest possible revenue, charging the batteries with the excess generation due to inverter limitations and also during the generation hours of low prices, discharging the stored electricity during price peaks. This strategy can be summarized as follows:

- The batteries are charged usually during the beginning of the day, when prices are lower
- The batteries are discharged during the hours when the prices are higher than the prices of the charging hours

- Priority is given to higher price periods; therefore, partial discharge may occur during an hour to later discharge the maximum possible electric energy during a higher price period
- Optimized charge of the batteries may occur at some periods of time, charging the batteries only partially with the required electricity to be completely charged at the following hour/s with lower prices, discharging later during price peaks

For the purpose of this thesis and to simplify the calculations, the battery system has been considered as ideal with no losses during the charging/discharging processes. Since the aim of this thesis is the estimation of the year, and not an exact date, when the LCOE would be lower than the electricity market price, this assumption is considered as valid.

5 Calculations and results

5.1 Introduction

This aim of this section is to provide the results of the different calculations performed for this thesis, as well as the results reached after these calculations were done. As shown in Table 14, the calculations are made on two PV power plants of 1 MW and 1.250 kWp each, located in Valle de Valdelucio (North of Spain) and Tíjola (South of Spain). For each PV plant, three different PR values (80%, 85% and 90%) are considered.

The calculations of this thesis are based on assumptions as per the information presented in Section 4 und further explained in section 5.2. The different calculations made in this thesis and their results are presented in subsequent chapters of this section 5. These calculations aim to obtain the following:

- Radiation over the considered yearly period in the considered PV plants
- Grid electricity delivery over the considered yearly period (without batteries)
- Grid electricity delivery over the considered yearly period (with batteries)
- Yearly revenues – June 2018 to May 2019
- Estimation of the year when the LCOW are lower than the market price (profitable scenarios to invest on PV plus lithium-ion battery storage)

5.2 Assumptions behind the calculations

As previously presented, two locations corresponding to two SIAR stations have been analyzed in this thesis: Valle de Valdelucio and Tíjola. The first in considered to be in a region of low irradiance in Spain while the second can be considered as located in a high irradiance region.

The nominal power of the PV plants considered in this study is 1 MW, as per the limitation of the inverters. Additionally, it is common in Spain to find PV plants with peak power values in the range of 20% to 30% above the nominal power. For this study a peak power of 1,250 kW, a 25% higher than the nominal power, has been considered in all the cases to study.

On the other hand, for the purpose of this study and for the sake of simplicity of the model, the PR values have been considered constant throughout the year despite what explained in section 4.3.2. Therefore, after the conclusions of the articles from

Reich et al (2012) and Leloux et al (2015), the PR values considered in this study and the model are those shown in Table 13 below.

Table 13 .- PR values considered in the study (own table)

PR	Value
Average value	80%
High value	85%
Optimistic value	90%

Therefore, the cases analyzed in this study are the ones presented in Table 14 below.

Table 14 .- Summary of the cases analyzed in this study (own table)

Case	Location/SIAR station	Output Power (kW)	Peak Power (kW)	PR
Case 1	Valle de Valdelucio	1,000	1,250	80%
Case 2	Valle de Valdelucio	1,000	1,250	85%
Case 3	Valle de Valdelucio	1,000	1,250	90%
Case 4	Tíjola	1,000	1,250	80%
Case 5	Tíjola	1,000	1,250	85%
Case 6	Tíjola	1,000	1,250	90%

5.3 Radiation over the considered yearly period

The six cases in Table 14 have been introduced in the model to obtain the yearly radiation, yearly generation and revenues of the PV plant. In order to calculate the radiation, the model takes into account the following:

- Latitude and longitude of each selected SIAR station
- Collector tilt angle: the model considers 30° as a standard value, valid for Spain. This value could have been optimized for each location but it was decided to take the standard value for simplicity
- Reflectance of surface: the value of the ground albedo around the PV panels is considered 0.20 as it is often estimated (Maleki et al (2017))

Figure 38 shows the hourly radiation in the selected SIAR stations for a late summer day of 2018. The behavior in this example for both stations is quite similar and show a clear day, with the rise of radiation until noon and decrease towards dusk. This is shown in the typical bell shape of the radiation during days under perfect weather conditions.

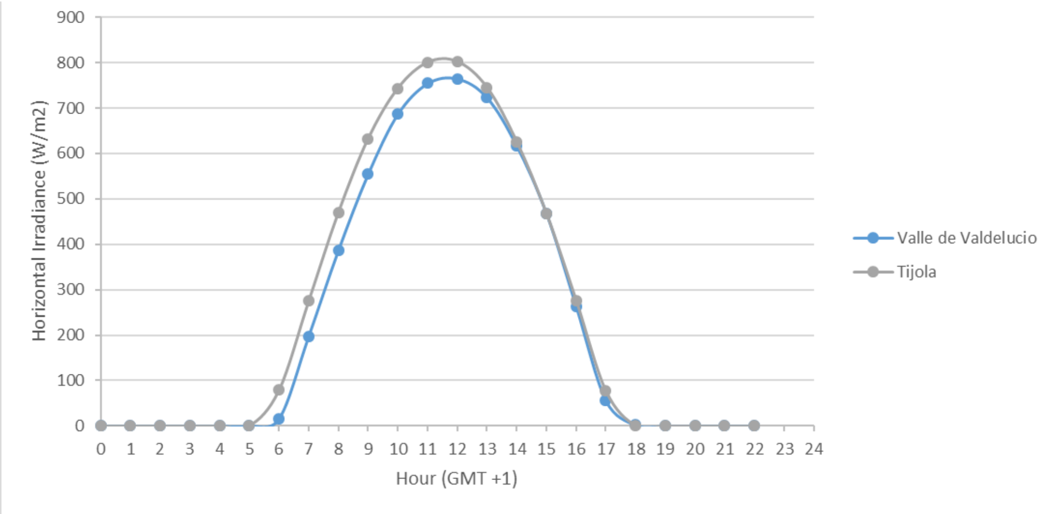

Figure 38 .- Radiation on 23rd September 2018 in Valle de Valdelucio and Tíjola SIAR stations (own figure)

Figure 39 shows a late autumn day of 2018, where again both stations measure radiation with a similar behavior. Around 11am, both stations register poor radiation, especially the station of Valle de Valdelucio, probably due to clouds or overcast skies. After the peak at noon, significantly lower for Valle de Valdelucio, the radiation behaves more normally as expected in a clear day.

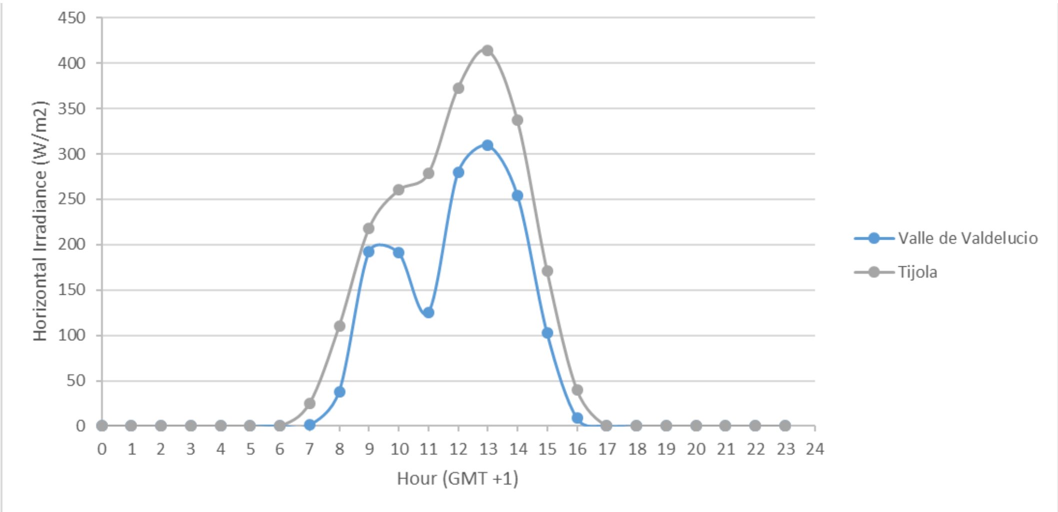

Figure 39 .- Radiation on 19th December 2018 in Valle de Valdelucio and Tíjola SIAR stations (own figure)

For a Winter day, Figure 40 shows the difference with Tíjola, where apparently the day was clear, and Valle de Valdelucio, where clouds or overcast skies may have lowered the radiation immediately before and after noon.

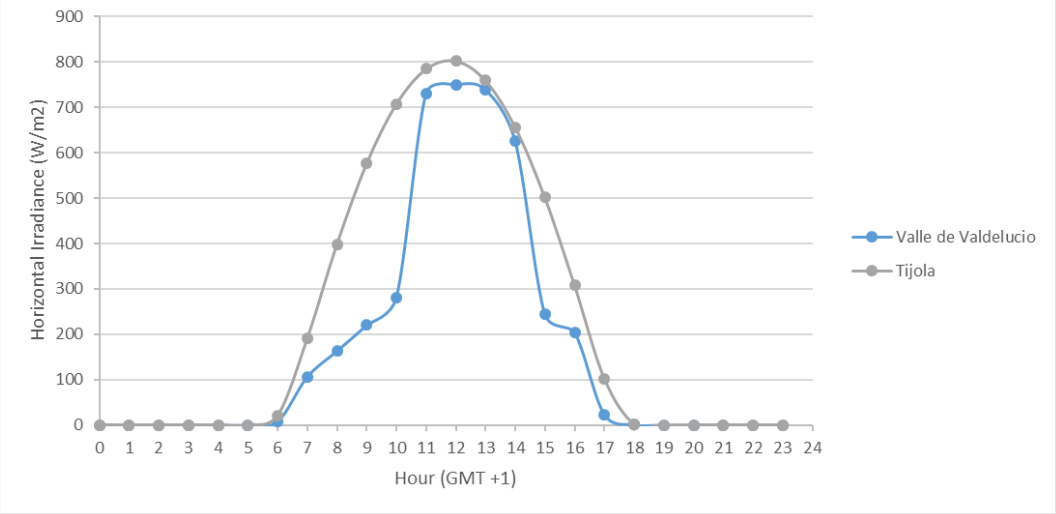

Figure 40 .- Radiation on 10th March 2019 in Valle de Valdelucio and Tíjola SIAR stations (own figure)

Finally, Figure 41 shows a day in Spring with varying behavior in both stations. Tíjola starts the day measuring radiation with apparent normal behavior but at 9am there is a drastic drop of the measured values (probably clouds or overcast sky). The lowest radiation value during the day occurs at noon, when the highest radiation is expected under normal weather conditions. That suggests that the day suffered from different weather phenomena that lowered the sun resource. Valle de Valdelucio also suffered from weather. Thus, early hours behave more or less normal until a radiation peak at 10am occurs. After that peak there is a sudden decrease in radiation (clouds or overcast sky again) before a small radiation peak occurs at 15pm, suggesting that the adverse weather conditions were somehow softened. Before dusk, the radiation drops but faster as expected, suggesting the negative influence of weather conditions again.

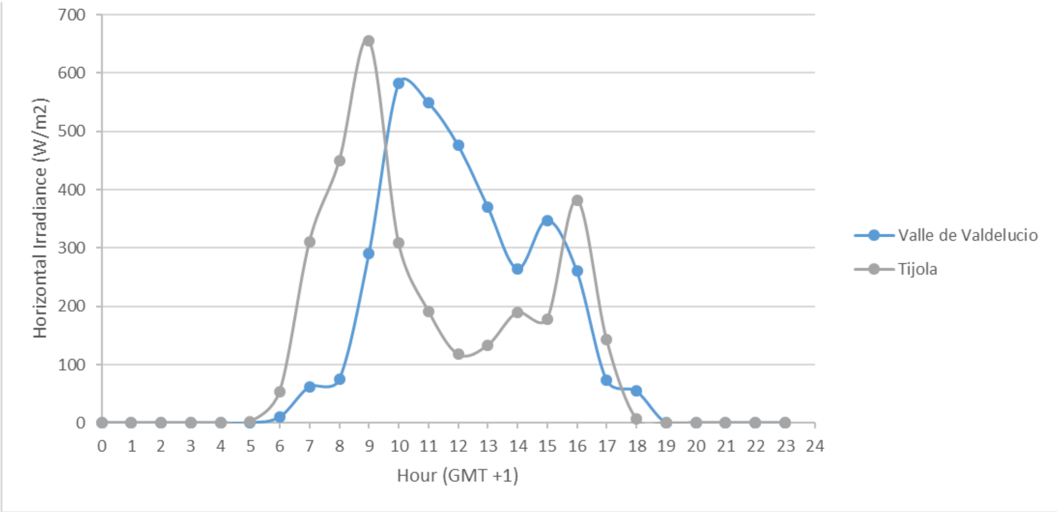

Figure 41 .- Radiation on 5th April 2019 in Valle de Valdelucio and Tíjola SIAR stations (own figure)

The yearly horizontal radiation obtained from SIAR in the selected period, June 2018 to May 2019, for each of the two stations[12] is shown in Table 15. The values have been obtained after adding all the hourly data of the selected SIAR stations and are compared to the yearly values available from three public sources.

Table 15 .- Yearly horizontal irradiation (June 2018 to May 2019) (own table)

Station	Yearly horizontal irradiation (kWh/m^2)			
	SIAR	PVGIS	Global Solar Atlas	SOLARGIS
Valle de Valdelucio	1,607	1,400	1,510	1,494
Tíjola	1,846	1,690	1,880	1,844

As it can be seen in the table above, the measured radiation data from the SIAR stations for the selected period is significantly higher than the data provided from PVGIS for a typical year. On the other hand, if the data is compared to the data provided by GSA and SOLARGIS, there is still a significant difference with the data from the SIAR ofValle de Valdelucio. The measured data is quite similar for the SIAR of Tíjola compared to GSA and SOLARGIS. Therefore, it can be considered that the

[12] This value is independent of the PR

period in analysis is a typical year for Tíjola station while higher than a typical year for Valle de Valdelucio station.

5.4 Electricity generation and grid supply over the considered yearly period (without batteries)

Section 4.3.2.1 presents the methodology to calculate the gross electricity generation of the cases in Table 14. With the value of the PR of each case, the peak power installed on the PV plant (1,25 MW) and the hourly radiation, the hourly electricity generation is very easily calculated. On the other hand, the yearly radiation is obtained by merely adding all the hourly radiation values.

It has to be noted that the calculations are done for an installed power of 1,25 MW but the hourly electricity generation is limited to 1 MW according to the assumed power of the inverters. Therefore, the hourly electricity generation exceeding 1 MW is lost due to this restriction and the electricity generation of the different cases is shown in Table 16. The table includes the values calculated with the online tool of PVGIS for the optimized slope and azimuth. As it can be seen in the table, the electricity generation obtained with the model for Valle de Valdelucio is slightly lower, while for Tíjola the electricity generation in the three cases is around 5% lower. Therefore, taking into account the assumptions of the model and the purpose of the study, the model used is considered conservative but valid.

Table 16 .- Yearly electricity generation (MWh) without batteries (own table)

Case	Location/ SIAR station	Peak Power (kW)	PR	Electricity generation (MWh)	Electricity generation with PVGIS (MWh)	Difference
Case 1	Valle de Valdelucio	1,250	80%	1,608	1,630	-1.3%
Case 2	Valle de Valdelucio	1,250	85%	1,708	1,730	-1.3%
Case 3	Valle de Valdelucio	1,250	90%	1,799	1,840	-2.2%
Case 4	Tíjola	1,250	80%	1,846	1,930	-4.4%
Case 5	Tíjola	1,250	85%	1,961	2,060	-4.8%
Case 6	Tíjola	1,250	90%	2,067	2,180	-5.2%

It has to be pointed out that, since the PV plants have an installed power of 1 MW, the nominal power and the full load hours match each other.

5.5 Electricity generation and grid supply over the considered yearly period (with batteries)

The methodology to obtain the electricity generation of the PV plant with batteries is the same as described in the previous section: the yearly radiation is obtained by merely adding all the hourly radiation values. In this case, the change lies on the shifting of electric energy supplied to the grid with the help of the batteries, when the electricity generation during low price hours is stored to be later discharged during high price hours. For this purpose, the charge/discharge strategy presented in section 4.3.2.2 is used.

An example of the charging/discharging strategy is shown in Table 17 for the SIAR station of Valle de Valdelucio with PR 80% during 15th December 2018, a winter day with low solar resource. The day starts with low market prices and the electricity generation of the day is entirely used to charge the batteries, which never reach the maximum load. Therefore, at 20:00, when the daily price is the highest, the load of the battery is fully discharged.

Table 17 .- Example of charging/discharging strategy (case: Valle de Valdelucio, PR 80%, 15th December 2018) (own table)

Hour	Prod. (kWh)	Charg.	Battery level (kWh)	Disch.	Price (€/MWh)	Supply from panel (kWh)	Supply from battery (kWh)	Total supply (kWh)
1	0,00		0,00		66,3	0,00	0,00	0,00
2	0,00		0,00		60,9	0,00	0,00	0,00
3	0,00		0,00		58	0,00	0,00	0,00
4	0,00		0,00		52,74	0,00	0,00	0,00
5	0,00		0,00		51,25	0,00	0,00	0,00
6	0,00		0,00		50,81	0,00	0,00	0,00
7	0,00		0,00		51,76	0,00	0,00	0,00
8	0,36	yes	0,36		56,7	0,00	0,00	0,00
9	4,88	yes	5,24		57,5	0,00	0,00	0,00
10	11,57	yes	16,82		64,18	0,00	0,00	0,00
11	34,39	yes	51,20		65,96	0,00	0,00	0,00
12	52,42	yes	103,62		64,97	0,00	0,00	0,00
13	31,12	yes	134,74		63,75	0,00	0,00	0,00
14	24,06	yes	158,80		63,1	0,00	0,00	0,00
15	18,82	yes	177,62		58	0,00	0,00	0,00
16	12,15	yes	189,77		58,72	0,00	0,00	0,00
17	1,59	yes	191,36		59,07	0,00	0,00	0,00
18	0,00		191,36		62,72	0,00	0,00	0,00
19	0,00		191,36		66,88	0,00	0,00	0,00
20	0,00		0,00	yes	67,5	0,00	191,36	191,36
21	0,00		0,00		60,78	0,00	0,00	0,00
22	0,00		0,00		59,53	0,00	0,00	0,00
23	0,00		0,00		60,48	0,00	0,00	0,00
24	0,00		0,00		59,41	0,00	0,00	0,00

Table 18 shows the case of Valle de Valdelucio, PR of value 85% and 25th March 2019. During the first hours of electricity generation the prices are low and the batteries are charged but not fully, due to insufficient resource. At the first price peak, occurring at 10:00 and happening to be the highest price of the day too, the battery is fully discharged to supply the grid with electricity. At 17:00 and 18:00 the battery is charged once again, when the next price valley occurs. Since the price is higher at 17:00, not all the electricity generation of that hour is used to charge the batteries but are however completely charged with the help of the electricity generation of 18:00. Finally, at 21:00 the battery is fully discharged again when the second highest price of the day occurs.

Table 18 .- Example of charging/discharging strategy (case: Valle de Valdelucio, PR 85%, 20th October 2018) (own table)

Hour	Prod. (kWh)	Charg.	Battery level (kWh)	Disch.	Price (€/MWh)	Supply from panel (kWh)	Supply from battery (kWh)	Total supply (kWh)
1	0.00		0.00		39	0.00	0.00	0.00
2	0.00		0.00		37.72	0.00	0.00	0.00
3	0.00		0.00		30.99	0.00	0.00	0.00
4	0.00		0.00		30	0.00	0.00	0.00
5	0.00		0.00		30.13	0.00	0.00	0.00
6	0.01	yes	0.01		34.85	0.00	0.00	0.00
7	11.54	yes	11.54		39.8	0.00	0.00	0.00
8	56.77	yes	68.32		51.33	0.00	0.00	0.00
9	124.77		0.00	yes	51.96	124.77	68.32	193.09
10	151.14		0.00		51.94	151.14	0.00	151.14
11	297.79		0.00		51	297.79	0.00	297.79
12	511.16		0.00		49.05	511.16	0.00	511.16
13	593.51		0.00		48.63	593.51	0.00	593.51
14	817.60		0.00		47.74	817.60	0.00	817.60
15	602.15		0.00		41.31	602.15	0.00	602.15
16	562.39		0.00		39.99	562.39	0.00	562.39
17	377.95	yes	324.58		39.3	53.37	0.00	53.37
18	175.42	yes	500.00		39	0.00	0.00	0.00
19	19.55		500.00		41.2	19.55	0.00	19.55
20	0.00		500.00		47.01	0.00	0.00	0.00
21	0.00		0.00	yes	51.94	0.00	500.00	500.00
22	0.00		0.00		49.32	0.00	0.00	0.00
23	0.00		0.00		39.99	0.00	0.00	0.00
24	0.00		0.00		37.56	0.00	0.00	0.00

An interesting case is presented in Table 19 (Tíjola, PR of 85% on 29th June 2018). During the first hours of the day the batteries are fully charged. At 10:00 the batteries are fully charged and the price is one of the highest of the day. However, the discharging process at that hour does not supply the maximum electric energy to the grid, in order to secure the maximum discharge for the next immediate hours until 14:00, when the electricity market prices are even higher than at 10:00. Therefore, between 11:00 and 14:00 the PV plant supplies the electric grid with the maximum allowed electricity thanks to the batteries. Therefore, the PV plant has performed at full load during 4 hours that day.

Table 19 .- Example of charging/discharging strategy (case: Tíjola, PR 85%, 29th June 2018) (own table)

Hour	Prod. (kWh)	Charg.	Battery level (kWh)	Disch.	Price (€/MWh)	Supply from panel (kWh)	Supply from battery (kWh)	Total supply (kWh)
1	0.00		0.00		61.89	0.00	0.00	0.00
2	0.00		0.00		60.43	0.00	0.00	0.00
3	0.00		0.00		59.98	0.00	0.00	0.00
4	0.00		0.00		59.18	0.00	0.00	0.00
5	0.54	yes	0.54		59.01	0.00	0.00	0.00
6	54.12	yes	54.66		60.13	0.00	0.00	0.00
7	208.13	yes	262.79		61.14	0.00	0.00	0.00
8	354.38	yes	500.00		61.76	117.17	0.00	117.17
9	630.95		500.00		63.17	630.95	0.00	630.95
10	772.11		307.38	yes	63.17	772.11	192.62	964.73
11	884.57		191.96	yes	63.19	884.57	115.43	1000.00
12	941.06		133.01	yes	63.17	941.06	58.94	1000.00
13	955.68		88.70	yes	63.19	955.68	44.32	1000.00
14	911.30		0.00	yes	63.17	911.30	88.70	1000.00
15	820.02		0.00		62.64	820.02	0.00	820.02
16	692.28	yes	500.00		62.01	192.28	0.00	192.28
17	519.90		500.00		62.01	519.90	0.00	519.90
18	323.02		350.52	yes	62.01	323.02	149.48	472.50
19	134.20	yes	484.71		62	0.00	0.00	0.00
20	15.29	yes	500.00		61.14	0.00	0.00	0.00
21	0.00		500.00		61.89	0.00	0.00	0.00
22	0.00		500.00		62	0.00	0.00	0.00
23	0.00		0.00	yes	62.52	0.00	500.00	500.00
24	0.00		0.00		61.89	0.00	0.00	0.00

Another interesting case, for Tíjola and PR 90% on 20th September 2018, is shown in Table 20 and the strategy is as follows:

- The electricity generation of the first three hours is completely used to charge the batteries
- At 9:00 the electricity generation is partially used to charge the batteries. The reason why they are not fully charged is that in the next hour (10:00) there is a peak of market price (the PV plant will perform at its maximum) and, right after, prices are lower than at 9:00. Therefore, the batteries are loaded to the load needed to help the system supply the maximum allowable electricity at 10:00, before the price drop.

- At 12:00 we find a valley of market prices which charges the batteries only up to the level needed for the next two hours, right before the next electricity market price valley.
- At 16:00 and 17:00 the batteries are fully charged and ready to be discharged at 20:00, when the market price is the highest of the day.

Table 20 .- Example of charging/discharging strategy (case: Tíjola, PR 90%, 20th September 2018) (own table)

Hour	Prod. (kWh)	Charg.	Battery level (kWh)	Disch.	Price (€/MWh)	Supply from panel (kWh)	Supply from battery (kWh)	Total supply (kWh)
1	0.00		0.00		74.89	0.00	0.00	0.00
2	0.00		0.00		73.95	0.00	0.00	0.00
3	0.00		0.00		72.3	0.00	0.00	0.00
4	0.00		0.00		71.75	0.00	0.00	0.00
5	0.00		0.00		71.22	0.00	0.00	0.00
6	0.73	yes	0.73		72	0.00	0.00	0.00
7	82.41	yes	83.14		74.21	0.00	0.00	0.00
8	272.01	yes	355.15		75.7	0.00	0.00	0.00
9	484.10	yes	365.30		75.94	473.95	0.00	473.95
10	634.70		0.00	yes	76.3	634.70	365.30	1000.00
11	731.80		0.00		75	731.80	0.00	731.80
12	788.99	yes	421.23		74.3	368.49	0.00	368.49
13	806.56		227.78	yes	74.73	806.56	193.44	1000.00
14	772.95		0.73	yes	74.3	772.95	227.05	1000.00
15	681.52		0.73		73.54	681.52	0.00	681.52
16	530.41	yes	188.59		73.5	342.55	0.00	342.55
17	312.14	yes	500.00		73.24	0.00	0.00	0.00
18	84.48		500.00		73.95	84.48	0.00	84.48
19	0.98		500.00		75.01	0.98	0.00	0.98
20	0.00		0.00	yes	79.63	0.00	500.00	500.00
21	0.00		0.00		78.89	0.00	0.00	0.00
22	0.00		0.00		76.04	0.00	0.00	0.00
23	0.00		0.00		72.3	0.00	0.00	0.00
24	0.00		0.00		74.01	0.00	0.00	0.00

The examples above show the complexity of the charging/discharging strategy in order to optimize the performance of a PV plant. In this case, the strategy takes into account every day as a separated event from another. That means that it is possible to charge the batteries during the end of one day to discharge them later next day when the prices are higher, increasing the complexity of the process. However, for the purpose of this study, the strategy shown in this report has been considered as optimal.

Finally, Table 21 shows the yearly electricity generation of the PV plants, in the different cases, with and without batteries. The results show that for a PR of 80% and 85% the difference is zero or almost zero, being the difference in electricity generation more noticeable for the cases of PR 90%. This means that the PV plan does not exceed the nominal power very often and, thus, not much electricity is lost due to the constrains of the inverter. In this respect, the role of the batteries is more important in shifting the supply of electricity to the grid during hours of higher electricity price rather than saving the electricity generation potentially lost due to inverter restrictions. It has to be noted that the electricity generation with batteries is higher than without batteries since the battery system has been considered as ideal (no losses during charging/discharging) and the system can store the energy that would have been lost during the hours when the PV plant produces more electricity than its limitation (the power of the inverter is 1 MW).

Table 21 .- Yearly electricity generation (MWh) with batteries - June 2018 to May 2019 (own table)

Case	Location/SIAR station	Peak Power (kW)	PR	Electricity generation without batteries (MWh)	Electricity generation with batteries (MWh)
Case 1	Valle de Valdelucio	1,250	80%	1,608	1,608
Case 2	Valle de Valdelucio	1,250	85%	1,708	1,708
Case 3	Valle de Valdelucio	1,250	90%	1,799	1,808
Case 4	Tíjola	1,250	80%	1,846	1,846
Case 5	Tíjola	1,250	85%	1,961	1,962
Case 6	Tíjola	1,250	90%	2,067	2,077

5.6 Yearly revenues (June 2018 to May 2019) and investment analysis

The yearly revenues of the different cases have been obtained by addition of the product of the electricity generation times the electricity market price for each hour of the time period considered. Results are shown in Table 22. With these figures the

LCOE for each of the cases has been subsequently calculated and shown in Table 23.

Table 22 .- Yearly revenues (€) of the different cases without and with batteries - June 2018 to May 2019 (own table)

Case	**Location/SIAR station**	**Electricity generation without batteries (MWh)**	**Incomes without batteries (€)**	**Electricity generation with batteries (MWh)**	**Incomes with batteries (€)**
Case 1	Valle de Valdelucio	1,608	96,758	1,608	98,631
Case 2	Valle de Valdelucio	1,708	102,732	1,708	104,666
Case 3	Valle de Valdelucio	1,799	108,353	1,808	110,721
Case 4	Tíjola	1,846	111,116	1,846	113,147
Case 5	Tíjola	1,961	118,015	1,962	120,110
Case 6	Tíjola	2,067	124,431	2,077	126,983

Table 23 .- LCOE of the different cases without and with batteries - June 2018 to May 2019 (own table)

Case	**Location/SIAR station**	**LCOE (€/MWh)**		**Average market price (June 2018-May 2019) (€/MWh)**
		Without batteries	**With batteries**	
Case 1	Valle de Valdelucio	71.49	86.74	59.05
Case 2	Valle de Valdelucio	67.31	81.67	
Case 3	Valle de Valdelucio	63.91	77.15	
Case 4	Tíjola	62.28	75.56	
Case 5	Tíjola	58.63	71.10	
Case 6	Tíjola	55.62	67.16	

For the cases that have been analyzed and under the considered assumptions, only Tíjola without battery storage system and PR of 85% and 90% is profitable, with LCOE values lower than the average market price of electricity in the analyzed yearly period. Since a PR of 85% in Spain is something realistic and with a significant occurrence (Figure 35), it can be considered that PV in Spain is a mature technology, without the need of feed-in tariffs or any other subsidies/support, and which can be run under the current electricity market prices. This is confirmed by the results of the second renewable energy auction that took place in 2018 (Lamoncloa (2017)), when 1,037 MW of PV projects were awarded to different developers, showing their trust to invest without support and relying only on the prices of the market.

5.7 Estimation of the year to invest on PV plus lithium-ion battery storage based on cost reduction

This section shows an analysis and the estimation, under given assumptions, of the (profitable) year when the investment in PV plants with lithium-ion battery storage may be positively interesting from the economic point of view, that's it, when the LCOE is lower than the electricity market price.

The investment parameters of PV plants have future projections that may turn a project into a profitable one or vice versa. One of these parameters is the electricity market price, whose future projection has been already analyzed in section 4.2. As a result, the electricity market prices have a clear upward trend, though smoother during the last years. It is expected that these prices continue with this tendency of smooth increase in the future. However, for the sake of a conservative analysis, the future prices of the electricity market are considered to remain constant as the ones of the analyzed period.

On the other hand, investment costs, and more specifically the ones related to battery storage, are expected to decrease significantly in the future, As an example, the LCOE of PV projects is expected to halve in the second half of the decade of 2030´s (Vartainen et al (2017)) and the battery costs even earlier, by the second half of the decade of 2020´s (Curry (2017)). Therefore, the estimated battery cost reduction based on the above information are summarized in Table 24.

Table 24 .- Expected battery cost reduction based on the information in (own table from the data from Vartainen et al (2017) and Curry (2017))

Investment cost reduction	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	95%
Battery system	75%	80%	85%	88%	93%	95%

The calculations of the LCOE of the six cases considered in this thesis show that, taking only into consideration the reduction of the battery storage costs and not changing the remaining costs as per the current time and the electricity market price, the LCOE of the six cases remains above the electricity market price. Only the LCOE in the case of Tíjola with PR of 90% is close to the el electricity market price value when the battery system costs are reduced to values expected by 2030, though still slightly above: 60.03 €/MWh vs 59.05 €/MWh.

Only a combination of the cost reduction of PV plants and battery systems makes the LCOE values of the studied cases interesting from the investment point of view, that's it, lower than the electricity market price. Table 25 shows a summary of the calculations presented in the corresponding appendix in section 10.3.

Table 25 .- LCOE of the different cases considering cost reductions for different years (own table)

	Valle de Valdelucio			Tíjola		
	PR 80%	PR 85%	PR 90%	PR 80%	PR 85%	PR 90%
2020	77.89	73.34	69.28	67.86	63.85	60.31
2022	71.94	67.74	63.99	62.67	58.97	55.70
2024	67.60	63.65	60.13	58.90	55.41	52.35
2026	63.94	60.21	56.88	55.71	52.41	49.51
2028	61.90	58.28	55.06	53.92	50.74	47.93
2030	60.09	56.58	53.45	52.35	49.25	46.53

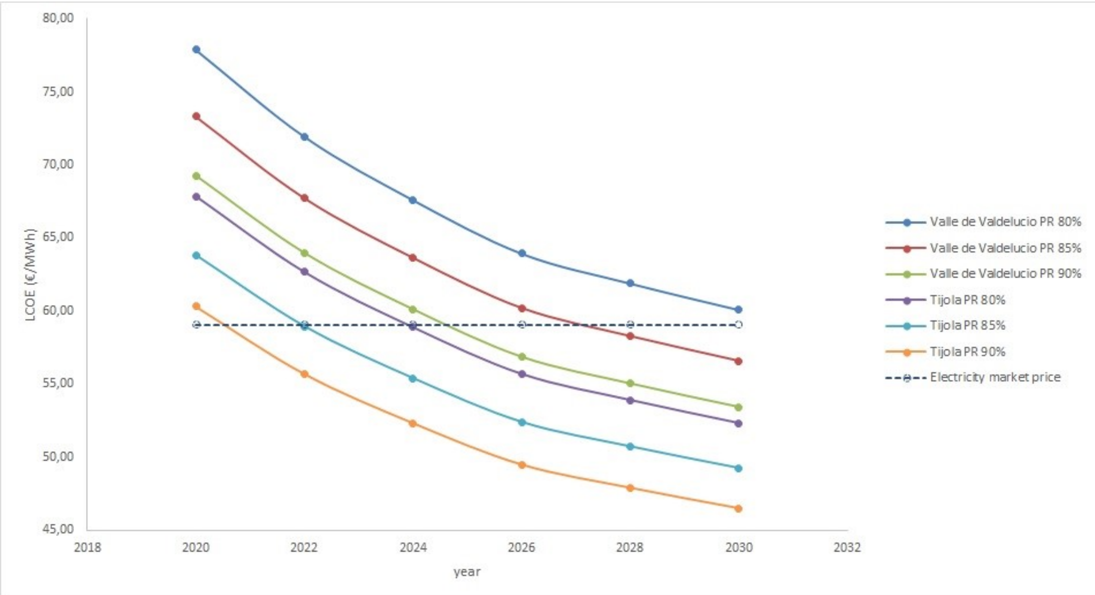

Figure 42 .- LCOE of the different cases considering cost reductions for different years (own figure)

Of all the cases analyzed, the LCOE of Valle de Valdelucio with PR of 80% would be the latest one to be lower than the electricity market prices, estimated to happen after

2030. The two remaining cases of Valle de Valdelucio are expected to be below electricity market prices after 2026 (PR 85%) and 2024 (PR 90%). On the other hand, Tíjola with PR 80% and 85% are expected to improve the investment costs below the electricity market prices by 2024 and 2022 respectively, while Tíjola with PR 90% would have a LCOE value below market prices already in 2020.

6 Summary and conclusions

Two PV plants of 1 MW of installed power, respectively situated in the north and south of Spain, have been analyzed. The PV plants have been analyzed under two different scenarios: with and without lithium-ion battery storage of 0.5 MW of nominal power.

The analysis in this thesis is based on the electricity prices of the Spanish market. The tendency of these prices is to slightly increase yearly, though they have been considered as constant with time for the purpose of this thesis.

On the other hand, PV investment costs are expected to decrease with time during the next years. The investment costs have been enormously reduced since the middle 70's and are still expected to be reduced in the future. For example, in Spain by the year 2050 the LCOE is expected to be around 20 €/MWh in comparison to 50 €/MWh expected in year 2020.

PV is a mature technology in the Spanish market. With the current investment costs for PV plants without storage and the electricity market prices, it is possible to invest without big risks as it expected from the latest renewable energy auction, when 1,037 MW of PV projects were awarded to different developers.

The challenges that PV plants with lithium-ion battery storage will have to face in the future is the lack of specific regulations on this field, as well as the real changes in costs. As it happened in the past with the price of the PV panels, a high demand of lithium-ion batteries would eventually drop prices due to factors like the scale economy. However, a larger number of PV plants with storage may change the electricity market prices and make them lower with respect to today's prices. Therefore, the next few years need to be monitored to check the real trends and analyze the suitability of lithium-ion storage as a solution for PV plants.

From the calculations performed in this thesis and under the considered assumptions, PV plants without storage in the south of Spain may be profitable (LCOW < electricity market prices) when the PR is equal or above 85%. In the north of Spain, with lower sun resource, the LCOE values still remain above the electricity market prices. Only when the PR is 90%, the LCOE is closer to the average market price considered, 63.91 €/MWh against 59.05 €/MWh respectively.

Therefore, the investment in the south of Spain in a PV plant without storage system, under electricity market prices and the assumptions in this thesis, could be profitable at the moment considering the electricity market prices as unchanging and PR of 85% or above. With the expected evolution of investment costs, the same conclusion my soon be valid for the rest of the country.

Regarding lithium-ion battery storage systems, the prices are high at the moment and, though they should decrease significantly during the next years, they are also expected to remain still high. That means that, considering the PV plant investment costs constant throughout the years and only taking into consideration the battery system cost reduction, the LCOE in the analyzed cases will still be above the electricity market price by the year 2030. Only the combined reduction of PV plant and battery storage costs will bring the total costs to LCOE values below the electricity market prices.

With the assumptions considered in this thesis, the investment in PV plus lithium-ion battery storage would be profitable during different years between 2020 and 2030 depending on different technical and economic assumptions. Of all the cases analyzed, the investment on a PV plant with lithium-ion batteries and PR of 80% in Valle de Valdelucio would be profitable (LCOE < electricity market prices) only after 2030. On the other hand, the same location but with PR of 80% and 90% would be profitable already in 2026 and 2024 respectively.

Being in an area of higher sun resource, a PV plant with lithium-ion batteries in Tíjola is expected to have an LCOE below the electricity market price sooner than in Valle de Valdelucio. Thus, considering a PR of 80% and 85%, the LCOE would be below the electricity market price already by 2024 and 2022 respectively. For the higher PR considered, 90%, the LCOE would be below the electricity market price as soon as in 2020, considering the investment costs presented in this thesis.

A challenge for PV plants with storage is to estimate the size of the storage solution. In this thesis a 0.5 MW battery system has been considered, but a sensitivity analysis combining installed power of the PV plant plus storage size may lead to better results than the ones shown in this thesis.

As a summary, it can be concluded that:

- at the moment, PV plants with lithium-ion battery storage in Spain are not attractive from the economic point of view, since the LCOE values are above electricity market prices
- considering the expected reduction of the investment costs, PV plants with lithium-ion battery storage would present LCOE values below the electricity

market prices as soon as in 2020 but only in the south of the country for very high but realistic PR values

- in the north of Spain, where the sun resource is lower, the investment on PV plants with lithium-ion battery storage would be attractive (LCOE < electricity market values) only after 2024, if the investment costs are reduced as expected. If considering the average PR (<85%), this occurrence would not happen until, at least, 2030.

7 Bibliography

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8 List of abbreviations

ASAE	American Society of Agricultural Engineers
BoS	Balance of costs
CPI	Consumers Price Index
CSP	Concentrated Solar Power
EPC	Engineering, procurement and construction
GSA	Global Solar Atlas
FAO	Food and Agriculture Organization
INM	Instituto Nacional de Meteorología – National Meteorological Institute
kWp	Kilo-Watt peak
LCOE	Levelized costs of electricity
Li-ion	Lithium-ion
MPP	Maximum power point
NPV	Net present value
O&M	Operation and maintenance
OPEX	Operational expenditure
PER	Plan de Energías Renovables
PR	Performance ratio
PV	Photovoltaic or photovoltaics
PVGIS	Photovoltaic geographical information system (European Commission)
R&D	Research and Development
RPM	Revolutions per Minute
SEI	Solid electrolyte interface
STC	Standard test conditions
TIR	Tasa Interna de Retorno
TMR	Tarifa Media de Referencia
WMO	World Meteorological Organization
V	Volt/volts
VAN	Valor Neto Actual
Wp / kWp / MWp	Watt peak/kilowatt peak / megawatt peak

9 List of figures/tables

List of figures

List of tables

10 List of appendixes

10.1 Appendix 1: Economic analysis – current situation

The tables in this appendix show the economic calculations performed for the six cases considered in this thesis: the two PV plants in Valle de Valdelucio and Tíjola with different PR of 80%, 85% and 90%. The economic input data is the same for the six cases. Only the electricity generation and yearly incomes differ, depending on the location ad PR selected. For each case, the economic calculation is performed without and with lithium-ion battery storage system.

Economic analysis – current situation

Valle de Valdelucio – PR 80%

With batteries - Valle de Valdelucio (PR - 80%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,50	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 608	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-1 000 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)																					100 000
Nominal Cash-flow (€)	-1 000 000	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	194 552
Discounted Cash-flow (€)	-1 000 000	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	45 800
Discounted Costs (€)	1 000 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	-209 194
Annuity	-20 520
NPV of costs	1 422 031
Annuity of costs	139 490
LCOE	86,74

Without batteries - Valle de Valdelucio (PR - 80%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)		hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)		€/W
Running costs	35 000	€
Yearly incomes	96 758	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 608	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-750 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		98 693	100 667	102 680	104 733	106 828	108 965	111 144	113 367	115 634	117 947	120 306	122 712	125 166	127 670	130 223	132 827	135 484	138 194	140 957	143 777
Wind farm selling (€)																					75 000
Nominal Cash-flow (€)	-750 000	62 993	64 253	65 538	66 848	68 185	69 549	70 940	72 359	73 806	75 282	76 788	78 324	79 890	81 488	83 118	84 780	86 475	88 205	89 969	166 768
Discounted Cash-flow (€)	-750 000	58 598	55 600	52 755	50 056	47 495	45 065	42 759	40 572	38 496	36 526	34 658	32 884	31 202	29 606	28 091	26 654	25 290	23 996	22 768	39 259
Discounted Costs (€)	750 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	12 331
Annuity	1 210
NPV of costs	1 172 031
Annuity of costs	114 967
LCOE	71,49

Economic analysis – current situation

Valle de Valdelucio – PR 85%

With batteries - Valle de Valdelucio (PR - 85%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,50	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 708	MWh

Scenario 1	year										
	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-1 000 000										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587
Wind farm selling (€)											
Nominal Cash-flow (€)	-1 000 000	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922
Discounted Cash-flow (€)	-1 000 000	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204
Discounted Costs (€)	1 000 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	year									
	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)										100 000
Nominal Cash-flow (€)	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	203 519
Discounted Cash-flow (€)	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	47 911
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	-136 428
Annuity	-13 383
NPV of costs	1 422 031
Annuity of costs	139 490
LCOE	81,67

Without batteries - Valle de Valdelucio (PR - 85%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)		€/W
Running costs	35 000	€
Yearly incomes	102 732	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 708	MWh

Scenario 1	year										
	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-750 000										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		104 786	106 882	109 020	111 200	113 424	115 692	118 006	120 366	122 774	125 229
Wind farm selling (€)											
Nominal Cash-flow (€)	-750 000	69 086	70 468	71 877	73 315	74 781	76 277	77 802	79 358	80 946	82 564
Discounted Cash-flow (€)	-750 000	64 266	60 978	57 858	54 898	52 089	49 424	46 896	44 496	42 220	40 060
Discounted Costs (€)	750 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	year									
	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	127 734	130 289	132 894	135 552	138 263	141 028	143 849	146 726	149 661	152 654
Wind farm selling (€)										75 000
Nominal Cash-flow (€)	84 216	85 900	87 618	89 370	91 158	92 981	94 841	96 737	98 672	175 646
Discounted Cash-flow (€)	38 010	36 065	34 220	32 469	30 808	29 232	27 736	26 317	24 971	41 349
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	84 366
Annuity	8 276
NPV of costs	1 172 031
Annuity of costs	114 967
LCOE	67,31

Economic analysis – current situation

Valle de Valdelucio – PR 90%

With batteries - Valle de Valdelucio (PR - 90%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,50	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 808	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-1 000 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)																					100 000
Nominal Cash-flow (€)	-1 000 000	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	212 518
Discounted Cash-flow (€)	-1 000 000	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	50 029
Discounted Costs (€)	1 000 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	-63 409
Annuity	-6 220
NPV of costs	1 422 031
Annuity of costs	139 490
LCOE	77,15

Without batteries - Valle de Valdelucio (PR - 90%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)		hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)		€/W
Running costs	35 000	€
Yearly incomes	108 353	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 799	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-750 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		110 520	112 730	114 985	117 285	119 630	122 023	124 463	126 953	129 492	132 082	134 723	137 418	140 166	142 969	145 829	148 745	151 720	154 755	157 850	161 007
Wind farm selling (€)																					75 000
Nominal Cash-flow (€)	-750 000	74 820	76 316	77 843	79 400	80 988	82 607	84 259	85 945	87 664	89 417	91 205	93 029	94 890	96 788	98 723	100 698	102 712	104 766	106 861	183 999
Discounted Cash-flow (€)	-750 000	69 600	66 039	62 660	59 454	56 413	53 526	50 788	48 189	45 724	43 384	41 165	39 059	37 060	35 164	33 365	31 658	30 038	28 502	27 043	43 316
Discounted Costs (€)	750 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	152 148
Annuity	14 925
NPV of costs	1 172 031
Annuity of costs	114 967
LCOE	63,91

Economic analysis – current situation

Tijola – PR 80%

With batteries - Tijola (PR - 80%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,50	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 846	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-1 000 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)																					100 000
Nominal Cash-flow (€)	-1 000 000	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	216 122
Discounted Cash-flow (€)	-1 000 000	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	50 878
Discounted Costs (€)	1 000 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	-34 162
Annuity	-3 351
NPV of costs	1 422 031
Annuity of costs	139 490
LCOE	75,56

Without batteries - Tijola (PR - 80%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)		hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)		€/W
Running costs	35 000	€
Yearly incomes	111 116	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 846	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-750 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		113 339	115 605	117 918	120 276	122 681	125 135	127 638	130 190	132 794	135 450	138 159	140 922	143 741	146 616	149 548	152 539	155 590	158 701	161 876	165 113
Wind farm selling (€)																					75 000
Nominal Cash-flow (€)	-750 000	77 639	79 191	80 775	82 391	84 039	85 719	87 434	89 182	90 966	92 785	94 641	96 534	98 465	100 434	102 443	104 491	106 581	108 713	110 887	188 105
Discounted Cash-flow (€)	-750 000	72 222	68 527	65 021	61 694	58 538	55 543	52 701	50 005	47 446	45 019	42 716	40 530	38 457	36 489	34 622	32 851	31 170	29 575	28 062	44 282
Discounted Costs (€)	750 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	185 470
Annuity	18 193
NPV of costs	1 172 031
Annuity of costs	114 967
LCOE	62,28

Economic analysis – current situation

Tijola – PR 85%

With batteries - Tijola (PR - 85%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,50	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 962	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-1 000 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)																					100 000
Nominal Cash-flow (€)	-1 000 000	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	226 469
Discounted Cash-flow (€)	-1 000 000	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	53 314
Discounted Costs (€)	1 000 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	49 798
Annuity	4 885
NPV of costs	1 422 031
Annuity of costs	139 490
LCOE	71,10

Without batteries - Tijola (PR - 85%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)		€/W
Running costs	35 000	€
Yearly incomes	118 015	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 961	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-750 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		120 376	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)																					75 000
Nominal Cash-flow (€)	-750 000	84 676	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	201 469
Discounted Cash-flow (€)	-750 000	78 768	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	47 428
Discounted Costs (€)	750 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	291 926
Annuity	28 636
NPV of costs	1 172 031
Annuity of costs	114 967
LCOE	58,63

Economic analysis – current situation

Tijola – PR 90%

With batteries - Tijola (PR - 90%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,50	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	2 077	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-1 000 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)																					100 000
Nominal Cash-flow (€)	-1 000 000	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	236 681
Discounted Cash-flow (€)	-1 000 000	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	55 718
Discounted Costs (€)	1 000 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	132 673
Annuity	13 014
NPV of costs	1 422 031
Annuity of costs	139 490
LCOE	67,16

Without batteries - Tijola (PR - 90%)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)		hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)		€/W
Running costs	35 000	€
Yearly incomes	124 431	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	2 067	MWh

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-750 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		126 919	129 458	132 047	134 688	137 381	140 129	142 932	145 790	148 706	151 680	154 714	157 808	160 964	164 184	167 467	170 817	174 233	177 718	181 272	184 897
Wind farm selling (€)																					75 000
Nominal Cash-flow (€)	-750 000	91 219	93 044	94 904	96 803	98 739	100 713	102 728	104 782	106 878	109 015	111 196	113 420	115 688	118 002	120 362	122 769	125 224	127 729	130 284	207 889
Discounted Cash-flow (€)	-750 000	84 855	80 514	76 394	72 486	68 777	65 258	61 920	58 752	55 746	52 894	50 187	47 620	45 183	42 872	40 678	38 597	36 622	34 749	32 971	48 940
Discounted Costs (€)	750 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	346 014
Annuity	33 941
NPV of costs	1 172 031
Annuity of costs	114 967
LCOE	55,62

10.2 Appendix 2: Economic analysis – LCOE estimation after battery investment cost reduction by 2030

The tables in this appendix show the economic calculations performed for the six cases considered in this thesis: the two PV plants in Valle de Valdelucio and Tíjola with different PR of 80%, 85% and 90%. The economic input data is the same for the six cases. Only the electricity generation and yearly incomes differ, depending on the location ad PR selected. For each case, the LCOE is calculated for 2030, considering the battery investment cost reduction shown in Table 24.

Economic analysis – LCOE estimation after battery investment cost reduction by 2030

Valle de Valdelucio – PR 80%

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 608	MWh

Scenario 1	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-849 129										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231
Wind farm selling (€)											
Nominal Cash-flow (€)	-849 129	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566
Discounted Cash-flow (€)	-849 129	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634
Discounted Costs (€)	849 129	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)										84 913
Nominal Cash-flow (€)	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	179 465
Discounted Cash-flow (€)	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	42 248
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NVP	-61 874
Annuity	-6 069
NVP of costs	1 271 160
Annuity of costs	124 691
LCOE	77,53

Economic analysis – LCOE estimation after battery investment cost reduction by 2030

Valle de Valdelucio – PR 85%

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 708	MWh

Scenario 1	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-849 129										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587
Wind farm selling (€)											
Nominal Cash-flow (€)	-849 129	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922
Discounted Cash-flow (€)	-849 129	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204
Discounted Costs (€)	849 129	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)										84 913
Nominal Cash-flow (€)	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	188 432
Discounted Cash-flow (€)	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	44 359
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NVP	10 891
Annuity	1 068
NVP of costs	1 271 160
Annuity of costs	124 691
LCOE	73,00

Economic analysis – LCOE estimation after battery investment cost reduction by 2030

Valle de Valdelucio – PR 90%

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 808	MWh

Scenario 1	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-849 129										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969
Wind farm selling (€)											
Nominal Cash-flow (€)	-849 129	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304
Discounted Cash-flow (€)	-849 129	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785
Discounted Costs (€)	849 129	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)										84 913
Nominal Cash-flow (€)	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	197 431
Discounted Cash-flow (€)	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	46 478
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NVP	83 911
Annuity	8 231
NVP of costs	1 271 160
Annuity of costs	124 691
LCOE	68,97

Economic analysis – LCOE estimation after battery investment cost reduction by 2030

Tijola – PR 80%

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 846	MWh

Scenario 1	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-849 129										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925
Wind farm selling (€)											
Nominal Cash-flow (€)	-849 129	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260
Discounted Cash-flow (€)	-849 129	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220
Discounted Costs (€)	849 129	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)										84 913
Nominal Cash-flow (€)	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	201 035
Discounted Cash-flow (€)	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	47 326
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NVP	113 157
Annuity	11 100
NVP of costs	1 271 160
Annuity of costs	124 691
LCOE	67,55

Economic analysis – LCOE estimation after battery investment cost reduction by 2030

Tijola – PR 85%

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	1 962	MWh

Scenario 1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-849 129																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)																					84 913
Nominal Cash-flow (€)	-849 129	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	211 382
Discounted Cash-flow (€)	-849 129	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	49 762
Discounted Costs (€)	849 129	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NVP	197 118
Annuity	19 336
NVP of costs	1 271 160
Annuity of costs	124 691
LCOE	63,55

Economic analysis – LCOE estimation after battery investment cost reduction by 2030

Tijola – PR 90%

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,75	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly production	2 077	MWh

Scenario 1	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-849 129										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791
Wind farm selling (€)											
Nominal Cash-flow (€)	-849 129	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126
Discounted Cash-flow (€)	-849 129	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403
Discounted Costs (€)	849 129	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)										84 913
Nominal Cash-flow (€)	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	221 594
Discounted Cash-flow (€)	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	52 166
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NVP	279 992
Annuity	27 465
NVP of costs	1 271 160
Annuity of costs	124 691
LCOE	60,03

10.3 Appendix 3: Economic analysis – profitable year to invest on PV plus lithium-ion battery storage based on cost reduction

The tables in this appendix show the economic calculations performed for the six cases considered in this thesis, with batteries, considering the year and costs reduction that make the investment on PV plus lithium-ion battery storage attractive (LCOE < electricity market price) from the economic point of view. The table situated in the top-center of the calculations shows the investment cost reduction up to the year when, for each of the cases, the LCOE is below or almost equal to the electricity market price.

Economic analysis – profitable year to invest (LCOE < electricity market price) on PV plus lithium-ion battery storage based on cost reduction

Valle de Valdelucio – PR 80%

Vlle de Valdelucio - PR 80% (year 2020)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,67	€/W
Investment Costs (Battery system)	0,38	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 608	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%					
Battery system	75%					

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-855 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)																					85 500
Nominal Cash-flow (€)	-855 000	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	180 052
Discounted Cash-flow (€)	-855 000	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	42 387
Discounted Costs (€)	855 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	-67 607
Annuity	-6 632
NPV of costs	1 277 031
Annuity of costs	125 267
LCOE	77,89

Vlle de Valdelucio - PR 80% (year 2022)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,61	€/W
Investment Costs (Battery system)	0,30	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 608	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%				
Battery system	75%	80%				

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-757 425																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)																					75 743
Nominal Cash-flow (€)	-757 425	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	170 295
Discounted Cash-flow (€)	-757 425	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	40 090
Discounted Costs (€)	757 425	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	27 671
Annuity	2 714
NPV of costs	1 179 456
Annuity of costs	115 695
LCOE	71,94

Vlle de Valdelucio - PR 80% (year 2024)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,56	€/W
Investment Costs (Battery system)	0,26	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 608	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%			
Battery system	75%	80%	85%			

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-686 331																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)																					68 633
Nominal Cash-flow (€)	-686 331	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	163 185
Discounted Cash-flow (€)	-686 331	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	38 416
Discounted Costs (€)	686 331	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	97 091
Annuity	9 524
NPV of costs	1 108 362
Annuity of costs	108 722
LCOE	67,60

Vlle de Valdelucio - PR 80% (year 2026)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,51	€/W
Investment Costs (Battery system)	0,22	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 608	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%		
Battery system	75%	80%	85%	88%		

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-626 325																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)																					62 632
Nominal Cash-flow (€)	-626 325	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	157 185
Discounted Cash-flow (€)	-626 325	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	37 003
Discounted Costs (€)	626 325	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	155 685
Annuity	15 271
NPV of costs	1 048 356
Annuity of costs	102 836
LCOE	63,94

Vlle de Valdelucio - PR 80% (year 2028)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,49	€/W
Investment Costs (Battery system)	0,21	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 608	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	
Battery system	75%	80%	85%	88%	93%	

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-592 764																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)																					59 276
Nominal Cash-flow (€)	-592 764	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	153 829
Discounted Cash-flow (€)	-592 764	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	36 213
Discounted Costs (€)	592 764	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	188 455
Annuity	18 486
NPV of costs	1 014 796
Annuity of costs	99 544
LCOE	61,90

Vlle de Valdelucio - PR 80% (year 2030)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,46	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	98 631	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 608	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	95%
Battery system	75%	80%	85%	88%	93%	95%

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-563 126																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		100 604	102 616	104 668	106 761	108 897	111 074	113 296	115 562	117 873	120 231	122 635	125 088	127 590	130 141	132 744	135 399	138 107	140 869	143 687	146 560
Wind farm selling (€)																					56 313
Nominal Cash-flow (€)	-563 126	64 904	66 202	67 526	68 876	70 254	71 659	73 092	74 554	76 045	77 566	79 117	80 699	82 313	83 960	85 639	87 352	89 099	90 881	92 698	150 865
Discounted Cash-flow (€)	-563 126	60 375	57 286	54 356	51 575	48 936	46 432	44 057	41 802	39 664	37 634	35 709	33 882	32 149	30 504	28 943	27 462	26 057	24 724	23 459	35 516
Discounted Costs (€)	563 126	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	217 396
Annuity	21 325
NPV of costs	985 157
Annuity of costs	96 636
LCOE	60,09

Economic analysis – profitable year to invest (LCOE < electricity market price) on PV plus lithium-ion battery storage based on cost reduction

Valle de Valdelucio – PR 85%

Vlle de Valdelucio - PR 85% (year 2020)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,67	€/W
Investment Costs (Battery system)	0,38	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 708	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%					
Battery system	75%					

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-855 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)																					85 500
Nominal Cash-flow (€)	-855 000	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	189 019
Discounted Cash-flow (€)	-855 000	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	44 498
Discounted Costs (€)	855 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	5 158
Annuity	506
NPV of costs	1 277 031
Annuity of costs	125 267
LCOE	73,34

Vlle de Valdelucio - PR 85% (year 2022)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,61	€/W
Investment Costs (Battery system)	0,30	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 708	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%				
Battery system	75%	80%				

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-757 425																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)																					75 743
Nominal Cash-flow (€)	-757 425	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	179 262
Discounted Cash-flow (€)	-757 425	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	42 201
Discounted Costs (€)	757 425	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	100 436
Annuity	9 852
NPV of costs	1 179 456
Annuity of costs	115 695
LCOE	67,74

Vlle de Valdelucio - PR 85% (year 2024)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,56	€/W
Investment Costs (Battery system)	0,26	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 708	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%			
Battery system	75%	80%	85%			

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-686 331																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)																					68 633
Nominal Cash-flow (€)	-686 331	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	172 153
Discounted Cash-flow (€)	-686 331	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	40 527
Discounted Costs (€)	686 331	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	169 857
Annuity	16 662
NPV of costs	1 108 362
Annuity of costs	108 722
LCOE	63,65

Vlle de Valdelucio - PR 85% (year 2026)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,51	€/W
Investment Costs (Battery system)	0,22	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 708	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%		
Battery system	75%	80%	85%	88%		

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-626 325																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)																					62 632
Nominal Cash-flow (€)	-626 325	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	166 152
Discounted Cash-flow (€)	-626 325	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	39 114
Discounted Costs (€)	626 325	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	228 450
Annuity	22 409
NPV of costs	1 048 356
Annuity of costs	102 836
LCOE	60,21

Vlle de Valdelucio - PR 85% (year 2028)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,49	€/W
Investment Costs (Battery system)	0,21	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 708	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	
Battery system	75%	80%	85%	88%	93%	

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-592 764																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)																					59 276
Nominal Cash-flow (€)	-592 764	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	162 796
Discounted Cash-flow (€)	-592 764	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	38 324
Discounted Costs (€)	592 764	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	261 221
Annuity	25 624
NPV of costs	1 014 796
Annuity of costs	99 544
LCOE	58,28

Vlle de Valdelucio - PR 85% (year 2030)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,46	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	104 666	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 708	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	95%
Battery system	75%	80%	85%	88%	93%	95%

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-563 126																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		106 759	108 894	111 072	113 293	115 559	117 870	120 228	122 632	125 085	127 587	130 139	132 741	135 396	138 104	140 866	143 683	146 557	149 488	152 478	155 528
Wind farm selling (€)																					56 313
Nominal Cash-flow (€)	-563 126	71 059	72 480	73 930	75 408	76 916	78 455	80 024	81 624	83 257	84 922	86 620	88 353	90 120	91 922	93 761	95 636	97 549	99 500	101 490	159 832
Discounted Cash-flow (€)	-563 126	66 101	62 719	59 510	56 466	53 577	50 836	48 235	45 767	43 425	41 204	39 096	37 095	35 197	33 397	31 688	30 067	28 528	27 069	25 684	37 627
Discounted Costs (€)	563 126	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	290 161
Annuity	28 463
NPV of costs	985 157
Annuity of costs	96 636
LCOE	56,58

Economic analysis – profitable year to invest (LCOE < electricity market price) on PV plus lithium-ion battery storage based on cost reduction

Valle de Valdelucio – PR 90%

Vlle de Valdelucio - PR 90% (year 2020)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,67	€/W
Investment Costs (Battery system)	0,38	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 808	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%					
Battery system	75%					

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-855 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)																					85 500
Nominal Cash-flow (€)	-855 000	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	198 018
Discounted Cash-flow (€)	-855 000	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	46 616
Discounted Costs (€)	855 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	78 178
Annuity	7 669
NPV of costs	1 277 031
Annuity of costs	125 267
LCOE	69,28

Vlle de Valdelucio - PR 90% (year 2022)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,61	€/W
Investment Costs (Battery system)	0,30	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 808	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%				
Battery system	75%	80%				

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-757 425																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)																					75 743
Nominal Cash-flow (€)	-757 425	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	188 260
Discounted Cash-flow (€)	-757 425	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	44 319
Discounted Costs (€)	757 425	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	173 456
Annuity	17 015
NPV of costs	1 179 456
Annuity of costs	115 695
LCOE	63,99

Vlle de Valdelucio - PR 90% (year 2024)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,56	€/W
Investment Costs (Battery system)	0,26	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 808	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%			
Battery system	75%	80%	85%			

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-686 331																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)																					68 633
Nominal Cash-flow (€)	-686 331	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	181 151
Discounted Cash-flow (€)	-686 331	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	42 645
Discounted Costs (€)	686 331	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	242 876
Annuity	23 824
NPV of costs	1 108 362
Annuity of costs	108 722
LCOE	60,13

Vlle de Valdelucio - PR 90% (year 2026)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,51	€/W
Investment Costs (Battery system)	0,22	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 808	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%		
Battery system	75%	80%	85%	88%		

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-626 325																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)																					62 632
Nominal Cash-flow (€)	-626 325	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	175 150
Discounted Cash-flow (€)	-626 325	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	41 233
Discounted Costs (€)	626 325	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	301 470
Annuity	29 572
NPV of costs	1 048 356
Annuity of costs	102 836
LCOE	56,88

Vlle de Valdelucio - PR 90% (year 2028)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,49	€/W
Investment Costs (Battery system)	0,21	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 808	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	
Battery system	75%	80%	85%	88%	93%	

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-592 764																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)																					59 276
Nominal Cash-flow (€)	-592 764	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	171 794
Discounted Cash-flow (€)	-592 764	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	40 443
Discounted Costs (€)	592 764	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	334 240
Annuity	32 786
NPV of costs	1 014 796
Annuity of costs	99 544
LCOE	55,06

Vlle de Valdelucio - PR 90% (year 2030)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,46	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	110 721	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 808	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	95%
Battery system	75%	80%	85%	88%	93%	95%

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-563 126																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		112 936	115 194	117 498	119 848	122 245	124 690	127 184	129 728	132 322	134 969	137 668	140 421	143 230	146 094	149 016	151 997	155 036	158 137	161 300	164 526
Wind farm selling (€)																					56 313
Nominal Cash-flow (€)	-563 126	77 236	78 780	80 356	81 963	83 602	85 274	86 980	88 720	90 494	92 304	94 150	96 033	97 954	99 913	101 911	103 949	106 028	108 149	110 312	168 830
Discounted Cash-flow (€)	-563 126	71 847	68 171	64 683	61 374	58 234	55 255	52 428	49 745	47 200	44 785	42 494	40 320	38 257	36 300	34 442	32 680	31 008	29 422	27 916	39 745
Discounted Costs (€)	563 126	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	363 181
Annuity	35 625
NPV of costs	985 157
Annuity of costs	96 636
LCOE	53,45

Economic analysis – profitable year to invest (LCOE < electricity market price) on PV plus lithium-ion battery storage based on cost reduction

Tijola – PR 80%

Tijola - PR 80% (year 2020)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,67	€/W
Investment Costs (Battery system)	0,38	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 846	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%					
Battery system	75%					

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-855 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)																					85 500
Nominal Cash-flow (€)	-855 000	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	201 622
Discounted Cash-flow (€)	-855 000	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	47 464
Discounted Costs (€)	855 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	107 424
Annuity	10 537
NPV of costs	1 277 031
Annuity of costs	125 267
LCOE	67,86

Tijola - PR 80% (year 2022)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,61	€/W
Investment Costs (Battery system)	0,30	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 846	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%				
Battery system	75%	80%				

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-757 425																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)																					75 743
Nominal Cash-flow (€)	-757 425	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	191 864
Discounted Cash-flow (€)	-757 425	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	45 167
Discounted Costs (€)	757 425	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	202 702
Annuity	19 883
NPV of costs	1 179 456
Annuity of costs	115 695
LCOE	62,67

Tijola - PR 80% (year 2024)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,56	€/W
Investment Costs (Battery system)	0,26	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 846	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%			
Battery system	75%	80%	85%			

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-686 331																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)																					68 633
Nominal Cash-flow (€)	-686 331	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	184 755
Discounted Cash-flow (€)	-686 331	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	43 494
Discounted Costs (€)	686 331	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	272 122
Annuity	26 693
NPV of costs	1 108 362
Annuity of costs	108 722
LCOE	58,90

Tijola - PR 80% (year 2026)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,51	€/W
Investment Costs (Battery system)	0,22	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 846	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%		
Battery system	75%	80%	85%	88%		

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-626 325																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)																					62 632
Nominal Cash-flow (€)	-626 325	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	178 754
Discounted Cash-flow (€)	-626 325	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	42 081
Discounted Costs (€)	626 325	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	330 716
Annuity	32 441
NPV of costs	1 048 356
Annuity of costs	102 836
LCOE	55,71

Tijola - PR 80% (year 2028)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,49	€/W
Investment Costs (Battery system)	0,21	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 846	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	
Battery system	75%	80%	85%	88%	93%	

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-592 764																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)																					59 276
Nominal Cash-flow (€)	-592 764	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	175 398
Discounted Cash-flow (€)	-592 764	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	41 291
Discounted Costs (€)	592 764	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	363 486
Annuity	35 655
NPV of costs	1 014 796
Annuity of costs	99 544
LCOE	53,92

Tijola - PR 80% (year 2030)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,46	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	113 147	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 846	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	95%
Battery system	75%	80%	85%	88%	93%	95%

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-563 126																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		115 410	117 718	120 072	122 474	124 923	127 422	129 970	132 569	135 221	137 925	140 684	143 497	146 367	149 295	152 281	155 326	158 433	161 601	164 833	168 130
Wind farm selling (€)																					56 313
Nominal Cash-flow (€)	-563 126	79 710	81 304	82 930	84 589	86 280	88 006	89 766	91 561	93 393	95 260	97 166	99 109	101 091	103 113	105 175	107 279	109 424	111 613	113 845	172 435
Discounted Cash-flow (€)	-563 126	74 149	70 355	66 755	63 340	60 099	57 024	54 107	51 339	48 712	46 220	43 855	41 611	39 482	37 462	35 546	33 727	32 001	30 364	28 811	40 593
Discounted Costs (€)	563 126	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	392 427
Annuity	38 494
NPV of costs	985 157
Annuity of costs	96 636
LCOE	52,35

Economic analysis – profitable year to invest (LCOE < electricity market price) on PV plus lithium-ion battery storage based on cost reduction

Tijola – PR 85%

Tijola - PR 85% (year 2020)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,67	€/W
Investment Costs (Battery system)	0,38	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 962	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%					
Battery system	75%					

Scenario 1	year 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-855 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)																					85 500
Nominal Cash-flow (€)	-855 000	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	211 969
Discounted Cash-flow (€)	-855 000	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	49 900
Discounted Costs (€)	855 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	191 385
Annuity	18 773
NPV of costs	1 277 031
Annuity of costs	125 267
LCOE	63,85

Tijola - PR 85% (year 2022)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,61	€/W
Investment Costs (Battery system)	0,30	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 962	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%				
Battery system	75%	80%				

Scenario 1	year 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-757 425																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)																					75 743
Nominal Cash-flow (€)	-757 425	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	202 211
Discounted Cash-flow (€)	-757 425	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	47 603
Discounted Costs (€)	757 425	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	286 663
Annuity	28 119
NPV of costs	1 179 456
Annuity of costs	115 695
LCOE	58,97

Tijola - PR 85% (year 2024)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,56	€/W
Investment Costs (Battery system)	0,26	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 962	MWh

Investment costs	**2020**	**2022**	**2024**	**2026**	**2028**	**2030**
PV plant	89%	91%	92%			
Battery system	75%	80%	85%			

Scenario 1	year 0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-686 331										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413
Wind farm selling (€)											
Nominal Cash-flow (€)	-686 331	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748
Discounted Cash-flow (€)	-686 331	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338
Discounted Costs (€)	686 331	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	year 11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)										68 633
Nominal Cash-flow (€)	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	195 102
Discounted Cash-flow (€)	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	45 930
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	356 083
Annuity	34 929
NPV of costs	1 108 362
Annuity of costs	108 722
LCOE	55,41

Tijola - PR 85% (year 2026)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,51	€/W
Investment Costs (Battery system)	0,22	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 962	MWh

Investment costs	**2020**	**2022**	**2024**	**2026**	**2028**	**2030**
PV plant	89%	91%	92%	92%		
Battery system	75%	80%	85%	88%		

Scenario 1	year 0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-626 325										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413
Wind farm selling (€)											
Nominal Cash-flow (€)	-626 325	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748
Discounted Cash-flow (€)	-626 325	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338
Discounted Costs (€)	626 325	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1	year 11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)										62 632
Nominal Cash-flow (€)	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	189 101
Discounted Cash-flow (€)	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	44 517
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	414 677
Annuity	40 677
NPV of costs	1 048 356
Annuity of costs	102 836
LCOE	52,41

Tijola - PR 85% (year 2028)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,49	€/W
Investment Costs (Battery system)	0,21	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 962	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	
Battery system	75%	80%	85%	88%	93%	

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-592 764																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)																					59 276
Nominal Cash-flow (€)	-592 764	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	185 745
Discounted Cash-flow (€)	-592 764	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	43 727
Discounted Costs (€)	592 764	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	447 447
Annuity	43 891
NPV of costs	1 014 796
Annuity of costs	99 544
LCOE	50,74

Tijola - PR 85% (year 2030)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	hours/year
Investment Costs (PV plant)	0,46	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	120 110	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	1 962	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	95%
Battery system	75%	80%	85%	88%	93%	95%

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-563 126																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		122 512	124 962	127 461	130 011	132 611	135 263	137 968	140 728	143 542	146 413	149 341	152 328	155 375	158 482	161 652	164 885	168 183	171 546	174 977	178 477
Wind farm selling (€)																					56 313
Nominal Cash-flow (€)	-563 126	86 812	88 548	90 319	92 126	93 968	95 847	97 764	99 720	101 714	103 748	105 823	107 940	110 099	112 301	114 547	116 837	119 174	121 558	123 989	182 781
Discounted Cash-flow (€)	-563 126	80 755	76 624	72 703	68 984	65 454	62 105	58 928	55 913	53 052	50 338	47 763	45 319	43 000	40 800	38 713	36 732	34 853	33 070	31 378	43 029
Discounted Costs (€)	563 126	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	476 388
Annuity	46 730
NPV of costs	985 157
Annuity of costs	96 636
LCOE	49,25

Economic analysis – profitable year to invest (LCOE < electricity market price) on PV plus lithium-ion battery storage based on cost reduction

Tijola – PR 90%

Tijola - PR 90% (year 2020)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,67	€/W
Investment Costs (Battery system)	0,38	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	2 077	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%					
Battery system	75%					

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-855 000																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)																					85 500
Nominal Cash-flow (€)	-855 000	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	222 181
Discounted Cash-flow (€)	-855 000	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	52 304
Discounted Costs (€)	855 000	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	274 259
Annuity	26 903
NPV of costs	1 277 031
Annuity of costs	125 267
LCOE	60,31

Tijola - PR 90% (year 2022)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,61	€/W
Investment Costs (Battery system)	0,30	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	2 077	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%				
Battery system	75%	80%				

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-757 425																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)																					75 743
Nominal Cash-flow (€)	-757 425	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	212 424
Discounted Cash-flow (€)	-757 425	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	50 007
Discounted Costs (€)	757 425	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	369 537
Annuity	36 249
NPV of costs	1 179 456
Annuity of costs	115 695
LCOE	55,70

Tijola - PR 90% (year 2024)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,56	€/W
Investment Costs (Battery system)	0,26	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	2 077	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%			
Battery system	75%	80%	85%			

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-686 331																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)																					68 633
Nominal Cash-flow (€)	-686 331	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	205 315
Discounted Cash-flow (€)	-686 331	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	48 334
Discounted Costs (€)	686 331	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	438 957
Annuity	43 058
NPV of costs	1 108 362
Annuity of costs	108 722
LCOE	52,35

Tijola - PR 90% (year 2026)		
Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,51	€/W
Investment Costs (Battery system)	0,22	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	2 077	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%		
Battery system	75%	80%	85%	88%		

Scenario 1	year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment (€)	-626 325																				
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)																					62 632
Nominal Cash-flow (€)	-626 325	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	199 314
Discounted Cash-flow (€)	-626 325	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	46 921
Discounted Costs (€)	626 325	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	497 551
Annuity	48 806
NPV of costs	1 048 356
Annuity of costs	102 836
LCOE	49,51

Tijola - PR 90% (year 2028)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,49	€/W
Investment Costs (Battery system)	0,21	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	2 077	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	
Battery system	75%	80%	85%	88%	93%	

Scenario 1 (year)	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-592 764										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791
Wind farm selling (€)											
Nominal Cash-flow (€)	-592 764	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126
Discounted Cash-flow (€)	-592 764	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403
Discounted Costs (€)	592 764	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1 (year)	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)										59 276
Nominal Cash-flow (€)	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	195 958
Discounted Cash-flow (€)	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	46 131
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	530 321
Annuity	52 020
NPV of costs	1 014 796
Annuity of costs	99 544
LCOE	47,93

Tijola - PR 90% (year 2030)

Input Data		
Discount Rate / cost of capital	7,5%	%/year
Nominal power (inverters)	1	MW
Nominal power (batteries)	0,5	MW
Investment Costs (PV plant)	0,46	€/W
Investment Costs (Battery system)	0,20	€/W
Running costs	35 000	€
Yearly incomes	126 983	€
Real escalation of O&M costs	2,00%	%/year
Investment horizon	20	year
Yearly electricity generation	2 077	MWh

Investment costs	2020	2022	2024	2026	2028	2030
PV plant	89%	91%	92%	92%	95%	95%
Battery system	75%	80%	85%	88%	93%	95%

Scenario 1 (year)	0	1	2	3	4	5	6	7	8	9	10
Investment (€)	-563 126										
Running costs (€)		-35 700	-36 414	-37 142	-37 885	-38 643	-39 416	-40 204	-41 008	-41 828	-42 665
Electricity sale (€)		129 522	132 113	134 755	137 450	140 199	143 003	145 863	148 780	151 756	154 791
Wind farm selling (€)											
Nominal Cash-flow (€)	-563 126	93 822	95 699	97 613	99 565	101 556	103 587	105 659	107 772	109 928	112 126
Discounted Cash-flow (€)	-563 126	87 277	82 811	78 574	74 554	70 740	67 121	63 687	60 428	57 337	54 403
Discounted Costs (€)	563 126	33 209	31 510	29 898	28 368	26 917	25 540	24 233	22 993	21 817	20 701

Scenario 1 (year)	11	12	13	14	15	16	17	18	19	20
Investment (€)										
Running costs (€)	-43 518	-44 388	-45 276	-46 182	-47 105	-48 047	-49 008	-49 989	-50 988	-52 008
Electricity sale (€)	157 887	161 045	164 266	167 551	170 902	174 320	177 806	181 363	184 990	188 690
Wind farm selling (€)										56 313
Nominal Cash-flow (€)	114 369	116 656	118 989	121 369	123 797	126 273	128 798	131 374	134 001	192 994
Discounted Cash-flow (€)	51 620	48 979	46 473	44 095	41 839	39 698	37 667	35 740	33 912	45 433
Discounted Costs (€)	19 642	18 637	17 683	16 778	15 920	15 106	14 333	13 599	12 904	12 243

NPV	559 262
Annuity	54 859
NPV of costs	985 157
Annuity of costs	96 636
LCOE	46,53