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Analysis of a hybrid PV-CSP plant integration in the electricity market

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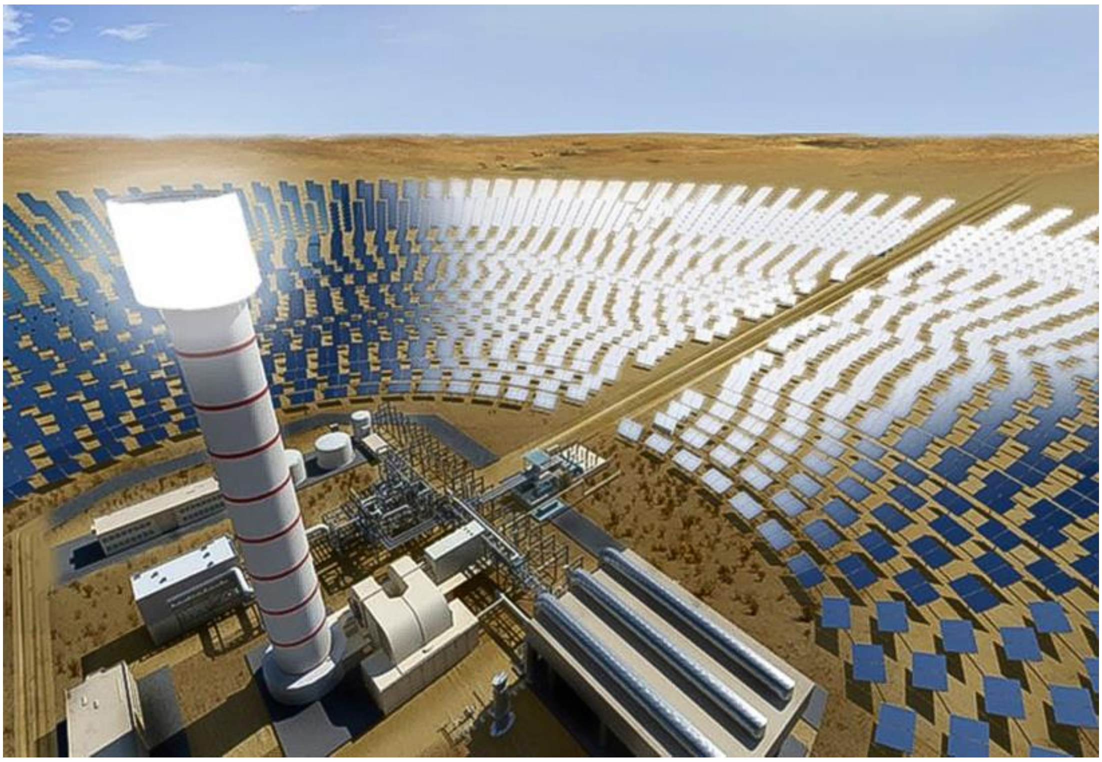

Master of Science Thesis

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Analysis of a hybrid PV-CSP plant integration in the electricity market

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Abstract

One of the key challenges the world will need to face during the 21st century is global warming and the consequent climate change. Its presence is indisputable, and decarbonizing the gird emerges as one of the required pathways to achieve global sustainable objectives.

Solar energy power plants have the potential to revert this situation and solve the problem. One way to harness this energy is through Concentrated Solar Power plants. The major advantage and potential of this technology is its ability to integrate cost-effective Thermal Energy Storage (TES), which is key with such an inherently intermittent resource. On the other hand, the drawback is the high current Levelized Cost of Energy (LCOE).

The other main way to harness that highlighted solar energy is the use of Photovoltaic panels, which have recently achieved very competitive LCOE values. On the other hand, the storage integration is still a very pricey option, normally done with Battery Energy Storage Systems (BESS).

As a conclusion, a hybrid power plant combining the LCOE of the PV and the TES of the CSP emerges as the key way of achieving a very competitive solution with a big potential. This master thesis aims at exploring the possibilities of a hybrid CSP and PV power plant with a sCO_2 power cycle, integrated in the primary, secondary and tertiary electricity markets.

To achieve this purpose, firstly, a Python-based Energy Dispatcher was developed to control the hybrid power plant. Indeed, the Dispatcher is the tool that decides when to produce, when to store… following an optimization problem. This can be formulated mathematically, and that was done and integrated into the Python code using Pyomo, a software for optimization problems.

As a result, the Dispatcher achieved an effective control of the plant, showing intelligent decisions in detailed hourly analyses. The results were very promising and included optimization functions as maximizing the profitability of the plant or the total production, among others.

To proceed with the Techno-economic assessment of the hybrid plant, the electricity markets were studied. The main source of income of any power plant is normally the revenue from selling electricity to the grid, but since there are several markets, there are also other possibilities. In this thesis, it was assessed from a Techno-Economic perspective how the performance and optimal design of the plants vary when providing different services extra to selling electricity to the grid.

The conclusion was that even though the Net Present Value (NPV) achieved working on the spot market was already very high, the extra value added from participating in the secondary or tertiary markets was indisputable. Indeed, the profits attained in those markets were between two and four times higher than the ones of the spot market. This is a specific case, but a trend was identified: these hybrid power plants have a huge possibility and a bright future on the service markets.

As a consequence, this thesis shows the huge potential of hybrid power plants integrated in the grid participating in several markets. It also lays the foundation for future studies in other locations, under different conditions and with different technologies, among others.

Keywords

Concentrated Solar Power (CSP), Photovoltaic (PV), Molten Salts, supercritical CO_2, Thermal Energy Storage, Battery Energy Storage System, MoSES, Energy Dispatcher

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1 Introduction

1.1 Background

Evidence for climate change is compelling and global warming has become an unequivocal fact during the last years [1]. Many efforts have been made through international agreements, as the Paris Agreement, to revert this situation, where the target is to limit the warming to 1.5ºC through reducing emissions.

If global emissions are analysed, it can clearly be seen how big the impact of the energy sector is, accounting for almost three-quarters of the emissions [2]. Decarbonising the electricity supply is one of the steps that need to be taken to improve this situation, and that must be done through renewable energy sources, such as solar, wind or hydropower.

Hydropower is still the biggest renewable energy contributor globally, but recently the world is seeing a big deployment of solar and wind power plants, with the three mentioned options considered the most relevant for the future of energy production. Focusing on relevant indicators as the LCOE, it points out that utility-scale renewable power generation with them has already reached the fossil fuel cost range [3]. This means that costs are no longer a boundary for increasing the deployment of renewable energy.

Out of the three mentioned sources, solar energy is the most abundant resource on earth [4], and the two more common ways of harnessing it are through Photovoltaic and Concentrated Solar Power (CSP). The latter represents a promising technology precisely due to its ability to integrate cost-effective thermal energy storage (TES) [5] [6]. However, according to [3], the LCOE (Levelized Cost Of Electricity) of the technology is still high compared to the other more developed ones, and the reason is coming from the TRL (Technology Readiness Level) being still too low, thus more investigation is needed.

Nevertheless, a promising strategy to reduce the LCOE has been identified, and that is through hybridising the CSP plant with a Photovoltaic one. The low current price of the latter contributes to reducing costs whereas the flexibility of the TES unit contributes to having a very high capacity factor and a less intermittent power supply. It emerges then as a win-win hybridising strategy for both technologies, which has shown a potential of a 25% reduction of costs compared to a CSP-only plant [7], [8].

To achieve these results, further studies must be carried out, having still a non-extensive research material. This Master Thesis, performing a Techno-Economic assessment of a hybrid PV-CSP solar power plant with a sCO2 power cycle, aims to be one of those, enhancing the competitiveness of the hybrid power plant by introducing an energy dispatcher.

1.2 Aim of the study

As previously mentioned, this project aims at studying hybrid PV-CSP power plants with sCO_2 power cycles to assess their techno-economic performance. The goal is to establish relevant conclusions on the capabilities of this hybrid plant, listing how it performs in relation to Key Performance Indicators (KPIs) such as LCOE, Annual Energy Yield or Capacity Factor, among many others. Similarly, the Thesis will reflect upon the limitations of the PV-CSP plant to analyse what are their root causes and what can be done to reduce them and improve the global performance.

In conclusion, the goals of the study can be listed as follows:

- Assess the techno-economic performance of a hybrid PV-CSP power plant with a sCO_2 power cycle when integrated in the primary, secondary and tertiary electricity markets

- Analyse the impact on the optimal design and performance when providing different services extra to selling electricity to the grid
- Conclude on the capabilities and limitations of the power plant based on its performance in relation with relevant KPIs

1.3 Scope and limitations

The scope of the Master Thesis will be non-limited geographically. The hybrid PV-CSP plant will be studied in different parts of the world to analyse the possibilities and the effects of different geographical deployments. Nevertheless, the locations for the study will be places with high solar resources, with the aim of establishing a more relevant and realistic set of conclusions. For obvious reasons, these power plants are installed where indicators such as the Global Horizontal Irradiation (GHI) are high.

The definition of the plant itself will only consider a sCO_2 power cycle due to its possibilities to enhance the overall performance of the CSP plants [6]. Indeed, this cycle has higher thermal efficiencies and compactness compared to traditional steam Rankine cycles [9], and that makes it emerge as the perfect candidate to lower the LCOE of CSP. Therefore, the Rankine cycle will only be used for performing secondary analyses with the only purpose of establishing relevant comparisons.

Focusing on the CSP part, the scope will be the use of a Tower CSP plant. To name a few advantages, it has higher capacity ratios, temperature and efficiency compared to Parabolic Trough, which is the other main technology that could be considered for this project. On the security and control side, the heat transfer fluid (HTF) commonly used, molten salts, is safer and easier to control and store than the oils used in Parabolic Trough. Finally, even though it is less mature tech, the tower plant technology that has been proven to be reliable with flagship projects as Gemasolar in Spain.

On the limitations of the project side, the study will be performed only using a Python-based code which will simulate the hybrid power plant. The limited number of such plants around the world makes the possibility of analysing real data unattainable. On top of that, the number of sensitivity analyses and different modes of operation that this project aims to perform (many yearly simulations) make a real study not viable.

This limitation, nevertheless, doesn't become a clear boundary or restriction for this project, accounting for the complexity of the tool used, named MoSES (Modelling of Solar Energy Systems). It has a holistic approach, considering all sorts of details to ensure a simulation close to what would be the real operation.

Another limitation is the detail to which the simulations can be performed, only accounting for hourly values as the lowest time step. Again on the code, the control strategy will be based on Mixed Integer Linear Programming, which means that it is not possible to control the operation of the plant with expressions containing non-linear terms.

Finally, the last limitation is that since MoSES is a Python-based code, the energy dispatcher model will almost surely need to be modelled also in the Python environment. That will then ensure an easy information exchange and the possibility of modify the MoSES as desired to accurately integrate the dispatcher.

1.4 Methodology

The study will be performed based on the tool previously mentioned, MoSES and an energy dispatcher that will control the hybrid power plant. MoSES is a simulation tool developed for assessing the techno-economic viability of CSP plants with sCO_2 power blocks, with the option of including the hybridization with PV. In other words, it emerges as the perfect tool for performing the aim of the project.

However, to complement the capabilities of the Python-based MoSES, it is required to design, build and integrate another tool that controls effectively the energy dispatching and the hybridization strategy. And that tool will perform all that according to different optimization functions and constraints.

The methodology to achieve the aim of the study will therefore include the following parts:

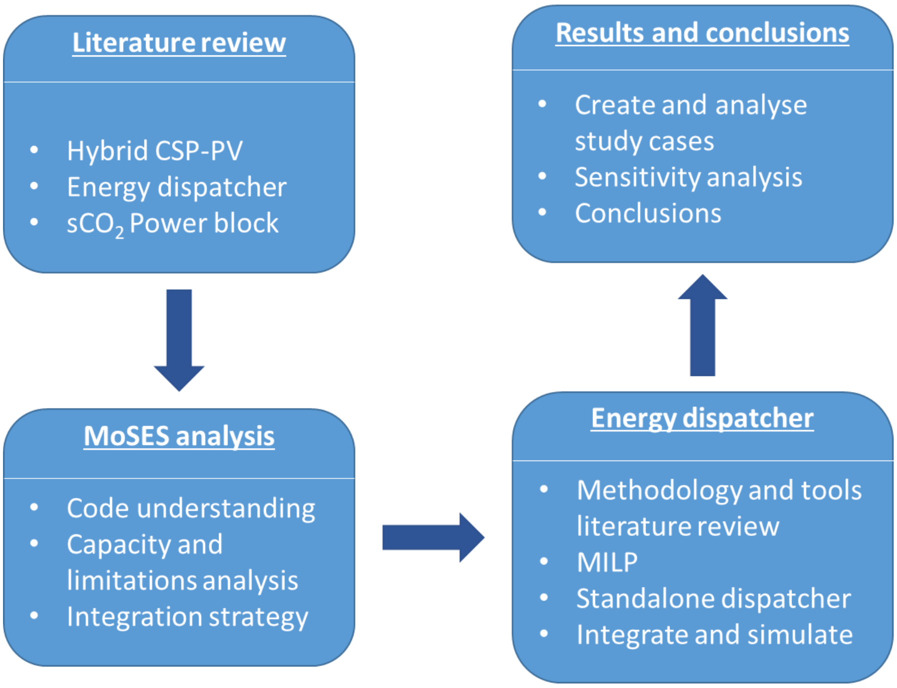

Figure 1-1 Master Thesis Methodology

During the first part, the literature review, several topics have to be studied. First of all, the configuration of a hybrid CSP-PV power plant has to be understood from the components themselves. Therefore, a previous CSP and PV separated literature review needs to be conducted, as well as two of the most important components: the TES and the Electric Heater. It is important to keep in mind that the electric heater is a crucial component for this type of hybrid systems, which can be even used as a bilateral interconnection between the grid and the plant, i.e., including buying electricity sometimes for powering the heater.

Secondly, the sCO_2 is the direct connection between the grid and the CSP plant, which makes it another key part that needs also a deep comprehension, to understand capabilities and limitations. Indeed, one of the parameters that can affect the performance of the plant is the level of complexity reached in the power block (reheating, recompressing…) [6].

To conclude the literature review, one crucial part of the thesis is the creation of the energy dispatcher, which makes inevitable to learn and understand how they are designed and built.

After that, the MoSES tool will be the basis of the study performed, as well as the main code in which the dispatcher will be integrated. This means that it is vital to analyse line by line how the tool was designed and how it operates. Firstly, a general understanding is required, with a capacity and limitations analysis performed, to even check if MoSES can have a dispatcher integrated and if that can be vital for the final results or not. To conclude, a thorough control study needs to be conducted, because that is where the energy dispatcher can act, in control variables such as the mass flow rates sent to the different components.

Next the energy dispatcher has to be built, and for that a separate literature analysis has to be done to know the state-of-the-art tools most commonly used, which would help later to know which one fits better the requirements and characteristics of the desired energy dispatcher. An important strategy widely used is the Mixed-Integer Linear Programming (MILP), and as such it also requires an understanding, because it would be important for the final designed code. To conclude, the dispatcher needs to be simulated as a standalone tool, to check that it works, and then integrated with the MoSES.

Finally, after everything has been integrated it becomes necessary to start creating and analysing the most relevant study cases, to then perform a sensitivity analysis on them which helps drawing and determining the conclusions of the project.

1.5 Previous work on the topic

Several studies have been conducted on the hybrid PV-CSP plants topic [6], [10]–[12], however, none of identified research papers is focused on the field that this project is targeting. Some study hybrid PV-CSP with Rankine cycles, some focus the investigation on hybrid PV-CSP-Wind plants and some others are only analysing plants already deployed or in a certain location. The most similar research paper in which this project is based is the Techno-Economic Optimization of a Hybrid PV-CSP Plant with Molten Salt Thermal Energy Storage and Supercritical CO2 Brayton Power Cycle [6]. Indeed, this project uses the same tool with which that study was carried out.

However, the innovative characteristic of this project comes with two facts.

The first one is that it explores the control possibilities of these type of plants. The mentioned paper focuses on the optimization of the design, not the operation. The MoSES tool has been made to maximize the production for a year, however it doesn't take into account other possible optimization strategies such as maximizing the profit selling energy at defined periods or minimizing the energy waste of the plant.

Any power plant and specially a hybrid one relies its yearly performance heavily on the control strategy that is followed. The energy resource is there fixed, the important part is to decide when to produce, when to store, what quantities… And indeed many studies have been performed in this area, also with hybrid solar power plants [13]–[15], but none of them being specifically focused on hybrid power plants with sCO_2 cycles.

The second novel approach of this thesis is including the possibility of buying electricity from the grid, which opens up the hybrid plant possibilities even more. It also adds other optimization viable strategies, such as including different tariffs for buying and selling electricity or focusing on minimizing the CO_2 production due to buying that electricity, among others. On top of that, it creates the possibility of performing grid control operations (having the TES as a buffer) to minimize the already seen intermittency due to the renewable energy increasing its share.

In conclusion, this thesis emerges as a necessary study to investigate what are the implications of enhancing a better performance of this hybrid power plant by including an energy dispatcher control algorithm. The TRL of this type of plants is still relatively low and the CSP LCOE has already been proved to be reduced only by hybridizing to reach competitive values.

This project will therefore establish important conclusions on the limits, capabilities and potential future steps of hybrid PV-CSP power plants as well as provide with a novel energy dispatcher. The latter will help understanding the full potential of one the most important features of the power plant per se, the possibility of storing energy.

2 Theoretical background

2.1 Solar Power Technologies

2.1.1 Concentrated Solar Power

The concentrated solar power plants are increasingly being deployed all over the world, with the first large scale projects already being more than 10 years old. The basis of this technology is that it generates electricity provided by solar irradiation concentrated on a small area [16]. The procedure consists of heating up that small area where a receiver is placed, having a heat transfer fluid (HTF) taking that concentrated solar energy. After that, the HTF normally heats up another fluid, such as water, that then goes into the power block to finally go through a power cycle to generate electricity.

The configuration used in this project is the Tower disposition.

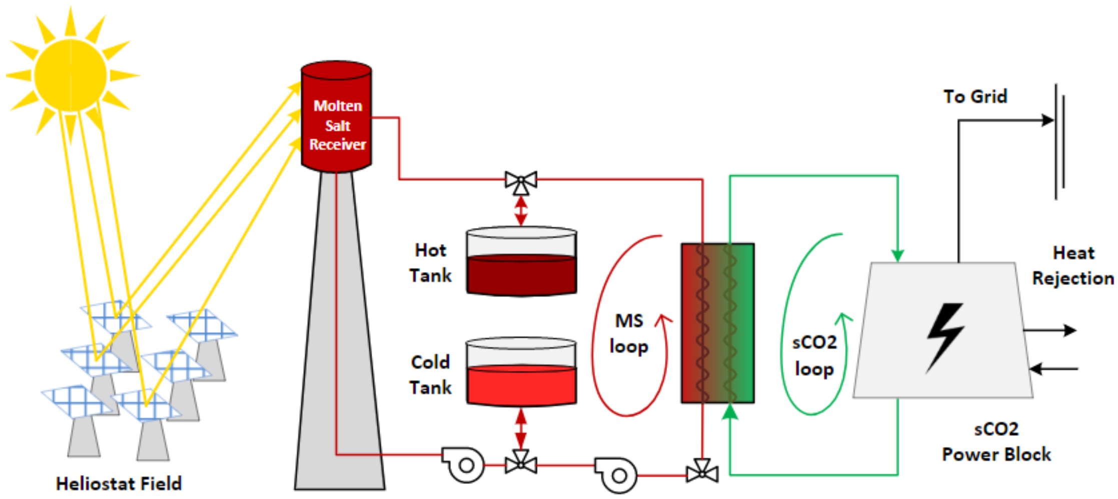

Figure 2-1 Layout of a Tower CSP plant

The previous scheme reflects what has been stated, with the heliostats concentrating the energy in the Receiver, in which the HTF is Molten Salts. Then the fluid that goes into the power block is carbon dioxide in this case, which goes through the cycle providing finally electricity to the grid.

2.1.2 Photovoltaic

The photovoltaic technology is widely used nowadays in all scales, such as in the utility, the commercial and the residential. The process is also well-known, and it consist of irradiate certain materials with solar energy, such materials designed and prepared to absorb the light particles, photons, to release electrons generating an electric current [17].

In the case of the project, the photovoltaic utility scale is already at very low LCOEs, reaching even values of around 30 $/MWh [18], well below the approximately 60 €/MWh[6] of the complete solar power plant, which is already competitive. As a note, it is important to keep in mind that this does not mean that installing photovoltaic is substantially better and less expensive than the combination. With a standalone photovoltaic power plant, the intermittency of the system is obvious, and the installation of batteries to store energy has normally a very relevant share of the total cost.

On the other hand, the photovoltaics' intermittency leads to grid problems already being substantial in some parts of the world where the solar energy share (with photovoltaics) is big. That is the known as duck curve, which triggers other problems such as very important ramp up curves on gas or other type of power plants.

In conclusion, all the previous underlines the potential of having photovoltaics not as a standalone but rather as a part of a hybrid PV-CSP, whose potential benefits will be shown further on.

2.1.3 Thermal Energy Storage

The other key part of the hybrid PV-CSP power plant is the Thermal Energy Storage. It basically consists of one or several tanks where the heat produced both in the CSP and in the Electric Heater is stored to be used later on.

In the case of this project, the fluid used is Molten Salts. They are one of the most studied and used HTF worldwide for CSP plants, so they are a proven material that performs very well under the required conditions of the plant. As a comment, they also have some limitations such as a high melting temperature, corrosion problems or thermal instability at high temperatures (chemical decomposition), all the previous having ongoing investigations to improve them.

The disposition is simple and shown in the Figure 2-1. Figure 2-1 Layout of a Tower CSP plantWhen charging, the molten salts go from the cold tank to the receiver or the electric heater to be heated up and then placed back in the hot tank. When discharging, the process is the opposite, the salts leave the hot tank in this case, lose their enthalpy in favour of the sCO_2 that is heated up, and then they go back to the cold tank.

2.2 Energy Dispatcher – Mixed-Integer Linear Programming

As discussed before, the design and construction of a code capable of managing the hybrid PV-CSP production is of enormous relevance for the project. The code is an energy dispatcher capable of operating or controlling the plant as desired according to the KPI or objective function that needs to be optimized. And indeed, the last word summarises what needs to be done in this matter, it is an optimization problem.

The optimization problem has basically the following features [19] [20]:

- An objective function. It characterises what needs to be maximized or minimized. It is normally made with a set of variables combined together to represent the concept that needs to be optimized (profit, production, energy waste…)
- Constraints. They represent are the physic or logic limitation that the variables need to follow. In short, they constrain the variables to lie within a domain that limits the final solution, so they ensure that the mathematical solution follows the limits of reality. It also acts guiding the tool to decide to set the variables at some values rather than other ones falling outside the constraints. They are defined using the parameters, which in combination with the variables help creating the mathematical expression what will be the constraint.
- Variables. They are changed around by the optimization tool until it finds the optimal solution to the problem.
- Parameters. The parameters are fixed values given to the optimization tool to be used for building the constraints. They are not changed by the dispatcher during the total optimization process.

Mathematically speaking, the problem can be defined as follows [21]:

$$maximize\ or\ minimize\ f(x) = \sum_{i=1}^{n} c_i x_i$$

$$subject\ to\ \sum_{i=1}^{n} a_{ji} x_i \geq b_j, \forall j = 1 \dots, m$$

Where x_i are the variables and a_{ji}, b_j and c_i are parameters. The first row is the objective function and the second the constraints.

Geometrically speaking, the constraints are inequalities that form half-planes that when combined together they form the feasible region where the variables must lie in the final solution, region that take the form of a convex polyhedron.

The problems can be linear/non-linear and continuous, integer, or mixed integer. Linear problems are clearly much simpler and easier to solve than non-linear ones (changes in the objective function follow a linear contour). Another important feature of linear programming is that taking feasible and bounded problems there is a singe guaranteed optimal solution without any local maximums/minimums to test for that will lie at one of the vertices of the feasible region.

Non-linear problems are way more complex to model and to simulate, taking much more time and sometimes not finding feasible solutions for several reasons. All the previous argues for a linear programming strategy, which indeed can be always achieved through different simplifications.

Many physical phenomena or processes object to an optimization problem are by definition non-linear, and therefore the most obvious or intuitive way of modelling them is by staying in the non-linear area. However, it is definitely worth to try a linear formulation to build the optimization problem that can always be checked for discrepancies afterwards, to ensure that they are held within an acceptable degree. For all the stated before, the energy dispatcher will be designed firstly within the linear area and, if the discrepancies with the plant operation are high, a second more complex approach will be taken.

On the other problem characteristic, the continuous, integer and mixed-integer, they refer to how the variables are changed through the simulation. If they take only integer values then it's an integer, and similarly with the continuous. It is however more common to have mixed-integer problems in which the variables are of both types. The energy dispatcher will therefore be a mixed-integer problem, in which there will be integers such as the "ON" "OFF" state of some components and continuous values such as the TES state of charge.

As a comment on how the optimization problem will be solved, the models first solve it as if the variables were continuous. The optimal solution of this called linear programming relaxation is used as lower bound when looking for solutions satisfying the integer conditions. Clearly, the optimal solution of the continuous problem is always going to be equal or better than the one for the integer. Then the model looks for solutions for the integer problem, and the best feasible solution there will form the upper bound. What remains after that is to look for solutions closer to the lower bound until the optimality gap (difference between the upper and the lower bound) is below a desired tolerance [22].

It is important to keep in mind how this operate and how the definition of the optimization model affects the computational time and even the solution reached. There are two qualities that can be influenced by the model formulation, the tightness (small solution space, small optimality gap) and the compactness (small amount of constraints, variables and parameters). As an example to illustrate better, more constraints will produce a tighter moder but a less compact implementation [23].

In conclusion, when building the optimization model, all the previous will be taken into account to create an energy dispatcher fast, reliable and effective.

3 Modelling

3.1 Plant layout

The plant that will be modelled is based on [6] and it consists of the following parts:

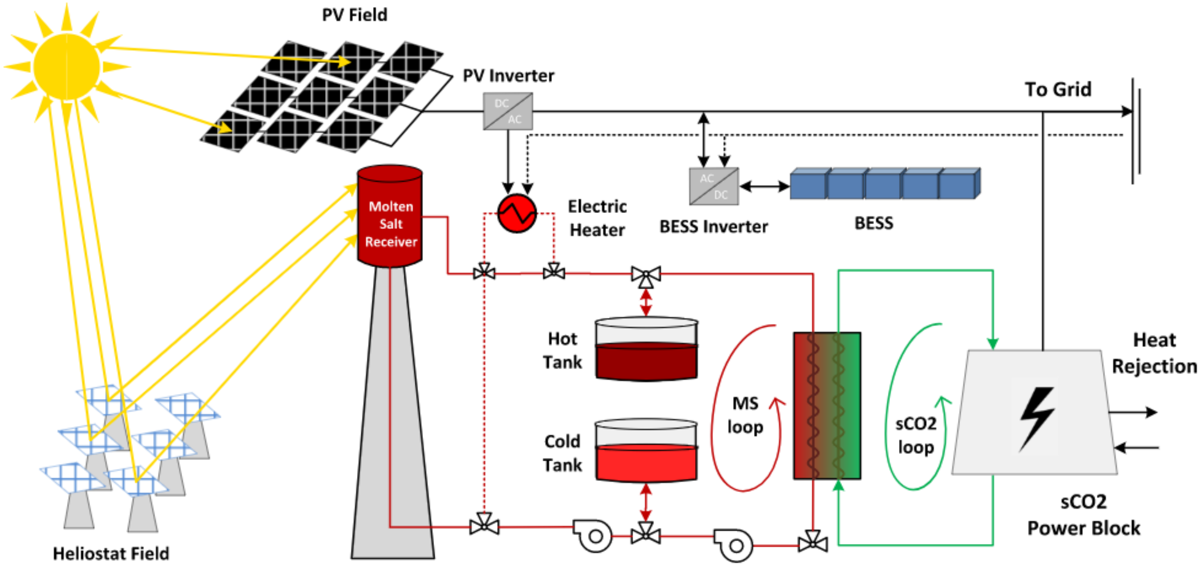

Figure 3-1 Hybrid PV-CSP layout

- The CSP plant, with a tower receiver with molten salts as a heat transfer fluid, as mentioned before
- The PV plant with an inverter to convert DC to AC and then send the electricity either to the grid or to the electric heater
- The Electric Heater, that is being activated by the electricity coming from the PV plant
- The Thermal Energy Storage, which consists of two tanks as explained in the section 2.1.3.
- The BESS, which can be Li-ion or Lead-acid
- The sCO_2 power block, which takes the heat from the Molten Salts through a heat exchanger and sends the power to the grid
- The heat exchanger that transfers the heat from the molten salts to the sCO_2.

As important comments on the layout, the specific values of each plant and part can be easily modified in the model with complete flexibility.

On the CSP side one can give a value to variables such as the Solar Multiple, the heliostats width and height, their reflectance and availability and the maximum and minimum land multipliers, among many others. This can be modified manually by the user but there is another option of optimizing the design based on a defined KPI and that will set the values of these variables for the user.

Moving to the tower and receiver, obviously the height of the tower can be changed, the absorptance and emissivity of the receiver and also details such as the receiver tube outer diameter and the thickness of the tube wall. As can be seen, the level of detail that can be reached is the one that ensures a proper simulation in the end, so that the final values are close to reality.

The thermal energy storage can also be designed with all sorts of details, deciding basic variables such as the hours of storage that the tank needs to be designed for and also more complex parts like the power parasitic coefficient of both tanks. These possibilities will then ensure a very broad and complete results analysis, with many cases to be studied.

On the BESS side, the most important factors are the power and capacity of the batteries, the round trip efficiency, as well as the number of cycles before replacement is needed.

To conclude, the sCO_2 power block can be modelled as a simple component but it can also reach very deep levels of complexity with reheating, recompression or intercooling, among others. The PV plant can also be designed as preferred, changing even the module type or the inverter efficiency.

Finally, there are also control variables that will be crucial for the operation of the plant, as the ramping up time of the power block, the minimum power of the electric heater of the tanks lower and upper boundaries. As a comment, these values are very important to control and to keep in mind because they will also be the basis for the energy dispatcher. Therefore, during the Code Understanding phase of Figure 1-1, a strong focus must be put on that part, because those variables will serve as an input for the Energy Dispatcher to then be able to simulate the plant accurately.

3.2 Introduction to *Pyomo*

When deciding on what software to use for the Energy Dispatcher, the project had a clear choice. The easiest and most efficient path to follow would be to directly model the dispatcher in Python, i.e., using the same programming environment. It can actually be seen as a limitation, but it is not in the end, due to the vast availability of tools or strategies already existing in Python that makes the design of an optimization model much easier.

The greatest advantage of modelling the Dispatcher in Python is the possibility of bilateral interconnection between both codes. At some point the dispatcher will need inputs from the MoSES and vice versa, so a Python-based tool emerges as the best and almost only option available for this case.

After studying what were the possibilities for the optimization model, Pyomo appeared as a great candidate for several reasons. The first one is that it does exactly what the energy dispatcher must do, i.e., it is "a software package that supports a diverse set of optimization capabilities for formulating, solving and analysing optimization problems" [24].

Another important point is that it is open-source, similarly to Python, and that is not only a monetary advantage. That certainly means a vast amount of information about it and troubleshooting, as well as a universal access to the tool so that the whole package can be used by anyone anywhere.

One of the future applications of the tool is the integration to the industry, to serve as a guideline on how to control the full hybrid plant. The plant controllers would only need to simulate with the tool and then see what the values of the most important control variables throughout the year are, or what needs to be done to optimize the objective function desired. Obviously, that will not give the exact values for the actual control as it is, simply because it can't know (only predict) how the weather or the electricity prices, for example, are going to be during the next day or even the next hours. Nevertheless, the simulation will give the clear guideline of the approximate profile that should be followed.

In the end, what it important to highlight is the fact that the tool won't be restricted to a particular set of end users, which will surely impulse the possibilities of learning about it, improving it and developing further these types of plants.

On Pyomo itself, the tool becomes very intuitive because it allows to formulate the problem exactly the same way as the mathematical: it has parameters, decision variables, objectives and constraints, similarly to what was explained in the section 2.2. That makes the modelling process much simpler, always keeping in mind that the functions must be kept linear and the variables a combination of continuous and integer.

As a solver for the optimization model, Pyomo supports many different options, having slight differences between themselves. And since there is no clear best candidate for this problem, an empirical approach was followed, in which several solvers were tested finally selecting Gurobi. The variables considered for that selection were the computational time and the obtained result, as well as the infeasible or unbounded cases during the simulation. In the end, Gurobi was performing the best, so the project continued with that one.

However, the differences were hard to notice, which means that Gurobi as a solver is not a must or a locked option. If any end user has been using a different one and has a clear preference, there clearly is the chance of testing it, compare the results and computational time and if the differences are tolerable, proceed with the change. In that sense, the energy dispatcher can be flexible.

3.3 Energy Dispatcher Model

3.3.1 Energy Dispatcher Layout

Before presenting the layout, it is important to highlight and explain what is the dispatcher's purpose and what it has to do. Basically it consists of simulating the behaviour of the whole hybrid PV-CSP plant, including all components, to then have as an output the control variables for the MoSES.

The next figure summarises what the dispatcher will simulate including the variables that will be explained in the next chapter. It is indeed what was presented earlier in Figure 3-1, the plant layout.

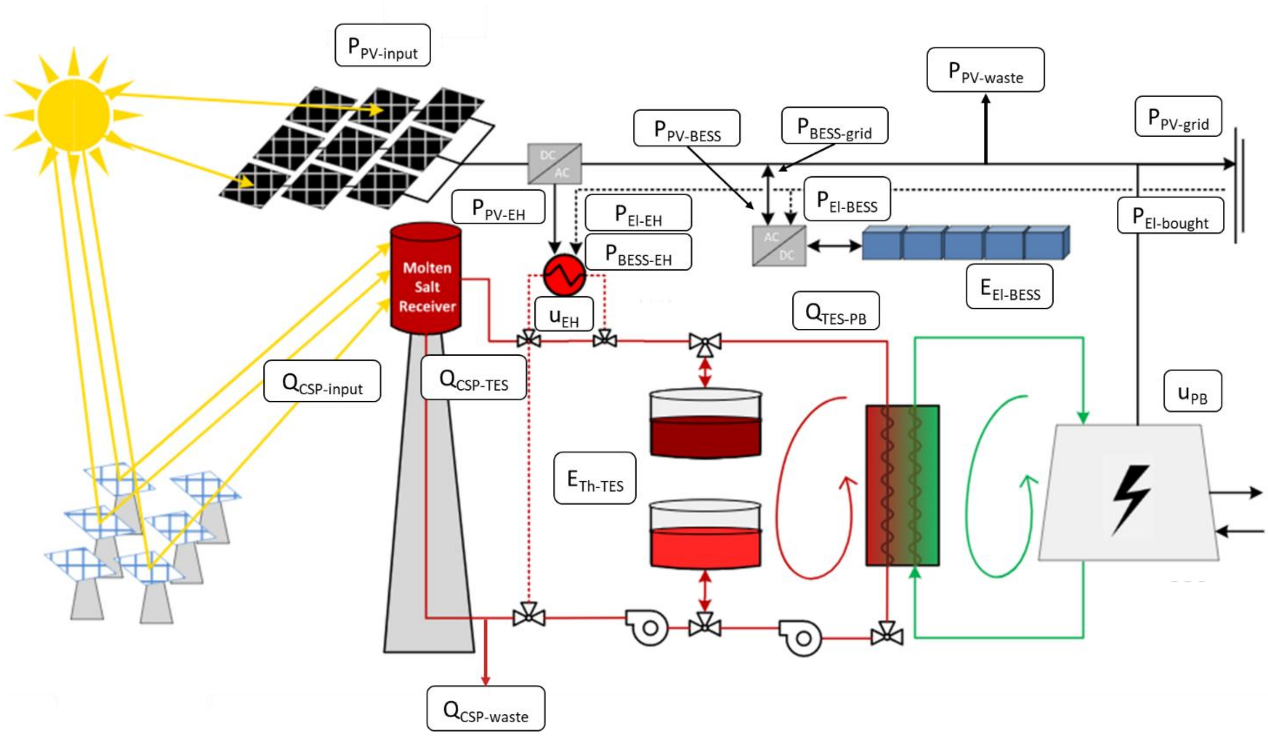

Figure 3-2 Plant layout with dispatcher variables

In short, the first part of the dispatcher comes with the input. It takes the $P_{PV\text{-}input}$ and $Q_{CSP\text{-}input}$, which are the values of the available energy coming from both components of the hybrid plant. The PV part is easy to calculate, just with the DNI and the efficiency of the modules, however, when it comes to the CSP part, the whole calculation process gets trickier because specially the receiver efficiency highly depends on the temperature there. In the end, the CSP input is calculated as follows:

$$Q_{CSP-input}[t] = Q_{SF\_out}[t] \cdot \eta_{rec} = Q_{SF\_in}[t] \cdot \eta_{field}[t] \cdot \eta_{rec}$$
$$= A_{SF} \cdot DNI[t] \cdot \eta_{field}[t] \cdot \eta_{rec}$$

Where η_{field} is the optical efficiency of the heliostat field (hourly) and η_{rec} is the total efficiency of the receiver, which is taken as an approximated value in this case. A_{SF} is the area of the solar field and $DNI[t]$ are the hourly values of the DNI for the location selected.

As a comment, the $Q_{CSP\text{-}input}$ is taken after the receiver, which is the total real input that comes from the CSP field to either the TES or the waste. It makes the optimization tool simpler and better in terms of the compactness and tightness mentioned before, and thus that part is pre-processed.

After that, the optimization tool can simulate the behavior of the plant with the variables and constraints that will be shown in the next section. But before that, it is relevant to clarify the meaning of the variables using the figure, for a better understanding.

The $P_{PV\text{-}input}$ is divided into the power that goes to the grid, the power that goes to the electric heater, the one that charges the BESS and the power that needs to be wasted, $P_{PV\text{-}grid}$, $P_{PV\text{-}EH}$, $P_{PV\text{-}BESS}$ and $P_{PV\text{-}wasted}$, respectively. The same applies to the $Q_{CSP\text{-}input}$ that has two options, either going to the TES or to waste, with $Q_{CSP\text{-}TES}$ and $Q_{CSP\text{-}waste}$ respectively.

Then the $E_{Th\text{-}TES}$ represents the State of Charge of the TES, and it is quite relevant for deciding values as how much power is sent to the TES from the CSP ($Q_{CSP\text{-}TES}$), how much from the Electric Heater, how much should be sent to waste…, and ultimately, how much power is sent from the TES to the Power Block, with $Q_{TES\text{-}PB}$.

$P_{El\text{-}bought}$ represents the hourly values of the power that is bought from the grid, and that power is used either for powering the electric heater directly or to charge the BESS, with the variables $P_{El\text{-}EH}$ and $P_{El\text{-}BESS}$ respectively.

The other energy storage available in the system is the BESS, whose State of Charge is represented with $E_{El\text{-}BESS}$, and that energy is charged with the mentioned $P_{PV\text{-}BESS}$ and/or $P_{El\text{-}BESS}$. The stored electric energy is then used to sell energy to the grid ($P_{BESS\text{-}grid}$) or to power the electric heater ($P_{BESS\text{-}EH}$).

To conclude, the variables u_{EH} and u_{PB} are binary variables (1 or 0) representing if the Electric Heater and the Power Block are ON or OFF.

3.3.2 Variables, constraints and parameters

As pointed out before, when designing the energy dispatcher optimization model, it is important to target its compactness and tightness, which will help a lot later when proceeding with the solving part.

The design variables, the ones that will be modified by the optimization tool during the process, have been already presented in the previous section and they are the following:

Variable	Unit	Explanation
$\mathbf{P_{PV\text{-}grid}}$	[MW]	Power that the **PV** system sends to the **Grid**
$\mathbf{P_{PV\text{-}EH}}$	[MW]	Power that the **PV** system sends to the **EH**
$\mathbf{P_{PV\text{-}BESS}}$	[MW]	Power that the **PV** system sends to the **BESS**
$\mathbf{P_{PV\text{-}waste}}$	[MW]	Power that the **PV** system sends to **waste**

$\mathbf{Q_{CSP-TES}}$	[MW]	Power that the **CSP** system sends to the **TES**
$\mathbf{Q_{CSP-waste}}$	[MW]	Power that the **CSP** system sends to **waste**
$\mathbf{Q_{TES-PB}}$	[MW]	Power that the **TES** system sends to the **Power Block**
$\mathbf{P_{El-bought}}$	[MW]	Electricity purchased
$\mathbf{P_{El-EH}}$	[MW]	Electricity purchased going to the **EH**
$\mathbf{P_{El-BESS}}$	[MW]	Electricity purchased going to the **BESS**
$\mathbf{P_{BESS-EH}}$	[MW]	Electricity going from the **BESS** to the **EH**
$\mathbf{P_{BESS-grid}}$	[MW]	Electricity going from the **BESS** to the **Grid**
$\mathbf{P_{EH}}$	[MW]	Total power going to the **EH**
$\mathbf{E_{Th-TES}}$	[MWh,th]	State of Charge of the **TES**
$\mathbf{E_{El-BESS}}$	[MWh,el]	State of Charge of the **BESS**
$\mathbf{u_{EH}}$	[Binary]	Mathematical value representing the state (ON/OFF) of the **Electric Heater**
$\mathbf{u_{PB}}$	[Binary]	Mathematical value representing the state (ON/OFF) the **Power Block**

Table 1. Variables of the Energy Dispatcher

The constraints of the optimization tool are the limits for the variables. They determine geometrically the feasible area where they have to be. They are the following:

Eq.1: "Demand"

$$Q_{TES-PB}[t] \cdot \eta_{PB} \cdot \eta_{HX} + P_{PV-grid}[t] + P_{BESS-grid}[t] \cdot RTEff \cdot \eta_{Inv} \leq P_{injecting}^{max}$$

The demand should be covered always. In the expression, η_{PB} and η_{HX} are the Power Block and Heat Exchanger efficiencies respectively. $P_{injecting}^{max}$ is the maximum power that can be injected to the grid. As a comment, the right side of the expression can be modified to be following a load, if that is the desired case.

Eq.2: "PV adds up"

$$P_{PV-grid}[t] + P_{PV-EH}[t] + P_{PV-BESS}[t] + P_{PV-waste}[t] = P_{PV-input}[t]$$

The sum of the three possible alternatives for PV should be equal to the total PV power input to the system.

Eq.3: "CSP adds up"

$$Q_{CSP-TES}[t] + Q_{CSP-waste}[t] = Q_{CSP-input}[t]$$

The sum of the two possible alternatives for CSP should be equal to the total CSP power input to the system.

Eq.4: "Calculation of the power to the EH"

$$P_{PV-EH}[t] + P_{El-EH}[t] + P_{BESS-EH}[t] \cdot RTEff \cdot \eta_{Inv} = P_{EH}[t]$$

The total power going into the electric heater comes from adding up the electricity bought and the photovoltaic power going into the heater.

Eq.5: "Energy balance TES"

$$E_{th,TES}[t] = E_{th,TES}[t-1] + P_{EH}[t] \cdot \eta_{EH} + Q_{CSP-TES}[t] \cdot \eta_{Rec} - Q_{TES-PB}[t]$$

The energy balance of the TES. η_{EH} is the efficiency of the EH and η_{Rec} is the total efficiency of the receiver. Again, η_{Rec} is the fixed value that can be used for these simulations

Eq.6: "Maximum ramp up EH"

$$P_{EH}[t] - P_{EH}[t-1] \leq \Delta P_{EH}^{up}$$

Maximum ramp up power of the electric heater.

Eq.7: "Maximum ramp down EH"

$$P_{EH}[t-1] - P_{EH}[t] \leq \Delta P_{EH}^{down}$$

Maximum ramp down power of the electric heater.

Eq.8: "Maximum power EH"

$$P_{EH}[t] \leq P_{EH}^{max}$$

The maximum power sent to the Electric Heater is limited by the maximum power of the electric heater.

Eq.9: "Minimum power EH"

$$P_{EH}[t] \geq P_{EH}^{min}$$

The power sent to the Electric Heater should be above a minimum value.

Eq.10 "ON EH time commitment"

$$t_{COM}^{ON} \cdot (u_{EH}[t] - u_{EH}[t-1]) \leq x_{COM}^{ON}$$

Once started the EH has to run for a minimum number of consecutive hours of at least t_{COM}^{ON}. Then, $u_{EH}[t]$ is a Boolean variable describing the activation state of the EH and x_{COM}^{ON} is defined as following:

$$x_{COM}^{ON} = \sum_{i=t}^{t+t_{COM}^{ON}} u_{EH}[i]$$

Eq.11: "OFF EH time commitment"

$$t_{COM}^{OFF} \cdot (u_{EH}[t-1] - u_{EH}[t]) \leq x_{COM}^{OFF}$$

Once turned off the EH has to stay like that a minimum number of consecutive hours of at least t_{COM}^{OFF}. The variable $u_{EH}[t]$ is a Boolean variable describing the activation state of the EH and x_{COM}^{OFF} is defined as following:

$$x_{COM}^{OFF} = \sum_{i=t}^{t+t_{COM}^{OFF}} (1 - u_{EH}[i])$$

Eq.12: "Maximum ramp up PB"

$$(Q_{TES-PB}[t] - Q_{TES-PB}[t-1]) \cdot \eta_{PB} \cdot \eta_{HX} \leq \Delta Q_{PB}^{up}$$

Maximum ramp up period of the power block.

Eq.13: “Maximum ramp down PB”

$$(Q_{TES-PB}[t-1] - Q_{TES-PB}[t]) \cdot \eta_{PB} \cdot \eta_{HX} \leq \Delta Q_{PB}^{down}$$

Maximum ramp down period of the power block.

Eq.14: “ON PB time commitment”

$$t_{PB\_COM}^{ON} \cdot (u_{PB}[t] - u_{PB}[t-1]) \leq x_{PB\_COM}^{ON}$$

Once started the PB has to run for a minimum number of consecutive hours of at least $t_{PB\_COM}^{ON}$. Then, $u_{PB}[t]$ is a Boolean variable describing the activation state of the PB and $x_{PB\_COM}^{ON}$ is defined as following:

$$x_{PB\_COM}^{ON} = \sum_{i=t}^{t+t_{PB\_COM}^{ON}} u_{PB}[i]$$

Eq.15: “OFF PB time commitment”

$$t_{PB\_COM}^{OFF} \cdot (u_{PB}[t-1] - u_{PB}[t]) \leq x_{PB\_COM}^{OFF}$$

Once turned off the PB has to stay off for a minimum number of consecutive hours of at least $t_{PB\_COM}^{OFF}$. The variable $u_{PB}[t]$ is a Boolean variable describing the activation state of the PB and $x_{PB\_COM}^{OFF}$ is defined as following:

$$x_{PB\_COM}^{OFF} = \sum_{i=t}^{t+t_{COM}^{OFF}} (1 - u_{PB}[i])$$

Eq.16: “Maximum power PB”

$$Q_{TES-PB}[t] \cdot \eta_{HX} \cdot \eta_{PB} \leq Q_{PB}^{max}$$

The maximum discharged power is limited by the maximum power of the power block.

Eq.17: “Minimum power PB”

$$Q_{TES-PB}[t] \cdot \eta_{HX} \cdot \eta_{PB} \geq Q_{PB}^{min}$$

A power block should be operated above a minimum level.

Eq.18: “Electricity bought limit”

$$P_{El-bought}[t] \leq P_{purchasing}^{max}$$

A power block should be operated above a minimum level.

Appendix 1. State of Charge limitation:

$$E^{min} \leq E[t] \leq E^{max}$$

This last one is not defined in the constraints, but the storage should be kept between the maximum and the minimum level, and that is done when defining the variable by setting as possible limits those two values.

As a comment, the number of constraints is defined in the optimization tool but the design of the tool has been done in a flexible way, i.e., adding the possibility of relaxing as many constraints as needed. This highlights the fact that the tool can be used not only with that plant layout but also with similar ones (even following a demand and not just injecting to the grid) and also relaxing and constraining whatever is desired.

The parameters used by the code are the values that are fixed and serve for creating the constraints and optimization functions, as shown before. They are the following:

Parameter	Unit	Explanation
$\boldsymbol{P_{injecting}^{max}}$	[MW]	Power limit that the hybrid plant can inject to the grid
$\boldsymbol{P_{purchasing}^{max}}$	[MW]	Power limit that the hybrid plant can purchase from the grid
$\boldsymbol{\eta_{EH}}$	-	Efficiency of the **Electric Heater**
$\boldsymbol{\eta_{PB}}$	-	Efficiency of the **Power Block** from the thermal energy input to the final electric energy output
$\boldsymbol{\eta_{HX}}$	-	Efficiency of the **Heat Exchanger** from the thermal energy output of the TES to the thermal energy input to the **Power Block**
$\boldsymbol{\eta_{Inv}}$	-	Efficiency of the Inverter converting the DC power from the **BESS** to AC power for the **EH** or the **grid**
$\boldsymbol{\Delta P_{EH}^{up}}$	[MW]	Maximum ramp up power of the **Electric Heater**
$\boldsymbol{\Delta P_{EH}^{down}}$	[MW]	Maximum ramp down power of the **Electric Heater**
$\boldsymbol{P_{EH}^{max}}$	[MW]	Maximum power of the **Electric Heater**
$\boldsymbol{P_{EH}^{min}}$	[MW]	Minimum power of the **Electric Heater**
$\boldsymbol{\Delta Q_{PB}^{up}}$	[MW]	Maximum ramp up power of the **Power Block**
$\boldsymbol{\Delta Q_{PB}^{down}}$	[MW]	Maximum ramp down power of the **Power Block**
$\boldsymbol{Q_{PB}^{max}}$	[MW]	Maximum power of the **Power Block**
$\boldsymbol{Q_{PB}^{min}}$	[MW]	Minimum power of the **Power Block**
$\boldsymbol{E_{Th-TES}^{min}}$	[MWh,th]	Minimum State of Charge of the **TES**
$\boldsymbol{E_{Th-TES}^{max}}$	[MWh,th]	Maximum State of Charge of the **TES**
$\boldsymbol{E_{El-BESS}^{min}}$	[MWh]	Minimum State of Charge of the **BESS**
$\boldsymbol{E_{El-BESS}^{max}}$	[MWh]	Maximum State of Charge of the **BESS**
$\boldsymbol{t_{COM}^{OFF}}$	[h]	"OFF" commitment time of the **Electric Heater**
$\boldsymbol{t_{COM}^{ON}}$	[h]	"ON" commitment time of the **Electric Heater**
$\boldsymbol{t_{PB\_COM}^{OFF}}$	[h]	"OFF" commitment time of the **Power Block**
$\boldsymbol{t_{PB\_COM}^{ON}}$	[h]	"ON" commitment time of the **Power Block**

$RTEff$	-	Round trip efficiency of the **BESS**
$I_{CO_2-El}[t]$	kgCO2/MWh	Carbon intensity of the **grid**
I_{CO_2-PV}	kgCO2/MWh	Carbon intensity of the production of **PV** power
I_{CO_2-CSP}	kgCO2/MWh	Carbon intensity of the production of **CSP** power
$p_{El-selling}[t]$	€/MWh	Price at which the electricity is sold in the grid
$p_{El-buying}[t]$	€/MWh	Price at which the electricity is bought in the grid

Table 2 Parameters of the Energy Dispatcher

3.3.2.1 Parameters values

After having presented the parameter list, it is now important to give them actual values. Some change depending on the simulation performed, some depend on the country in which the study will be conducted, and some others are fixed. Here it can be seen:

Parameter	Unit	Source/Explanation
$P_{injecting}^{max}$	Simulation based	Value depending on the simulation, will be tuned according to what is desired
$P_{purchasing}^{max}$	Simulation based	Value depending on the simulation, will be tuned according to what is desired
η_{EH}	0.95	Value extracted from the MoSES software [6], coming from [25]
η_{PB}	0.349	Value calculated from the MoSES software [6], coming from [26]
η_{HX}	1	Value extracted from the MoSES software [6], coming from [25]
η_{Inv}	0.98	Value extracted from the MoSES software [6], coming from [25]
ΔP_{EH}^{up}	Simulation based	Value depending on the simulation, will be tuned according to what is desired. Normally assumed to be 100% the value of the P_{EH}^{max}. 1 hour step assumed in the simulation, which is enough for the EH to ramp up and down
ΔP_{EH}^{down}	Simulation based	Value depending on the simulation, will be tuned according to what is desired. Normally assumed to be 100% the value of the P_{EH}^{max}. 1 hour step assumed in the simulation, which is enough for the EH to ramp up and down
P_{EH}^{max}	Simulation based	Value depending on the simulation, will be tuned according to what is desired.
P_{EH}^{min}	Simulation based	Value depending on the simulation, will be tuned according to what is desired.
ΔQ_{PB}^{up}	[MW]	Value depending on the simulation, will be tuned according to what is desired. Normally assumed to be 100% the value of the Q_{PB}^{max}. 1 hour step assumed in the simulation, which is enough for the PB to ramp up and down
ΔQ_{PB}^{down}	[MW]	Value depending on the simulation, will be tuned according to what is desired. Normally assumed to be 100% the value of the

		Q_{PB}^{max}. 1 hour step assumed in the simulation, which is enough for the PB to ramp up and down
$\boldsymbol{Q_{PB}^{max}}$	Simulation based	Value depending on the simulation, will be tuned according to what is desired.
$\boldsymbol{Q_{PB}^{min}}$	Simulation based	Value depending on the simulation, will be tuned according to what is desired.
$\boldsymbol{E_{Th-TES}^{min}}$	1%	Value extracted from the MoSES software [6] and selected as a common value for Molten Salts TES
$\boldsymbol{E_{Th-TES}^{max}}$	99%	Value extracted from the MoSES software [6] and selected as a common value for Molten Salts TES
$\boldsymbol{E_{El-BESS}^{min}}$	0%	Assumed a normal value for a Li-ion battery (the technology the thesis will be focused on)
$\boldsymbol{E_{El-BESS}^{max}}$	100%	Assumed a normal value for a Li-ion battery (the technology the thesis will be focused on)
$\boldsymbol{t_{COM}^{OFF}}$	1 h	Assumed a normal value for an electric heater. It doesn't have that many slow processes. If the power of the EH is very high, this commitment time value will be revisited
$\boldsymbol{t_{COM}^{ON}}$	1 h	Assumed a normal value for an electric heater. It doesn't have that many slow processes. If the power of the EH is very high, this commitment time value will be revisited
$\boldsymbol{t_{PB\_COM}^{OFF}}$	1 h	Assumed a normal value for a sCO_2 cycle. It doesn't go through important time-consuming processes. If the power of the PB is very high, this commitment time value will be revisited
$\boldsymbol{t_{PB\_COM}^{ON}}$	1 h	Assumed a normal value for a sCO_2 cycle. It doesn't go through important time-consuming processes. If the power of the PB is very high, this commitment time value will be revisited
$\boldsymbol{RTEff}$	80%	Obtained from [27]
$\boldsymbol{I_{CO_2-El}[t]}$	Simulation based	Values obtained depending on the country selected (the grid carbon intensity varies substantially)
$\boldsymbol{I_{CO_2-PV}}$	50 kgCO2/MWh	Value obtained from [28], [29]
$\boldsymbol{I_{CO_2-CSP}}$	22 kgCO2/MWh	Value obtained from [30], [31]
$\boldsymbol{p_{El-selling}[t]}$	Simulation based	Values obtained depending on the country selected (the spot prices vary substantially)
$\boldsymbol{p_{El-buying}[t]}$	Simulation based	Values obtained depending on the country selected (the spot prices vary substantially)

Table 3 Values for the Parameters of the Energy Dispatcher

3.3.3 Objective functions

The objective functions are the functions that the code needs to optimize, and they can take the form of minimizing or maximizing objectives. The ones selected for the optimization tool are based on what would be wanted to optimize in the case of the hybrid PV-CSP plant, but the number of functions that can be constructed is uncountable. The ones introduced in the energy dispatcher and tested are presented here below.

Objective 1: Minimize the wasted energy

$$\bar{\mathrm{F}} = \min\left[\sum_{t=0}^{n} P_{PV-waste}[t] + Q_{CSP-waste}[t]\right]$$

Objective 2: Maximize the income of the hybrid plant

$$\bar{F} = max\left[\sum_{t=0}^{n}\big(P_{PV-grid}[t] + P_{BESS-grid}[t]\cdot RTEff\cdot\eta_{Inv} + Q_{TES-PB}[t]\cdot\eta_{PB}\cdot\eta_{HX} - P_{El-bought}[t]\big)\cdot p_{El-selling}[t]\right]$$

Objective 3: Maximize the production of the hybrid plant

$$\bar{\mathrm{F}} = \max\left[\sum_{t=0}^{n}\big(P_{PV-grid}[t] + P_{BESS-grid}[t]\cdot RTEff\cdot\eta_{Inv} + Q_{TES-PB}[t]\cdot\eta_{PB}\cdot\eta_{HX} - P_{El-bought}[t]\big)\right]$$

Objective 4: Maximize the income having different tariffs

$$\bar{\mathrm{F}} = \max\left[\sum_{t=0}^{n}\big(P_{PV-grid}[t] + P_{BESS-grid}[t]\cdot RTEff\cdot\eta_{Inv} + Q_{PB}[t]\cdot\eta_{PB}\cdot\eta_{HX}\big)\cdot p_{El\_selling}[t] - P_{El\ bought}[t]\cdot p_{El\_buying}[t]\big)\right]$$

Where $P_{El\text{-}selling}$ and $P_{El\text{-}buying}$ are the prices of electricity for both selling and buying. These values are selected from data of the country in which the study is focused.

Objective 5: Minimize the CO_2 production

$$\bar{\mathrm{F}} = \min\left[\sum_{t=0}^{n}\big(El_{bought}[t]\cdot I_{CO_2-El}[t] + \big(P_{PV-grid}[t] + P_{PV-EH}[t] + P_{PV-BESS}[t] + P_{PV-waste}[t]\cdot M\big)\cdot I_{CO_2-PV} + (Q_{CSP-TES}[t] + Q_{CSP-waste}[t]\cdot M)\cdot\eta_{PB}\cdot\eta_{HX}\big)\cdot I_{CO_2-CSP}\right]$$

M is a selected value big enough so that the dispatcher prioritizes the actual production above wasting everything, without compromising the validity of the solution.

3.3.4 Integration of the energy dispatcher in MoSES

After the energy dispatcher has been designed and tested as a standalone tool, it comes the moment for the integration inside the MoSES. The way it is done is the following:

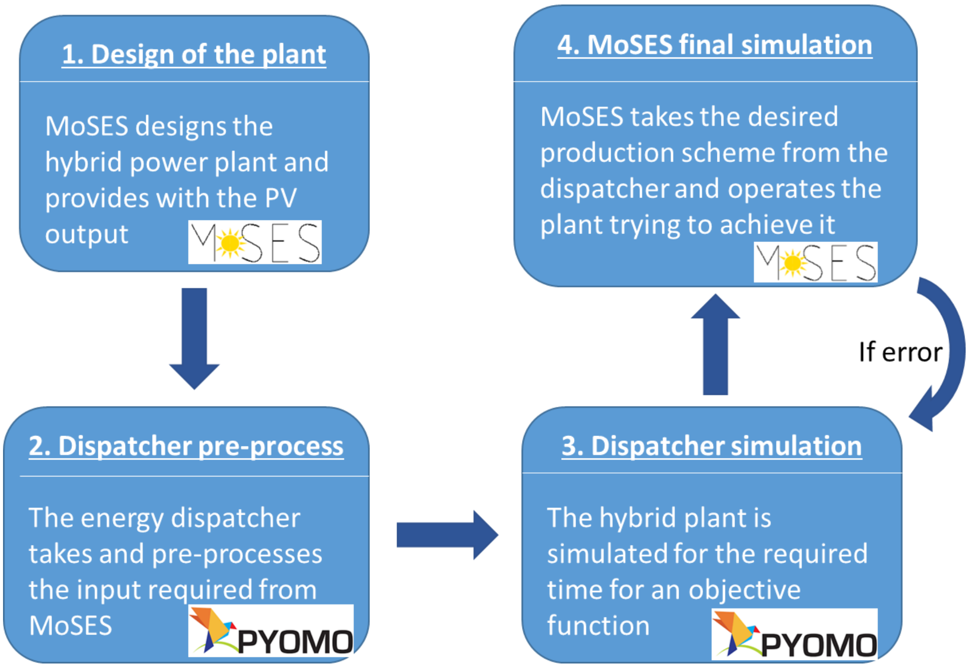

Figure 3-3 Dispatcher integration in MoSES

The first step is the initial design with MoSES, there MoSES takes all the values that the user wants to have as design variables. It basically calculates all the parameters of the different components as well as the sun operation. As a comment, MoSES already calculates the total PV output that is available there, which means that there is no need to pre-process that in Pyomo as intended from a first approach, the hourly values can be obtained from there.

And that is then what happens with step 2 of dispatcher pre-process. The optimization tool takes the necessary inputs from the design of the plant, such as all the parameters (efficiencies, minimum powers, max and min SoC…) and also the user inputs (which optimization function will be used, which constraints will prevail, which set-up will be selected for injecting or load following, buying electricity or not…).

With all those inputs, the dispatcher is ready to start its own simulation, in step 3, which can have a length of a year (what will be presented in the results later) or whatever value is required by the users. In those simulations the dispatcher optimizes the selected objective function and with that it provides as outputs the desired production and the control variables that will be vital for then operating MoSES.

Indeed, the fourth step consists of operating the hybrid plant with the MoSES simulation taking into account all the details and being very close to what a real operation would be. This is the moment then for checking how close the dispatcher production is from reality and how much difference there is between the desired production scheme and the real one. That is the reason why there is the back loop which considers iterations in case the mentioned difference is very high.

It is important to keep in mind that the dispatcher is limited in terms of the level of detail achieved, the TES is not taking into account any parasitic losses, both the power block and the receiver have a fixed efficiency which is not real, it changes every hour.

To solve that problem, the approach is to update the TES SoC with the values from MoSES. In the loop therefore the dispatcher simulates a block of time, for example 2 days. It then sends the data to MoSES and it operates the plant according to what the dispatcher wants. Due to the efficiencies and other details mentioned before, the biggest difference encountered is the value of the SoC. There are cases where the dispatcher's SoC is 10% but in reality it is 3%, and that means that the dispatcher sends the signal for producing maximum power, for example, but MoSES can't produce it and there appears the biggest difference between the two codes.

In conclusion, this loop updates the TES SoC with the values from MoSES so that the dispatcher's simulation is closer to reality and then the predicted or desired production schemes can be closer to what MoSES will do later.

After all that has been done, the results are post-processed and exported so that they can be analysed later on.

3.3.5 Code usability

In this chapter the code usability will be presented, in which it can be seen how flexible the dispatcher is and how many parts can be modified. The different sections will be shown as they look in the *Python* code, which is important to have a clearer idea of the dispatcher's possibilities and limitations.

Section 0. Activating the dispatcher

```
Dispatcher = True,                                        # [-]       -
Boolean to activate/deactivate the dispatcher

    # Choose "True/False" for the operation mode the dispatcher should have.
    # The selection blocks are: 1. Layout   2. Internal constraints 3.
Optimization function
```

Here the Dispatcher can be activated or deactivated. As mentioned before, if it is deactivated the default operation of the MoSES code is to maximize the production without taking into account any other factors. Once the Dispatcher is activated, many variables are adjusted internally so that the entire code is considering this control tool.

As shown above, there are three selection blocks, which contain the most important variables of the dispatcher. These sections are presented next:

Section 1. Layout

```
    # 1. Layout. Select the power plant layout to be implemented

    enable_EH = True,                                     # [-]       -
Boolean to include EH in the plant
    enable_battery = False,                               # [-]       -
Boolean to include BESS in the plant
```

Since the Thesis studies a hybrid PV-CSP plant with a sCO_2 cycle, the parts that are optional are the TES, the BESS and the EH. The EH and BESS are parts which include different equations and definitions inside the dispatcher, which makes it necessary to have them as Boolean variables. However, for the TES, the approach is different because there is a variable that can remove the TES from the picture without having to reorganize the Optimization problem, and that is the energy capacity. In short, if the value is set to 0, the plant doesn't have TES.

Section 2. Constraints

```
 # 2. Internal constraints. Select the constraints to be implemented
```

```
    # Relative to the EH:
    Max_Ramp_up_EH = False,                                       # [-]       -
Boolean to constrain the ramp up power [W] of the EH
    Max_Ramp_down_EH = False,                                     # [-]       -
Boolean to constrain the ramp down power [W] of the EH
    Commitment_time_on_EH = True,                                # [-]       -
Boolean to constrain the "ON" commitment time [h] of the EH
    Commitment_time_off_EH = True,                               # [-]       -
Boolean to constrain the "OFF" commitment time [h] of the EH
    Max_Power_EH = True,                                         # [-]       -
Boolean to constrain the maximum power [W] of the EH
    Min_Power_EH = True,                                         # [-]       -
Boolean to constrain the minimum [W] of the EH
    # Relative to the PB:
    Max_Ramp_up_PB = False,                                       # [-]       -
Boolean to constrain the ramp up power [W] of the PB
    Max_Ramp_down_PB = False,                                     # [-]       -
Boolean to constrain the ramp down power [W] of the PB
    Commitment_time_on_PB = True,                                # [-]       -
Boolean to constrain the "ON" commitment time [h] of the PB
    Commitment_time_off_PB = True,                               # [-]       -
Boolean to constrain the "OFF" commitment time [h] of the PB
    Max_Power_PB = True,                                         # [-]       -
Boolean to constrain the maximum power [W] of the PB
    Min_Power_PB = True,                                         # [-]       -
Boolean to constrain the minimum [W] of the PB

    # Select study case: load following OR injecting to the grid
    Load_following = False,                                      # [-]       -
Boolean to select the option of following an electric load
    Injecting = True,                                            # [-]       -
Boolean to select the option of injecting to the grid
    #Power_limit_injecting = P_max, Already defined
down                           # [MW]      - Power limit for injecting
electricity to the grid

    # Select study case: allow electricity purchase or not
    El_purchase = True,                                          # [-]       -
Boolean to select the option of buying electricity
```

The second section is used to define the constraints that are to be implemented when running the simulation. As presented in the section 3.3.2, there are several limitations imposed to the variables for the optimization problem. However, to be entirely flexible, there may be cases in which it is not relevant to limit the "Maximum Ramping up Power of the Electric Heater", for example, because of the study case. That was extended to all the relevant equations, but only restricting the ones in which it made sense. It is obvious, for example, that the PV energy input should be distributed among the options that it has, and that equation must remain regardless of the study case. Thus, some equations were omitted for this selection part, as can be seen.

After that, there are 2 options for selecting study cases. The first one is for the electricity produced, which can be connected directly to the grid or there may be the case of having the plant connected to a load. This intends to prepare the code for such case, however, for the scope of the Thesis project the selected option will be "Injecting", due to the analysis intentions.

The second one is to allow electricity purchase in the plant or not. This option is very relevant because it expands or restricts the limits of the hybrid power plant enormously. With the electricity bought the dispatcher can produce heat to store it in the TES and it can also store it directly in the BESS to be used later for selling that energy to the grid at a lower price. The intention of having it is to expand the possibilities as much as possible, so that all cases care studied and analysed, to have a holistic approach of the behaviour of the plant under many different circumstances.

<u>Section 3. Optimization function</u>

```
 # 3. Optimization function. Select one KPI to optimize

    Min_Total_energy_waste = False,                          # [-]       -
Boolean to have as optimization function to minimize the total energy waste
    Max_Profit = False,                                    # [-]       -
Boolean to have as optimization function to maximize the profit
    Max_Production = False,                              # [-]       -
Boolean to have as optimization function to maximize the production
    Max_Profit_diff_tariff = True,                                   # [-
]       - Boolean to have as optimization function to maximize the profit
    Min_CO2 = False,                                   # [-]       - Boolean
to have as optimization function to minimize the CO2 emissions
```

Here, out of the 5 objective functions presented, 1 should be selected to have the complete optimization problem ready to be solved.

When it comes to the parameters themselves, one of the important comments to be made is that, as mentioned before, most of the parameters used by the optimization tool are already defined in MoSES. Obviously, those parameters can be modified but that should be done indirectly through the MoSES itself. The parameters will be given to MoSES and then the dispatcher will take them from there to then proceed with the simulations.

4 Results

4.1 Study case 1: The Spanish electricity market

The first study case that will be presented in the Techno-Economic Assessment of the hybrid power plant will be a study of the Spanish electricity market and the integration of the plant in it.

Spain is a country with a great solar resource and a very dry climate, which makes it ideal for installing solar energy. Indeed, the country had a so-called "sun tax" during the past years but that has been eliminated now and Spain is experiencing a boom in the amount of solar capacity installed [32]. It is stunning that the country is still behind other European countries such as Germany and Netherlands in terms of rate of energy coming from solar resources.

The city that will be studied will be Seville. The capital of the autonomous community of Andalusia and the province of Seville is a fantastic place for installing solar power plants, and that has been seen, for example, with the installation of PS10 or PS20, two of the most powerful solar power towers of the world. Another flagship project installed in the province was Gemasolar, still operating very successfully.

In conclusion, Seville emerges as a very interesting location inside Spain for analysing the behaviour of hybrid PV-CSP power plant inside the electricity market of the country.

To clarify, this study case inside the Spanish electricity market is one way of focusing on the ultimate objective of the thesis, which is to assess the techno-economic feasibility of these power plants. For that purpose, it is necessary to create a particular case that can serve as indicator of a trend for the global picture.

The idea behind the electricity market study is to assess markets where these hybrid plants can play a key role and to try to exploit all the advantages they have. The most important feature for the current electricity grid is the flexibility and the ability to store energy with both the TES and the BESS. As mentioned in a previous chapter, some societies with a high solar penetration are starting to experience problems as well with the so-called duck curve, which reflects the impact of the intermittency of the solar resource, that can't be underestimated.

For those reasons, the participation of the hybrid power plant in markets as the secondary or the tertiary has been estimated as a relevant alternative that can be a decisive and heavy factor in the future profitability of the installation.

4.1.1 Introduction to the Spanish electricity market

Before entering simulation details and results presentation, it is relevant to first have a deep understanding of how the electricity market works in Spain.

Starting from the basics, the electricity is produced by companies in generation plants (thermal, wind, hydro, nuclear…) and then it has to go through transmission and distribution networks owned by regulated companies, before reaching the end customer through retail supply companies. That would be the lice cycle of electricity, from production to end customer. However, although it may sound simple it is not, and there are many players and different types of markets, which makes the whole electricity problem a complex one.

This transaction of electricity is done basically through two markets: the future market and the day-ahead or spot market[33]. The future market refers to long term contracts (months and years) for industrial companies or small private consumers in which they secure the energy the intend to consume with a price that can enable them to plan their activities.

This future market (financial trading) helps protecting the customer against the volatility of the spot market and the uncertainty of the future. These agreements can take place between players directly, usually with the help of brokers.

Then the spot or day-ahead market is basically an auction called daily for the delivery of electricity in each of the 24 hours of the following day. It is a "unit price" auction in which all agents charge and pay the same price each hour.

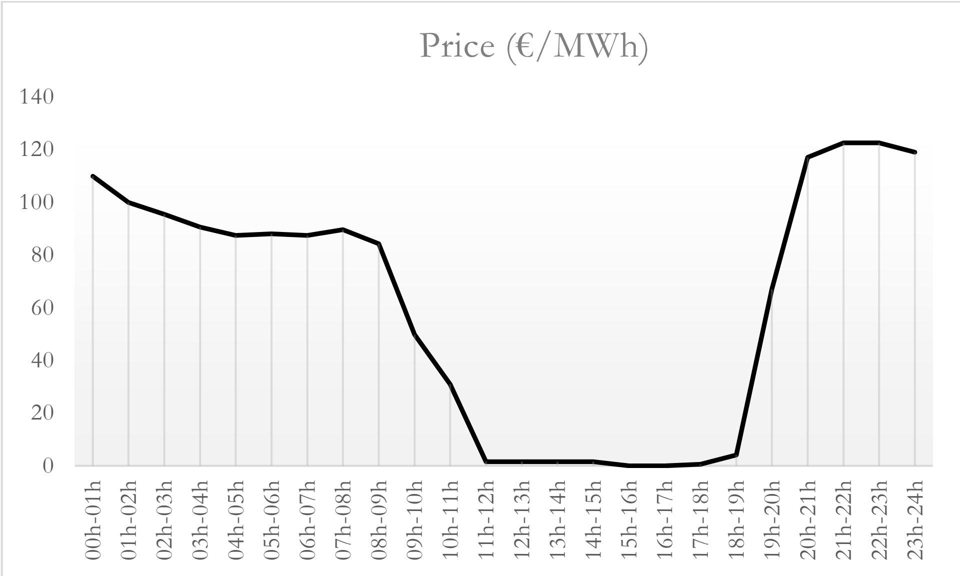

Figure 4-1 Spot price for Spain on the 1st of May

As can be seen[34], the spot price curve is normally characterized by two peaks one during the morning and one during the evening, which is when the consumption is high and there are no renewables available to produce that energy. Those peaks happen (in Spain) around 7-9 am and 8-11 pm, and after that the prices go down during the night.

One important factor that can be identified in this case is the fact that the price becomes almost 0 during the daylight period. That is due to the renewable penetration in the market, specially the solar energy, that brings the prices almost to 0. That is because normally the renewables participate in the market with a bet of 0€/MWh.

The reason behind having that low offer is that they get the energy "for free". The sunlight is providing power to the photovoltaic or CSP field and if that energy is not sold the power plant would get nothing, so they need to sell it at whichever price. Selling at a low price is always better than not selling at all.

On the contrary, gas power plants, coal, nuclear… use a fuel for producing their energy, and they need to pay for that in order to provide the energy to the grid. Therefore, they have to be more careful with the offers they make in order to reach profitability, which means higher prices coming from them.

To conclude, and to clarify, although the spot market is the widely known one when it comes to electricity markets, looking only at it can give a distorted picture of the situation. Indeed, most of the demand is contracted on the free market at a fixed price (77%) and only the rest (23%) is paying the daily market price[33] and thus being affected by the price fluctuations of this market.

4.1.2 Frequency regulation, secondary and tertiary market

For the purposes of this project, on top of the spot market, the hybrid power plant will target other markets, to explore the benefits and limitations of doing so. Examples of those markets are the frequency regulation, the secondary and the tertiary markets, which are part of the ancillary services of the grid[35].

The grid or system operator has to ensure there is balance in the electricity system. Electrical energy can't be stored in large quantities and that means that normally the amount of energy generated must be equal to the one that is being consumed. Some of these imbalances lead to problems as frequency deviations with regard to the nominal value of 50Hz.

These problems are normally solved with the balancing or ancillary services, which resolve the technical constraints of the system by limiting and modifying the production or demand schedules.

The balancing services are remunerated through market mechanisms, which are mostly the secondary and the tertiary. The frequency regulation market is not paid in Spain, if a market participant has the ability or possibility to operate with frequency regulation tasks, that participant is obliged to do so and there is no extra profit for that measure,

However, for the secondary and tertiary market the situation changes. First, the secondary control is a service whose purpose is to correct the deviations with respect to the anticipated power exchange schedule [35]. It acts between 20 seconds and 15 minutes and the plants participating in it get two income sources. First, there is a payment for being available, the so-called control band, which consists of getting remuneration for providing "X" MW that can be used whenever it is needed by the controller. The second source of income is from the net usage of energy, and it is the payment for the actual energy finally used by the operator.

On the other hand, the tertiary control purpose is also to adjust the deviations and on top of that to restore the secondary control band reserve used. Another difference with the secondary control is that it acts in a rage of 15 minutes to 2 hours. The next figure illustrates what has been said before in terms of how the frequency, secondary and tertiary control act with regards to time.

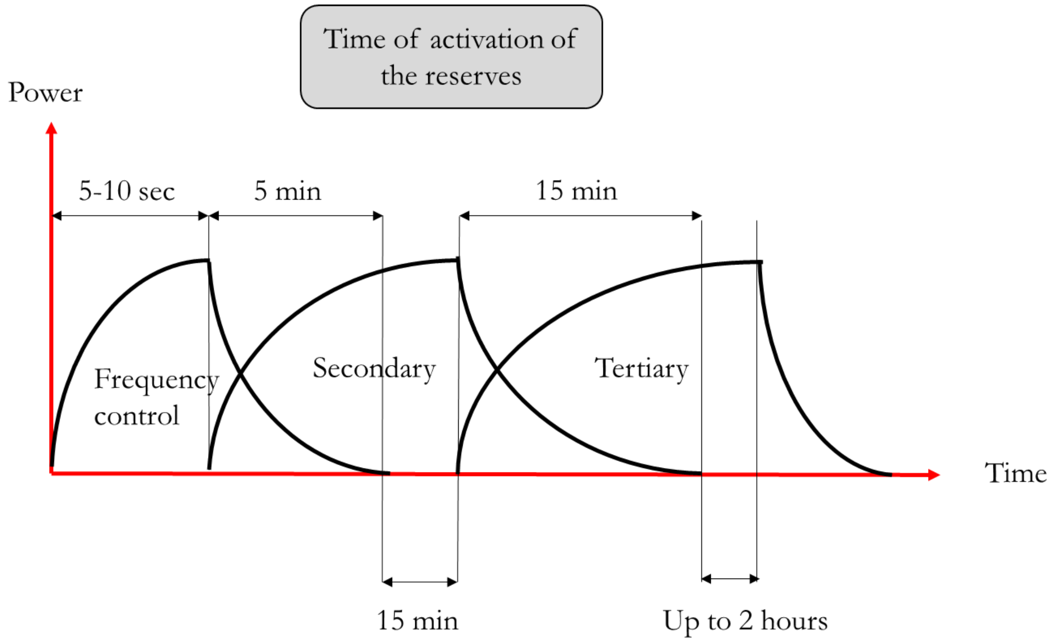

Figure 4-2 Time of activation of the reserves

As a comment, there is an extra service that has not been contemplated for this part, which is the service of Balancing energy from Replacement Reserves. It is a control feature of the Spanish market that acts after the tertiary control and whose impact and magnitude is not very high. Therefore, due to having a minor relevance, and to set the scope of the thesis in a both realistic and interesting manner, it was decided to focus on the spot, secondary and tertiary markets.

4.1.3 Secondary and tertiary market modelling

After presenting the main characteristics of the secondary and tertiary controls, this chapter will introduce their details and modelling methodology that was followed in the dispatcher. For this purpose and to clarify, it is important to define the day "D" as the day in which the electricity exchange will happen and "D-1" as the day before that exchange.

The next table represents all the important actions happening during D-1 and D in the real electricity market.

<table>
<tr><th>D-1</th><th>D</th></tr>
<tr><td>The system operator estimates the regulation reserve</td><td rowspan="3">The plant generates in the spot market during the day in a normal way. Whenever it is participating in the market, it increases its power output or buys electricity to take up for the imbalanced moments</td></tr>
<tr><td>The plants offer their available capacity at a defined price (€/MWh)</td></tr>
<tr><td>The final required reserve is defined at a price based on the minimum cost approach</td></tr>
</table>

Table 4 Secondary and tertiary market D-1 and D

During the D-1 day, the system operator estimates the regulation reserve needed for both the secondary and tertiary. It is relevant to mention that the system operators are every day estimating what would be the demand of electricity, to be able to provide that with the power plants of the country, and in that same way, they estimate what would be the regulation reserve.

After that, the plants offer their available regulation capacity for the next day at a defined price (€/MWh). As a comment, the capacity offered is the variation that the power plant can have during the hour at which the offer has been placed. For example, if a plant has a production capacity of 100 MW and offers 20 MW (injecting) for the secondary market, that means that at that time the plant can still participate in the spot market but only with 80 MW, because it needs to have 20 MW as a reserve that can be used whenever it is needed.

On the other hand, it is mentioned during the D day that the plant **increases** the power output or **buys** electricity because the secondary and tertiary markets are accounting for both ways. The imbalance of the grid can happen due to having a positive or negative supply vs. demand situation, and the operator needs to have covered both ways. In a hybrid power plant like the one studied in the Thesis, there is the possibility of both buying and injecting more or less electricity by several means. That is precisely the reason why this study case emerges as a very relevant one for the techno-economic assessment of the plant.

Now moving into the code and the dispatcher, it needs to recreate what has been mentioned that happens in real life, and the model will be designed accordingly.

Again, this table helps represent what happens in the code with regards to the secondary/tertiary market. It is presented in a similar way as the Table 4, to facilitate the understanding. However, since some parts require an extra explanation, the details are clarified after the summary is shown.

D-1	D
The dispatcher offers **"X" MW at "Y" €**	Since the dispatcher solves an optimization problem, the code will follow the objective function (maximizing or minimizing)
The offer enters the market **during that day:** • If the offer is below the price of one of the hours (taking the data of the market price in Spain) • If there is need for secondary/tertiary reserve (*taking the data of the reserve consumed during that day in Spain)	There is no possibility of having a hard constraint for generating the offered power. But, indeed, that is not the definition of how it works. The secondary/tertiary markets are reserves which are only used whenever the system operator requires them

Table 5 Dispatcher and code operation D-1 and D

As mentioned, the day D-1 the dispatcher creates an offer with the "extra" power that it can generate at a defined price. For that offer, many techniques can be followed, as forecasting the demand and supply for the D day or knowing what are the plant limits (what can be a profitable price and what can't). This can also depend on the weather forecast and obviously on the season of the year. However, in order to simplify and to get a better understanding of the outcomes of participating in these markets, the approach would be a fixed offer at the beginning.

This fixed offer throughout the year will be a price and power that will be tuned depending on the results, so there will be an optimization process for the two **X** and **Y** variables presented in the table. For further simulations, if deemed necessary, there will be a study on the offering strategy, in case it seems much more profitable, effective or realistic to follow a different approach.

Moving on to the second part of the D-1, the offer has to be below the price of one of the hours to enter the market that day.

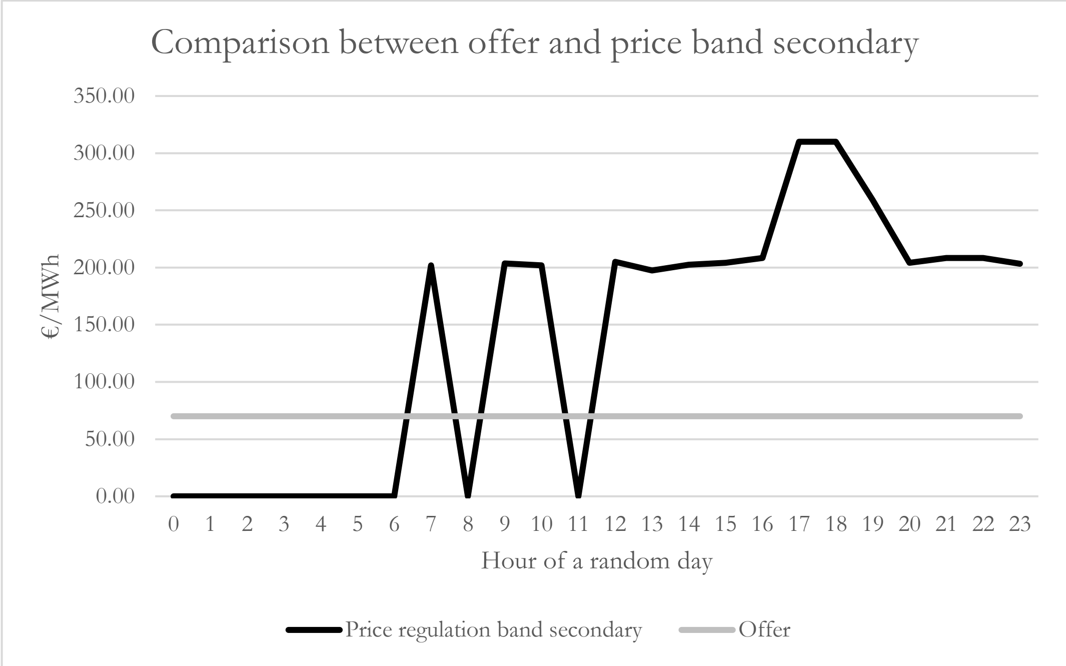

Figure 4-3 Comparison between offer and price band secondary

The Figure 4-3 highlights what was mentioned in regard to the offer (selected a random number only for visual reasons) and the market price. One comment important to be made is the fact that the comparison is between the offer and the secondary **band** price. What the plant offers is the reserve, the **X** MW that it can vary its production in case it is necessary, so that offer at **Y** € is compared in the code with the Spanish data of that market. In case it is lower than the market price, the power plant enters then the secondary market during that day, and it will have that capacity available.

As a reference, the price in the market for the secondary band is different than the actual price of the energy sold in that market. This figure highlights this difference:

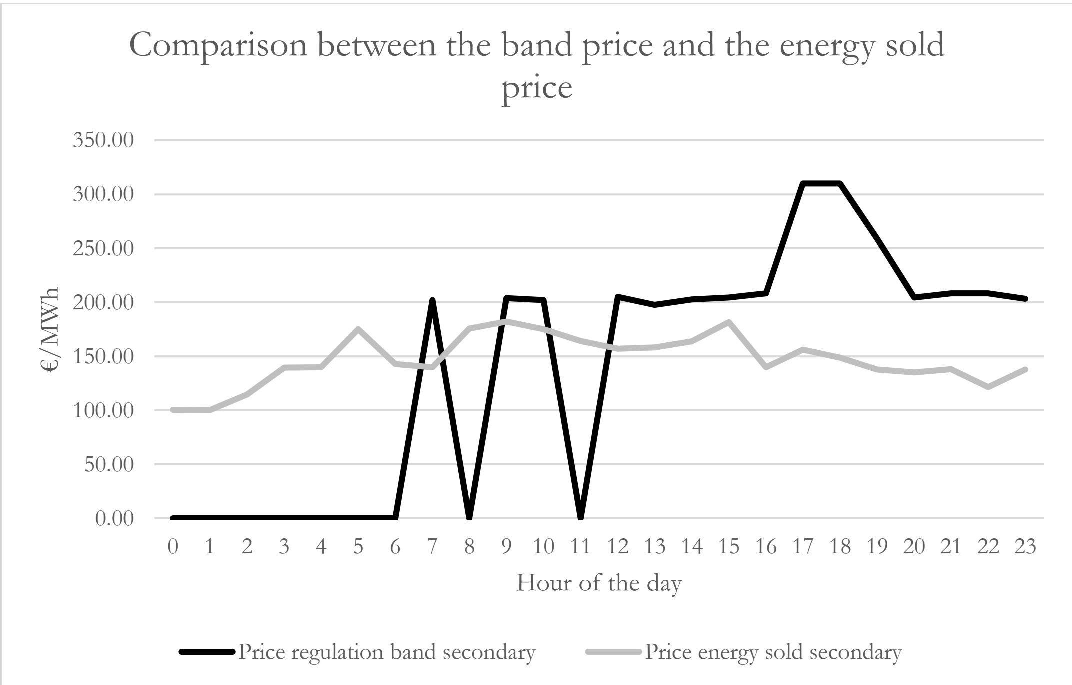

Figure 4-4 Comparison between the band price and the energy sold price

And as explained in the previous chapter, there are two sources of remuneration in the secondary market, one from the capacity that the plant offers, from being available to generate that power, and the other from the actual energy finally sold. These two curves represent that difference, in which the black corresponds to the price for the capacity and the gray for the final energy sold.

When it comes to the tertiary, the story is different and what is used as a comparison is the actual final price of the power sold in the tertiary market. There is no remuneration for the band and thus, no market with a defined price for that. The next figure shows the equivalent to Figure 4-3 but for the tertiary market. And that is what is used for selecting if the offer can be accepted or not.

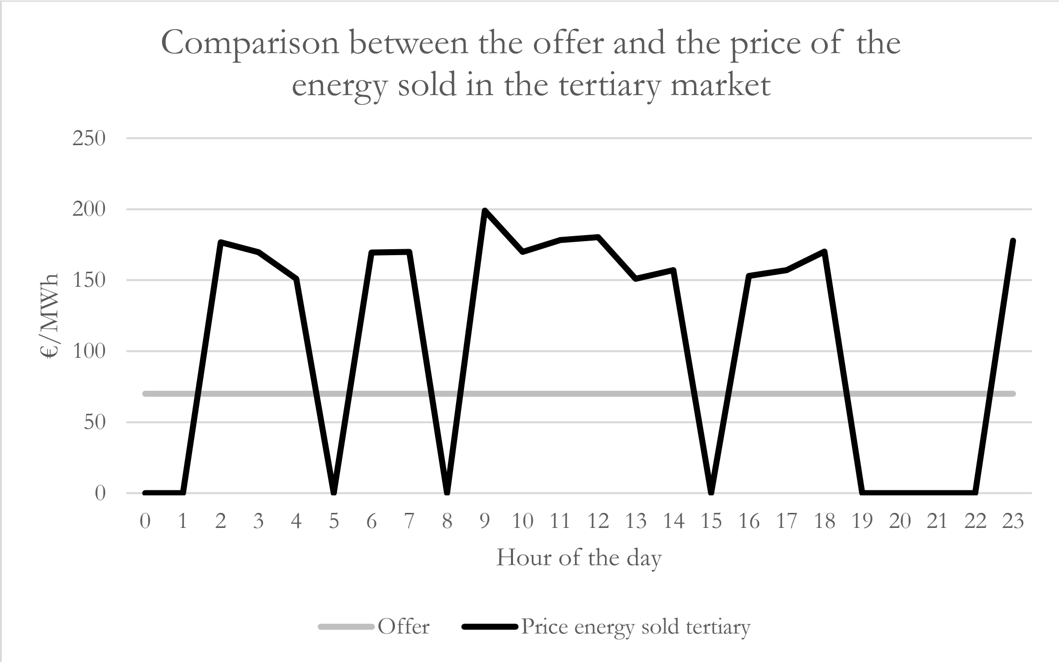

Figure 4-5 Comparison between the offer and the price of the energy sold in the tertiary market

Regardless of the targeted market, it is relevant to also mention that during the D day the plant must be generating the total capacity -(minus) the offered power band. As explained before, the offer is the **variation** of power output that the plant can perform, if the output is already the total capacity there can't be any variation.

Once that is performed, there is still one extra gate to be passed in order to finally generate and sell energy in either market, and that one is that the secondary or tertiary reserve is actually used. Although there is market data for the prices, it might be the case that in the end that energy was not consumed by the grid. To be completely fair and more realistic, the energy sold in the code needs to be restricted by the real energy sold in the country.

The way the previous restriction is performed is by checking the total energy sold in the secondary/tertiary market in Spain and making sure the energy produced by the hybrid power plant is below that value. To be fairer, since the data is for the total Spanish grid and the country is divided in 10 regulation zones [36], the values are divided by 10, since the plant will be located in Seville, in one of those 10 zones.

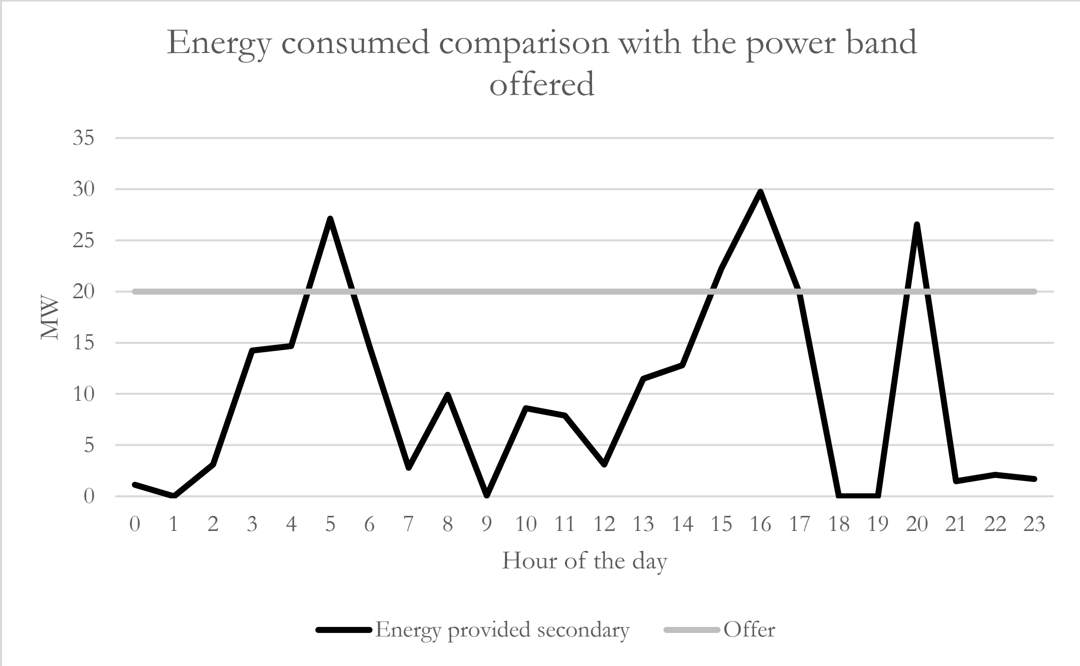

Figure 4-6 Energy consumed comparison with the power band offered

The previous figure represents the energy that was consumed during the day in the secondary market. If the offer is below those values, that means that it is not realistic to be generating that power for selling in the secondary market, and therefore, that has been taken into account when modelling.

To conclude this chapter, it is important to mention that all that was explained before was based on the selling case, but the same applies to the buying case. The grid balancing happens in both ways, either having positive or negative supply vs. demand, as explained before. Therefore, the same curves shown for both the energy provided and the prices for the energy sold exist for the energy consumed (the power plant buys energy from the grid) and the prices for that energy.

The dispatcher was designed accordingly, to take into account the grid balancing in both ways, due to having with the power plant the possibility to perform it.

4.1.4 Simulation strategy

To begin with, it is vital to have a clear and defined path for the simulations that will be conducted. Otherwise, the efficiency of the whole simulation process might be enormously decreased. Therefore, the simulation strategy has to be defined now, although it is not a hard fix: there might be some findings that make it inevitable to shift to another path or to modify slightly the next steps.

The flowchart summarizing it goes as follows:

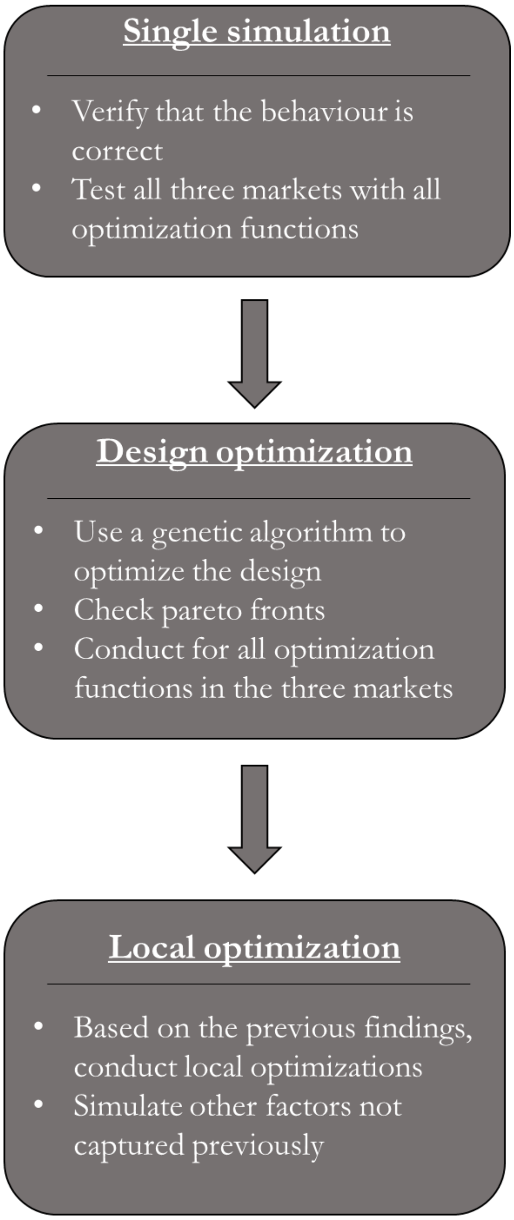

Figure 4-7 Simulation strategy flowchart

During the first phase, the aim is to verify that everything is working properly. One of the most difficult parts of the project is to integrate the dispatcher in the MoSES, so it is vital to double-check every variable to prevent any major mistake from happening. The plant operation in MoSES must follow what the dispatcher decides, and that integration is not immediate. Therefore, many adjustments and minor corrections are expected during the first phase.

Once that is solved and a satisfactory solution has been reached, it is relevant to test all three markets with all the optimization functions (maximizing profit and production and minimizing waste and CO2). Although the design would be randomly selected, the only purpose of this first simulation is to test that all the functions are working properly and to start having an understanding of what the main features of each case are.

After having that first understanding and simulation, the next step is to do a complete design optimization. That involves using a genetic algorithm integrated in MoSES, which is by definition a method for solving constrained and unconstrained optimization problems based on natural selection[37].

This flowchart facilitates the understanding of the optimization process, in which now there are two optimization problems: the dispatcher and the genetic algorithm for the design.

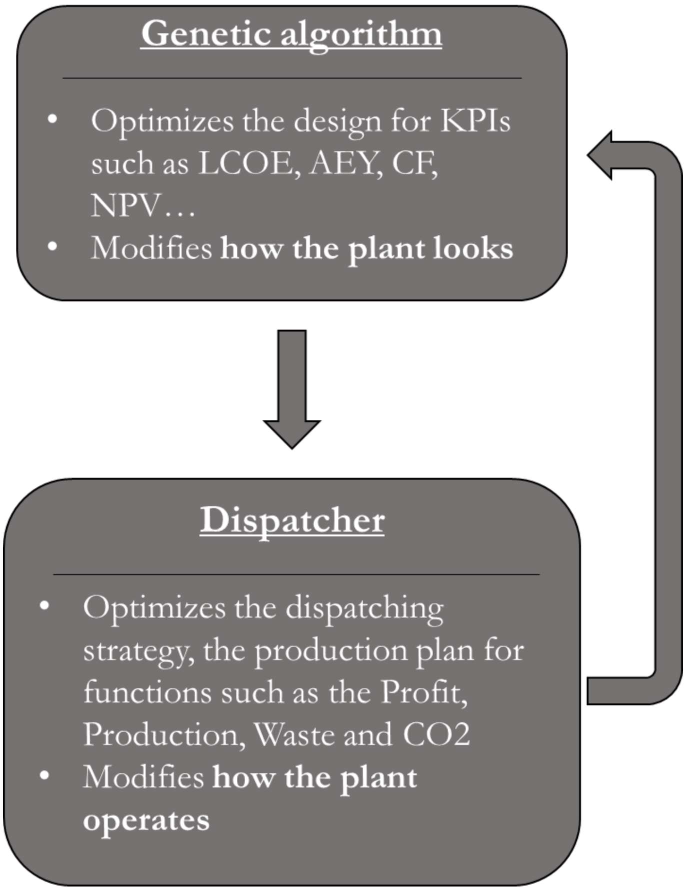

Figure 4-8 Optimization process flowchart

So first the genetic algorithm proposes a design for optimizing one of the shown KPIs. That design is taken by the Dispatcher, which creates a production plan (when to buy, store, sell…) in order to optimize one of the optimization functions defined before.

This process is repeated countless times by the genetic algorithm, which proposes the designs that are then tested. The loop can be stopped whenever the amount of data is enough for the study, since the problem would reach a Pareto front that then would be the limitation of the study case. However, in order to get a complete analysis of the three markets, it is needed to conduct 12 full simulations, 4 (each optimization function) for each market. If deemed irrelevant, some of the mentioned cases can be skipped.

Finally, it is time to conduct local optimizations and explore other cases. For example, it might be the case that it becomes relevant to study what happens if the connection with the grid is unilateral, the plant can only sell and not buy electricity. Another example might be to change dispatcher parameters such as the number of hours that it has in the optimization problem, it might be better to only focus on 24 hours or to extend it to 1 week of view for optimizing.

And those changes can actually have a big impact on the total results, which would lead to repeating the full simulations with the genetic algorithm for that case. Therefore, although the strategy for the first round is clear, it is not a hard fix and it is likely that the process needs to be slightly adjusted, after the third step in particular.

4.1.5 Results. Single simulation

To introduce the details of how the hybrid power plant operates and to show how each dispatcher optimization function affects the results, this chapter presents a single simulation for every case. Repeated behaviors or very similar results will be obviously omitted, and since the markets were previously explained, the scope of this part will be focused on the spot market, adding comments when relevant for the secondary and tertiary.

Since this section is only for giving an overview of the general operation, detailed data regarding the plant design becomes irrelevant and thus, it won't be shown.

4.1.5.1 Spot market optimizing the profit

To start, a typical winter day will be presented.

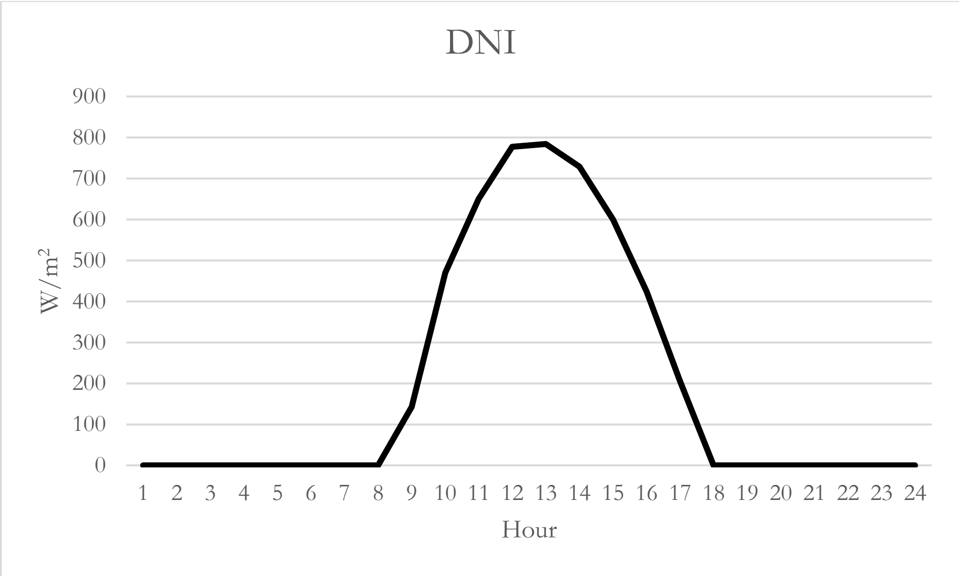

Figure 4-9 DNI for a winter day

The DNI follows the usual distribution, with the sun rising at 8 and setting at 18. This DNI is almost directly translated into the CSP and PV inputs for the Dispatcher. For the PV the translation is direct but for the CSP there are other factors that affect it, as for example the efficiency of the receiver, which varies a lot with the temperature, the need for defocus during some cases or a minimum startup value. After taking into account all those factors, the input that the dispatcher gets as actual available power is according to the next figure (the Q_out_SF is the CSP input for the dispatcher and the W_tot_PV is the PV input).

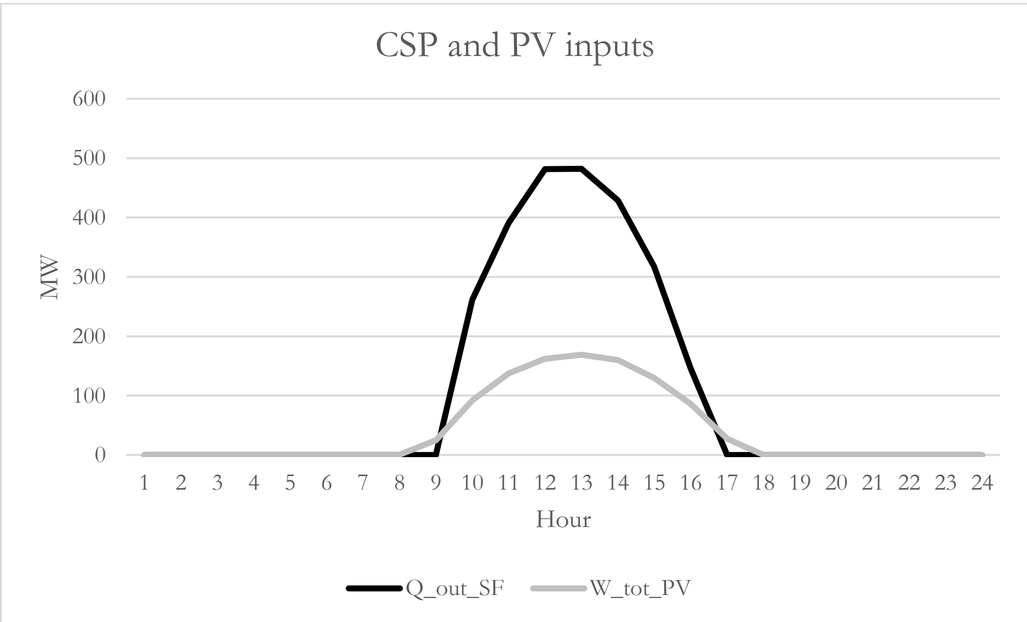

Figure 4-10 CSP and PV inputs for a winter day

A comment to be made is that the power coming from the Solar Field (after the receiver), the CSP input, is thermal power. And the big difference between them is due to having an installed capacity of 180 MW-el for PV and 619.4 MW-th for the Solar Field.

Now entering the more detailed part about the plant itself and how it operates, it is relevant to mention that this first case shows the operation **optimizing the profit**, trying to maximize it. When it comes to the PV part, which is the simplest, there is a difference between the total production and the net power that goes to the grid. Since there is a power limitation at 100 MW, the PV production is shaved at that point, and it can't go beyond it.

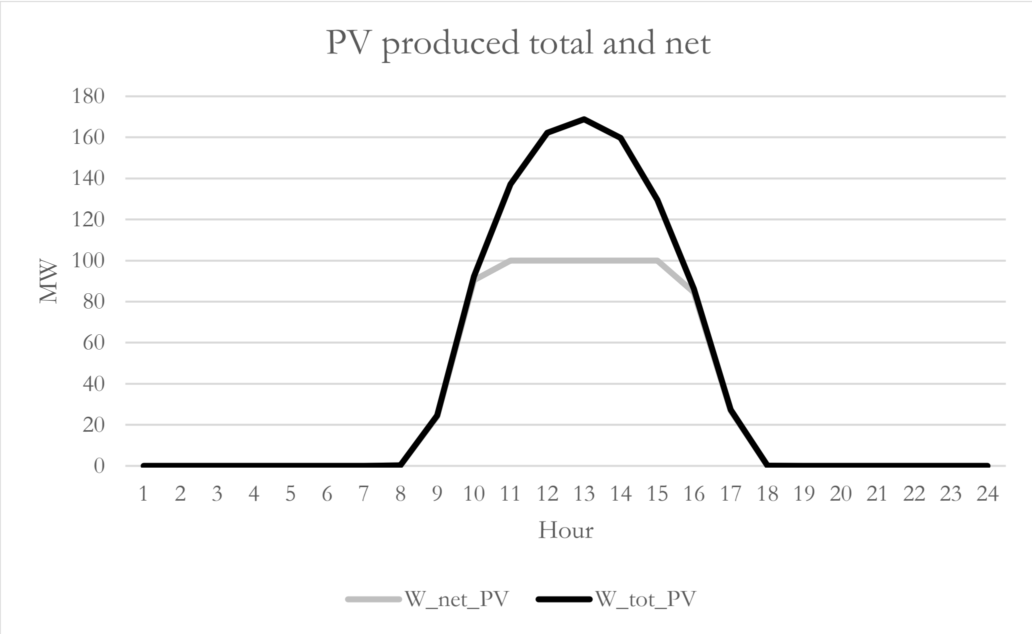

Figure 4-11 PV produced total and net for a winter day

Then the question is what happens with the PV extra production, and the answer is that it goes either to waste, to the Electric Heater or to the Battery Energy Storage System, as shown in the chapter 3.3.2. The next figure highlights exactly what was mentioned:

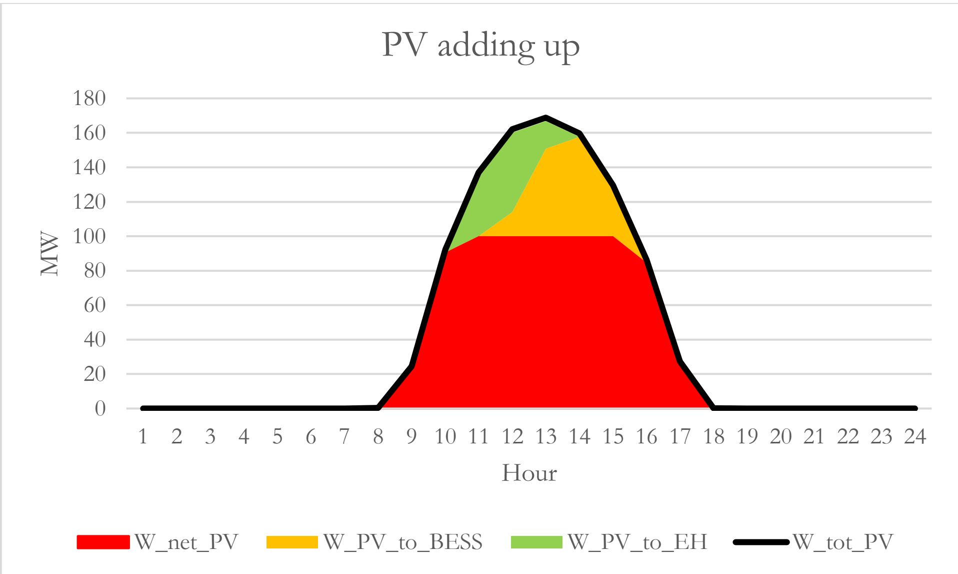

Figure 4-12 PV adding up for a winter day

The decision between sending it to the BESS or to the EH depends on profitability and limitations. First, either storage system needs to be available, i.e., to not be full and have room for the energy that is coming from the PV production. Once that is solved the dispatcher decides depending on what is considered as most profitable (since this case is maximizing the profit) according to the data it has, both in terms of parameters and also the future values it can play with (what comes after in the simulation).

Focusing now on the BESS, with a capacity of 166 MW for this simulation, it has the possibility to be filled with power from PV and also from the grid, and both sources are activated during that day.

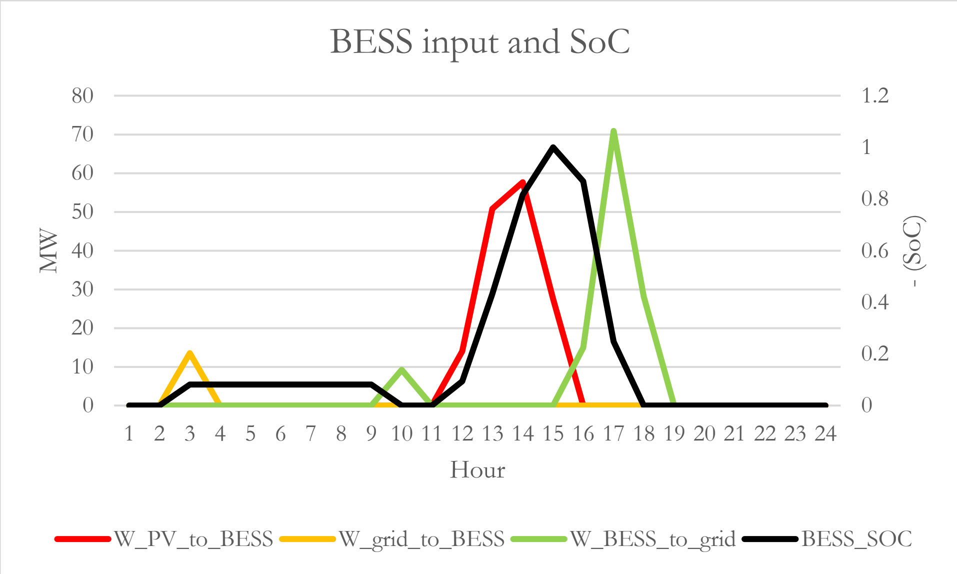

Figure 4-13 BESS input and SoC for a winter day

As can be seen, the BESS starts the day completely discharged and then the dispatcher decides to buy some energy during the morning to discharge it later. The quantity is decided based on the spot prices and the operational, replacement… costs of the BESS, and that is the optimum for maximizing the profit. If it was better profit wise to buy more to store it and use it later, the dispatcher would have done it, so it is not the case.

Then, as shown before, the PV charges it fully during the peak irradiation hours and after that the BESS is discharged at 16-17 to keep powering the grid once the PV production is going down.

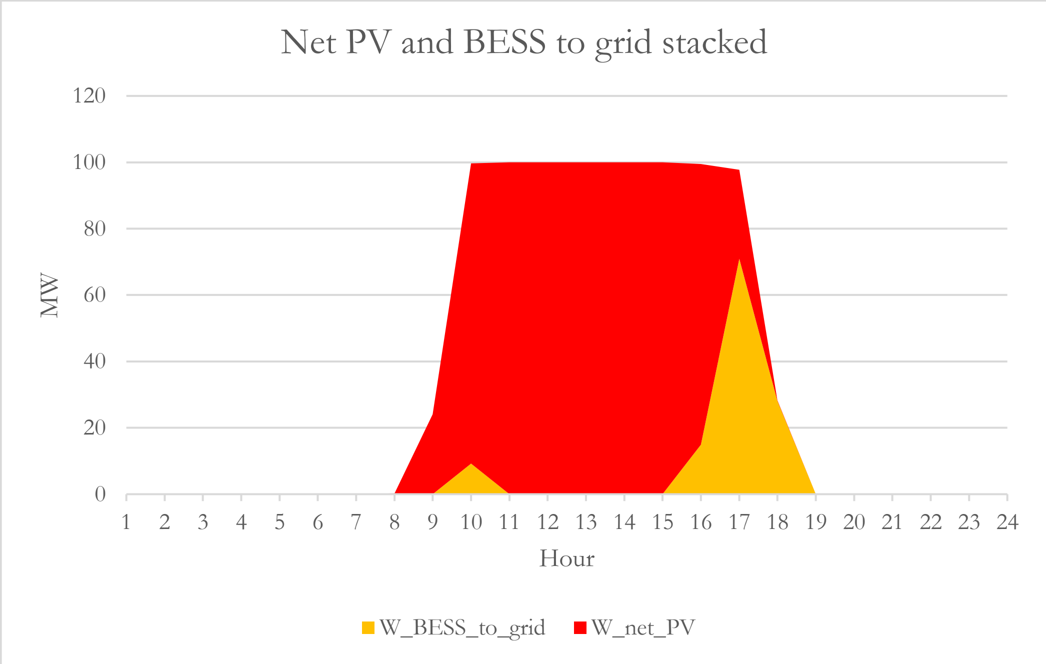

Figure 4-14 Net PV and BESS to grid stacked for a winter day

This stacked chart shows how when the PV production starts going down the BESS acts as that back up supply to keep generating 100 MW and get the revenue from selling on the spot market. What comes after that is the Power Block being powered by the Thermal Energy Storage, which takes over and starts producing more electricity to the grid. If that is analyzed, the data shows exactly how well chained they are:

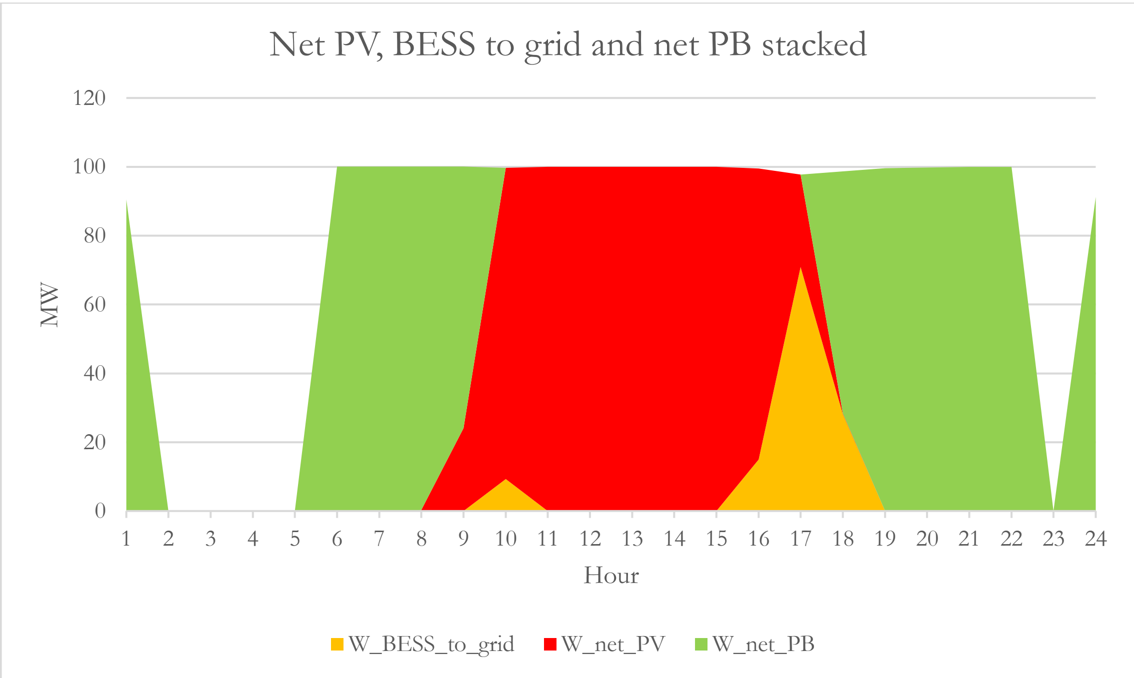

Figure 4-15 Net PV, BESS to grid and net PB stacked for a winter day

And this figure comprises all the electricity production of the hybrid power plant during that day, with some injection also during the first and the last hours of the day. Although it might look strange to stop producing with the power block during 11 pm and then produce again, the reason is always the profit in this case. This case might happen a lot, and the reasons here are two. The first one is that it is better to save that power to produce electricity later instead of doing it at that hour, because it is more costly in the spot market.

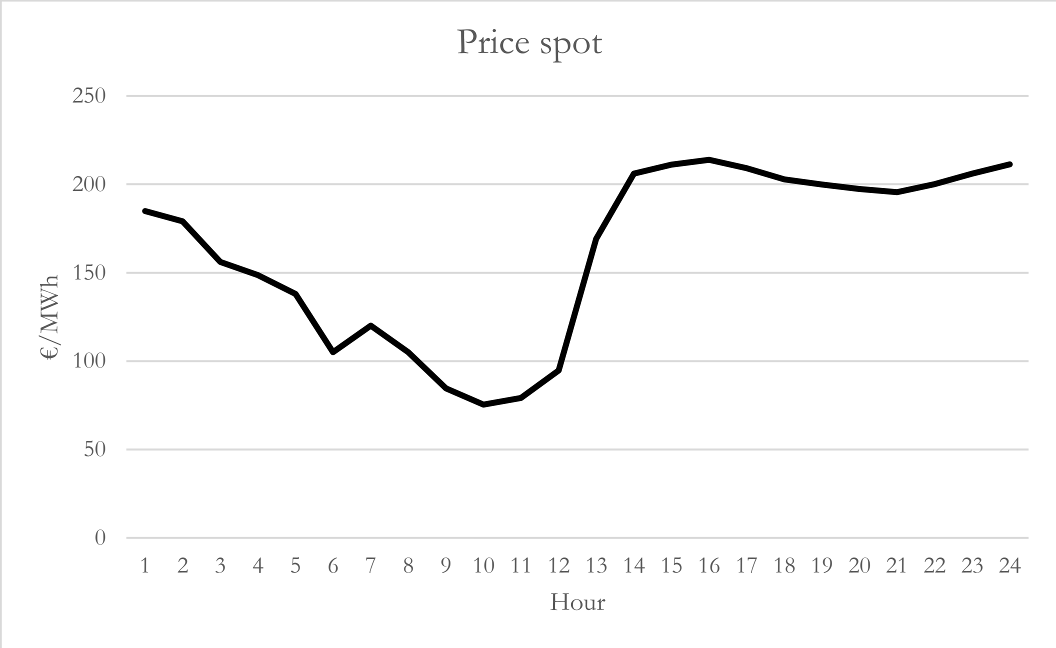

Figure 4-16 Spot price for a winter day

As can be seen, although the difference is not the biggest, it is better to produce at the peak of 12 pm instead of at the valley of 11 pm. And that can be done because the start up time of the Power Block is half an hour, so it can be stopped momentarily and turned on again the next hour.

This is according to the theoretical data extracted from the sCO2 model of MoSES, but if there is a case in which that can't be done, it is as easy as going to the model and adding a commitment time of 2 hours for when the PB is off. That will simulate everything with that constraint and make sure that when the PB is off it is 2 hours like that so that it has time to be turned on again (in case an analysis with blocks with more start up time is desired).

Going back to the PB production, as mentioned, there were two reasons which are actually the same but for different days. If the next day is studied, the spot price during the first hours of that day is way higher than the one shown in the last hours of the analyzed day. Therefore, the dispatcher decides to store that energy and produce it during those next hours.

Looking at the TES now, it is clear that the reason wasn't that it is empty:

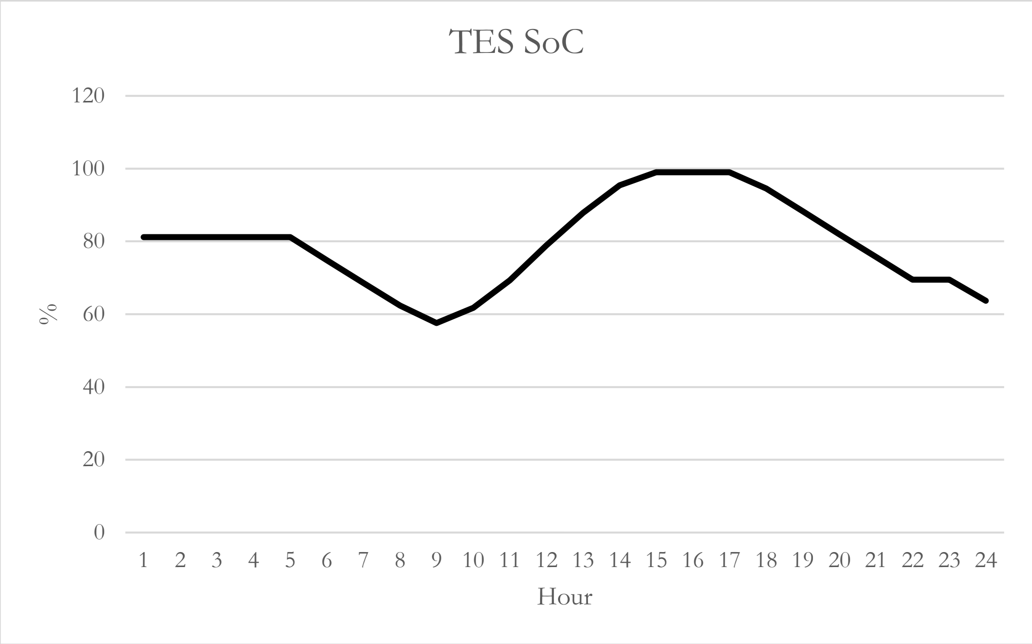

Figure 4-17 TES SoC for a winter day

And it is also relevant to analyze it with the PB and EH production as well as the power that the CSP field sends through the receiver and the heat exchanger to the TES, which shows how the TES is emptied whenever the PB is working and filled up when the CSP sends this power or when EH is activated.

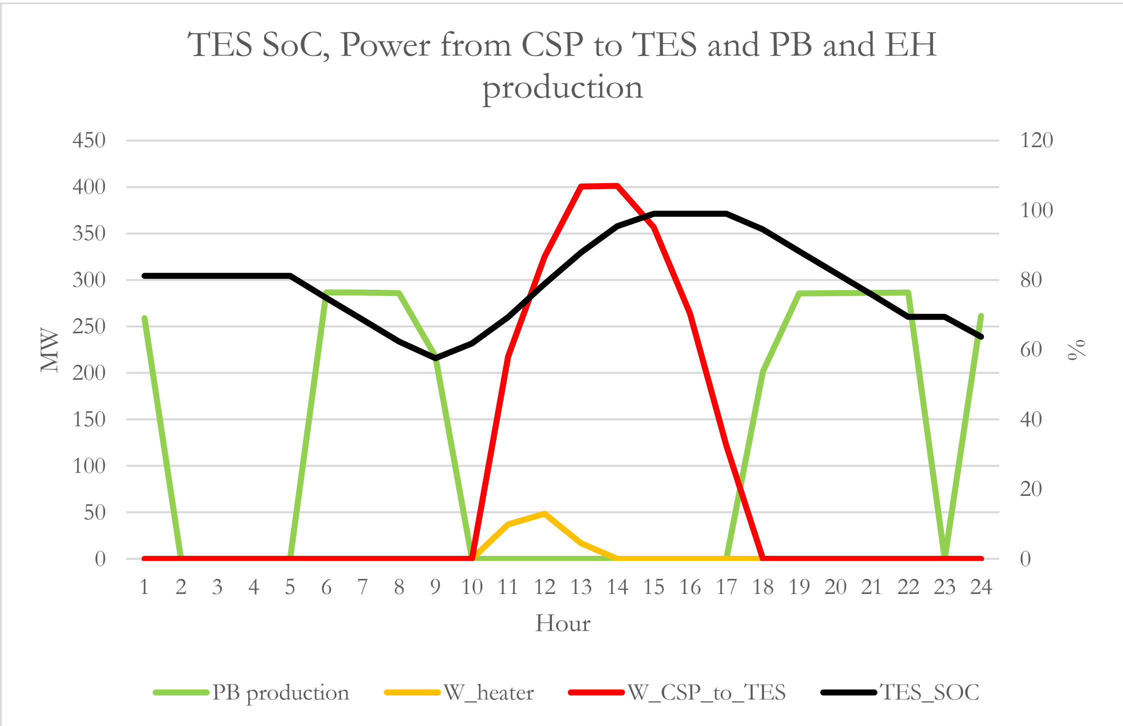

Figure 4-18 TES SoC, Power from CSP to TES and PB and EH production for a winter day

It is important to mention that the MW shown in the figure above are thermal, the thermal power going into or from the TES. And the power that the EH produces is supplied totally by the photovoltaic energy, the dispatcher decided not to buy electricity due to it not being profitable.

Once the winter day has been analyzed, it is interesting to switch to a summer day, where the DNI is higher and there are other phenomena happening. The general aspect of the curves and the data is basically the same, so, to not repeat the same, the only important part that should be highlighted is that it is possible to get full capacity production all day long, as shown in the next figure:

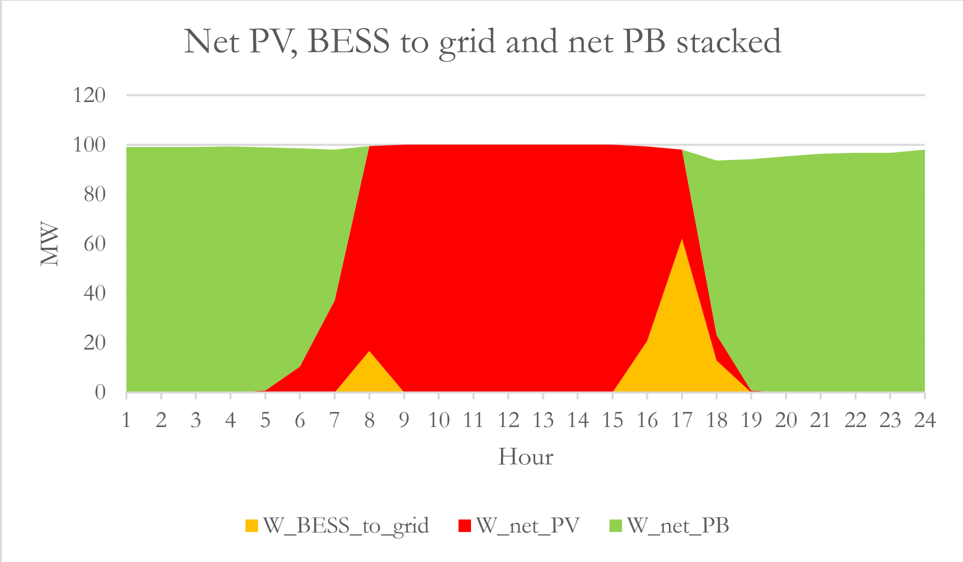

Figure 4-19 Net PV, BESS to grid and net PV stacked for a summer day

This is very relevant when it comes to grid stability problems and other similar factors, in which this power plant can have a major impact, being power from a non-intermittent renewable energy source.

As shown in the curve the operation of the PB is more stable here, with it having full power during the whole night:

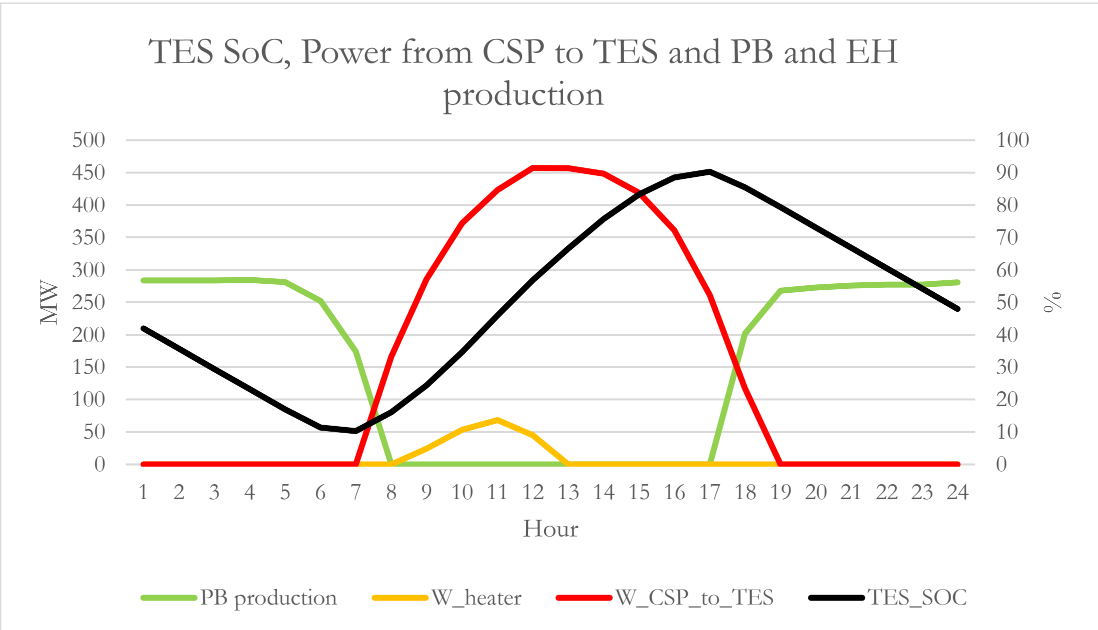

Figure 4-20 TES SoC, Power from CSP to TES and PB and EH production for a summer day

The rest of the charts show similar trends as the ones existing during winter but scaled up to the summer production. Therefore, after this analysis of the situation for the spot market optimizing the profit, now the next case will be the same spot market but now optimizing/maximizing the production.

4.1.5.2 Spot market optimizing the production

The main feature of this optimization part is that it will try to produce as much electricity as possible according to the equation presented in the chapter 3.3.2. This means that the electricity purchased acts in the opposite way of the optimization function (maximizing), so the dispatcher will try to restrict that amount to make it very low.

To start with, the DNI, CSP input, PV input the PV distribution to EH, grid… are basically the same, since the study is focused on the same day under the same conditions and there is not really any control operation taking place at that point. However, the first difference can be seen where the dispatcher can start affecting the simulation, with variables such as the BESS input and its SoC.

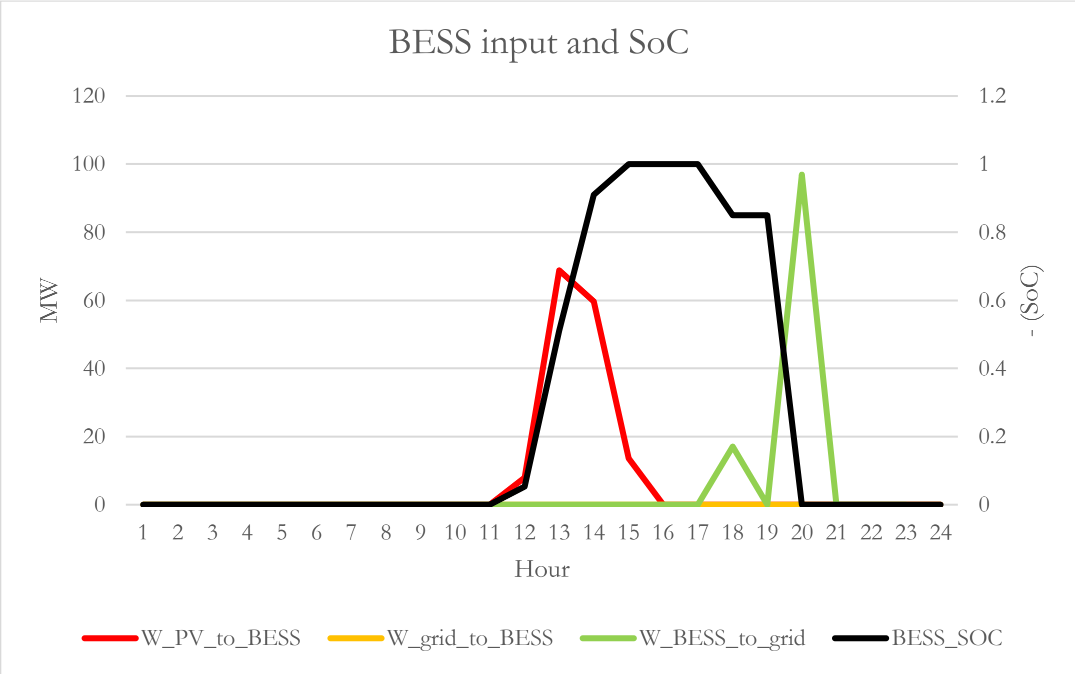

Figure 4-21 BESS input and SoC for a winter day optimizing the production

One of the first important facts is that the dispatcher doesn't buy now energy from the grid to power the BESS, as can be seen there in orange color. That would mean reducing the amount of energy produced and thus, moving away from the optimum, so that is why it doesn't do it.

In this case, the PV energy sent to the BESS is very similar to the one of the previous case and the only difference happens with the moment in which the BESS energy is sent to the grid, which is later, and that means the storage is full for more time. This next chart highlights the same behavior:

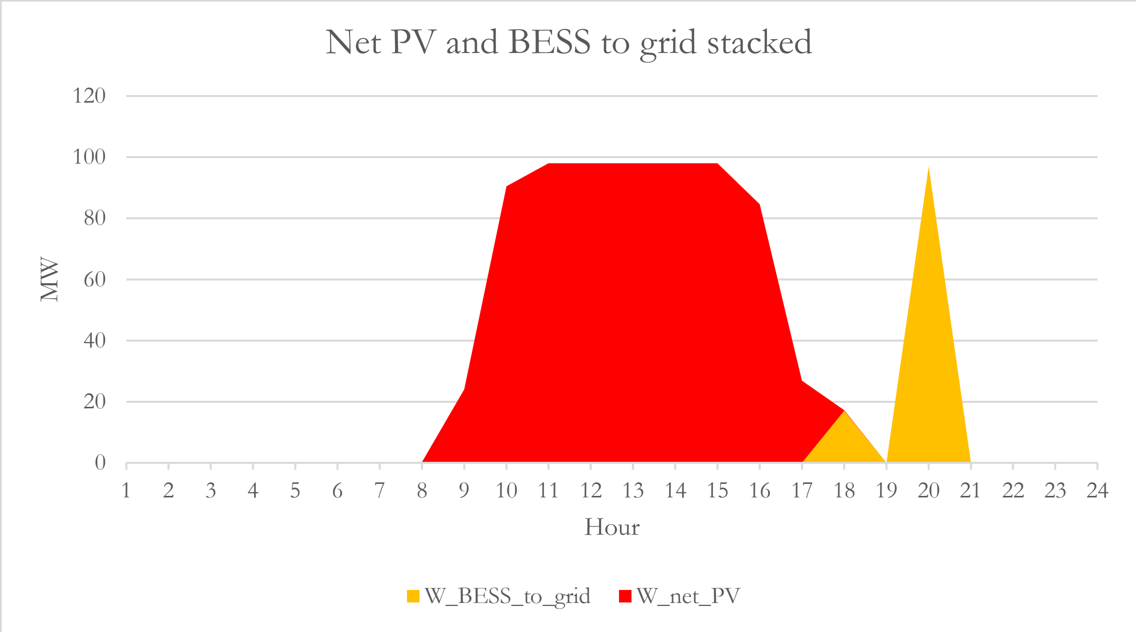

Figure 4-22 Net PV and BESS to grid stacked for a winter day optimizing the production

To have the full picture of it, the next chart shows the full electricity production of the power plant, with the PB added to the previous figure.

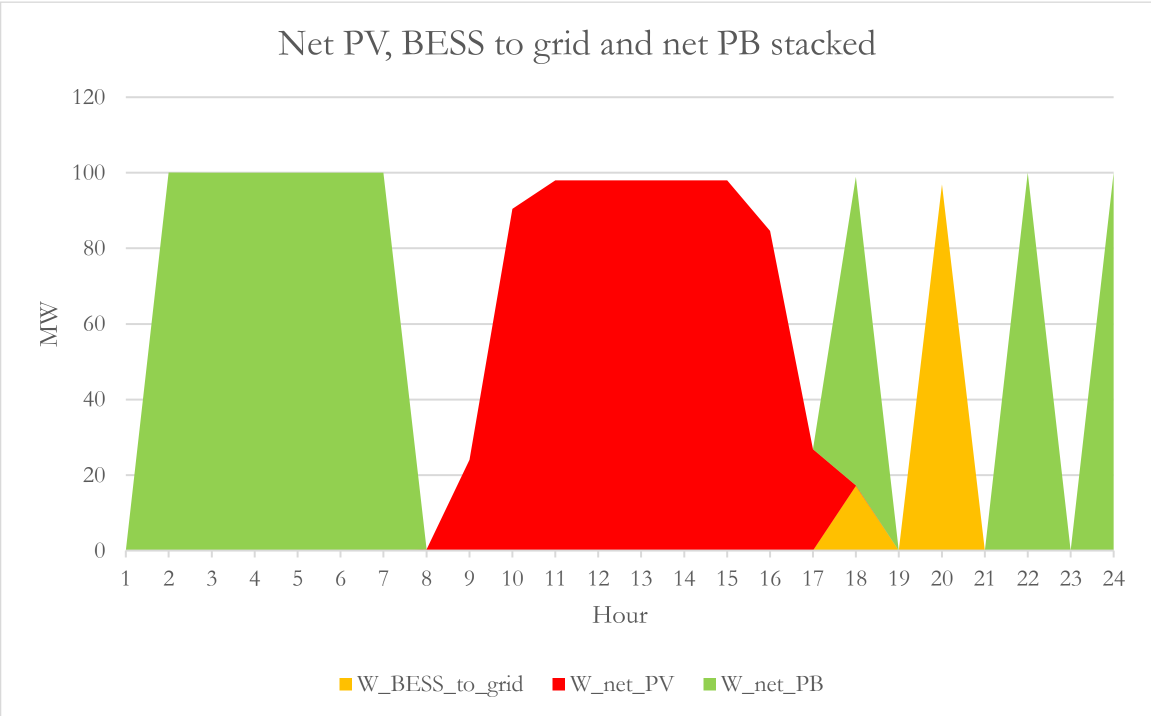

Figure 4-23 Net PV, BESS to grid and net PB stacked for a winter day optimizing the production

As can be seen in this case, there are two main differences when compared to optimizing the profit. The first one is that the spot price plays no role here, so the only important aspect is to produce, whenever. The spikes happening at the end of the day represent that precisely: since there is no commitment time for both the PB and the power sent by the BESS to grid, they are randomly located throughout the day, as long as there is electricity generated in the end.

The other big difference is that now the dispatcher tries to use the TES as much as possible to not lose any W of energy, and during the night hours the PB is still generating emptying it, whereas before it was more selective, keeping it for the right moment.

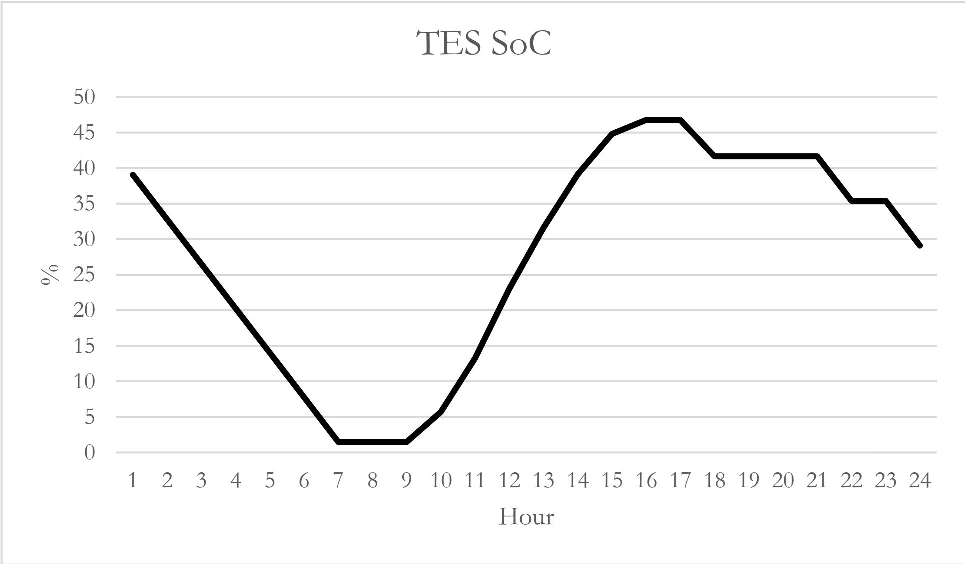

Figure 4-24 TES SoC for a winter day optimizing the production

Due to having a very similar case for the summer day between the profit and the production optimization, that data will not be shown.

If the general data is analyzed, then it can be seen that the differences between the case optimizing for the profit and the one optimizing for the production are not that high, being 3% for the production and 5 % for the profit. The numbers are not enormous but definitely important when it comes to such big plants with around 30 years of lifetime. For example, the NPV gives a 15 % increase when simulating optimizing the profit.

One of the reasons why the differences are not that big is that the spot price is relatively stable throughout the year, there is not much variation. And during the day it can be seen that although there is the classic ramp up during the night, there are no rocketing values, only during February, as shown in the figure below.

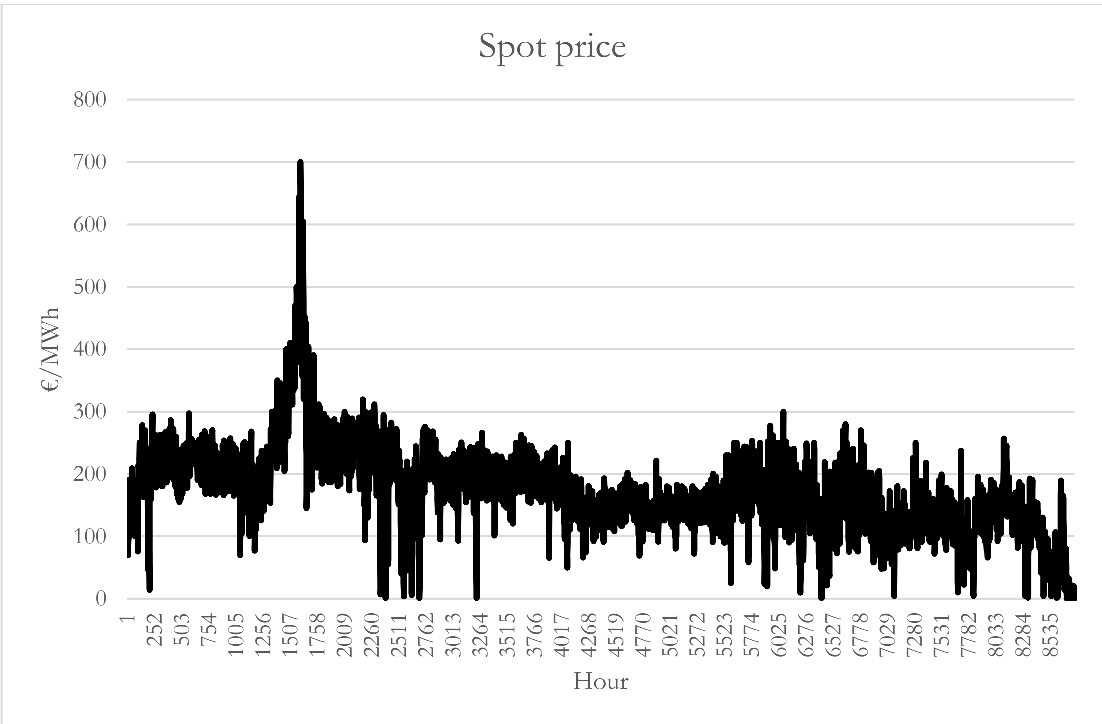

Figure 4-25 Spot price for the whole year

Another fact to consider is that the plant has not been designed for any of the cases. A plant optimized for production might look different than one optimized for profitability, and that would surely impact the values explained before.

4.1.5.3 Spot market optimizing the waste

In order to take advantage of all the solar resource, there is another optimization function which is trying to minimize the wasted energy. That energy waste happens due to having too much energy produced and no storage nor grid available to inject it, so this case will try to optimize that to reduce it as much as possible.

The first fact important to mention is that although having the same day and same conditions, now the dispatcher decides not to power the EH with the PV and instead use the BESS more than before.

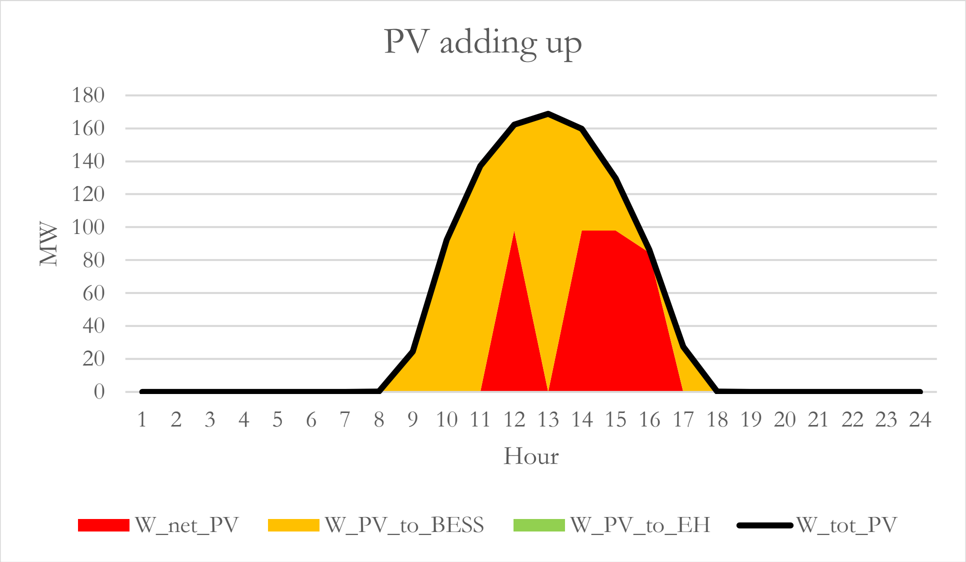

Figure 4-26 PV adding up for a winter day optimizing the waste

The reason behind this extra use of the BESS is that this optimization function doesn't take into consideration any cost nor production penalization by using BESS. The only objective is to minimize the total waste using the resources available.

Previously, since the BESS has a high cost due to their replacement after several cycles and also due to having other OPEX costs, the profit optimization didn't use it that much. On the other hand, since the BESS have the round trip and the inverter efficiency, it is not that worth it to use when trying to maximize the production. There will be many losses that will affect the performance and the objective function.

If that same day during the afternoon is analyzed, one can see that the power from the BESS is not used entirely to power the grid, it can be seen with the order of magnitude of the power it sends:

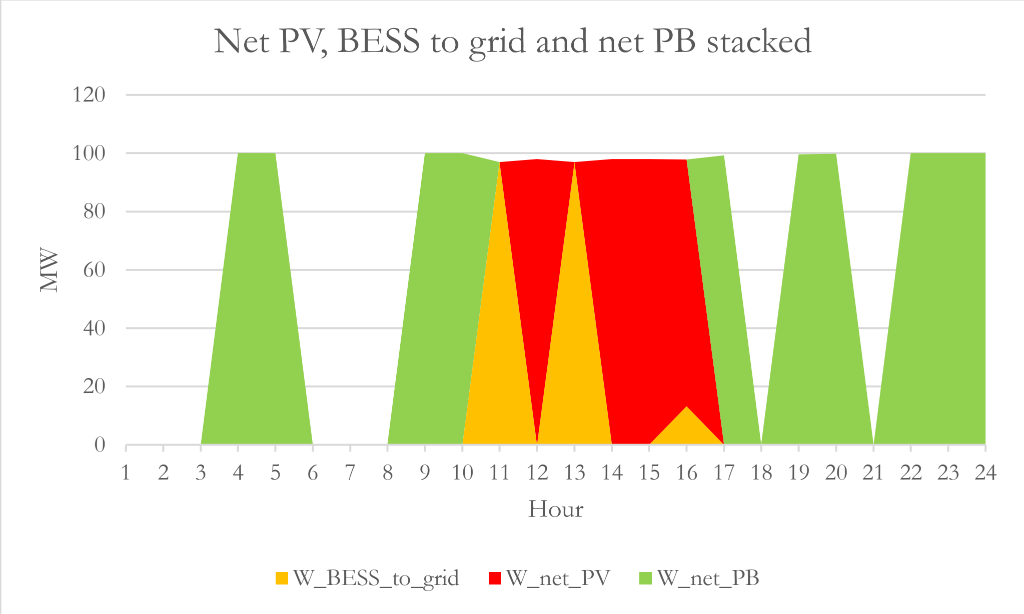

Figure 4-27 Net PV, BESS to grid and net PB stacked for a winter day optimizing the waste

And the relevant fact happening here is that the power in the BESS instead of going to the grid goes to the EH to charge the TES. That is what happens with this case, the dispatcher is only focused on minimizing the waste, and that leads to charging the BESS to then charge the TES, which includes many losses along the way. Consequently, the use of the TES and the BESS in this case is also high, to store and use as needed.

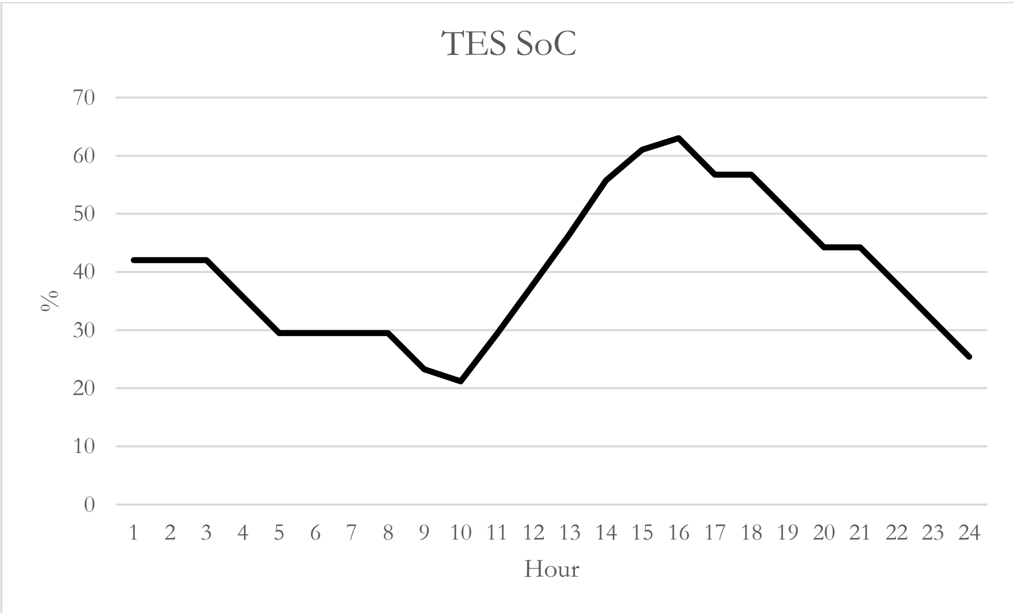

Figure 4-28 TES SoC for a winter day optimizing the waste

In the end, the key part of this simulation is to check the total energy wasted now compared to the one wasted in the previous cases. If that value is checked, it can be seen that the differences are noticeable but not very high.

Case	Energy wasted (GWh)	Energy wasted (% of AEY)
Optimizing profit	0.88781	0.1469
Optimizing production	1.24383	0.2044
Optimizing waste	0	0

Table 6 Energy wasted for the different cases

As can be seen, the GWh wasted are relevant, 1.24 or 0.887 GWh is indeed a lot of energy but, nevertheless, when compared with the AEY, which is around 600 GWh, the impact is not very big. The total energy wasted is below 1% of the generated, for both cases that don't have the waste optimization.

This is a good indicator, which highlights that the energy dispatcher works in a very efficient way and as it is supposed to. The reason is that, although the optimization functions don't include the waste directly, the most efficient way to increase the profit or the production is to waste as little as possible. The energy input must be distributed efficiently between the storage and the grid to maximize the other functions.

As a conclusion, the energy dispatcher is a very effective tool and depending on the impact of waste during further analyses (it must be kept in mind that this is just an arbitrary case), it might be the case that optimizing the waste does not have a great impact and thus, can be omitted, since the other functions are already doing it efficiently. Of course, the total energy produced is below the other two (8-9% less) and the profit is significantly lower (10-15%).

4.1.5.4 Spot market optimizing the CO_2

Although this plant uses renewable energy, there is a CO_2 factor associated with the energy that is generated by it. Likewise, buying electricity is another CO_2 emitting part, due to the grid being more or less carbon intensive. To take into account all these factors and to try to strive for a more sustainable future, there is a function minimizing the CO_2 production.

Similarly to the previous case, this objective function's intention is far from reaching top profits or production, which means that it moves away from the values achieved before (9-10% less production and 10-15% less profit).

As a comment, the hourly plots follow a similar behavior when compared to the waste optimization. There is no clear benefit from producing before or after other than buying electricity when the CO_2 factor is low. However, since the case analyzed is focused on only injecting power to the grid, there is no load to follow and thus, the dispatcher doesn't need to buy other than for trying not to waste the energy.

Because the latter is something added to the objective function as an extra condition, to penalize the CO_2 associated with wasting all that PV. Otherwise, the dispatcher was selecting to waste everything and to not produce anything at all, that way the CO_2 production was optimized to 0, the bare minimum. Therefore, it was needed to include that penalization factor to "tell" the optimizer that wasting energy can be even worse.

In conclusion, the CO_2 production is optimized as can be seen here:

Case	CO_2 produced (kg)
Optimizing profit	30.181.100
Optimizing production	25.577.689
Optimizing waste	27.295.139
Optimizing CO_2	24.378.982

Table 7 CO2 produced for the different cases

One important comment to be made here is the fact that the production is very similar for optimizing the CO_2 production and the profit because those 24-25 million kgs come from the hybrid plant generation itself. And that value is very similar in the end for all the cases, being the only difference the CO_2 generated by buying electricity.

Therefore, cases as optimizing the production in which the dispatcher chooses to buy as little electricity as possible have a very similar CO_2 total production. On the other hand, when optimizing the profit, the plant has to buy when the electricity is cheap to sell when it is expensive, and that means increasing the carbon dioxide production, as shown in the table.

As a conclusion, from optimizing the profit to optimizing the production the biggest difference is the electricity bought, and that can lead up to more than 15% less associated emissions. The CO_2 optimization increases that value to around 20%. Those are significant numbers that highlight the importance of the dispatcher and that will be brought up when designing and running more simulations.

4.1.6 Secondary and tertiary market impacts on the single simulation

When simulating the secondary and tertiary market, the impacts are noticeable when it comes to the profit.

Case	Profit (M€)	NPV (M€ considering 30 years of operation)
Spot market	104.82	423.12
Secondary market	210.15	1728.66
Tertiary market	123.28	651.73

Table 8 Profit and NPV for the markets

The fact of participating in other markets as an extra revenue stream with relevant values specially in the secondary market. When analyzed separately, the impact of the market is significant in the total final value.

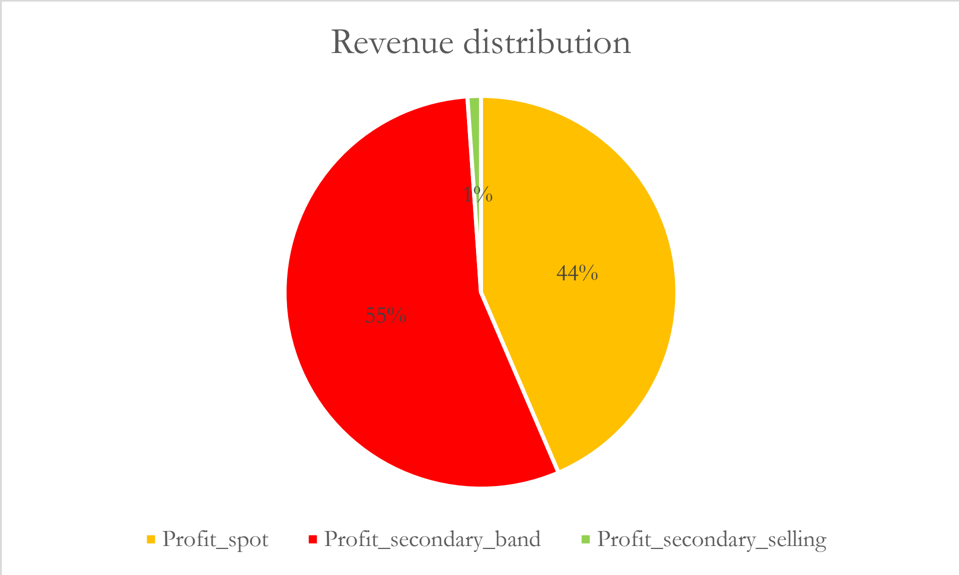

Figure 4-29 Revenue distribution for the secondary market case

There are two main contributors, one is the payment for being available, the revenue the plant gets for having capacity available during that day. The second is the actual revenue from selling in the spot market. Although the plant is participating in the secondary market it can still sell there, which is in the end a big part of the total revenue.

When it comes to the costs, the electricity bought is entirely in the spot market, the dispatcher decides not to participate in the secondary market for buying electricity, and that is basically due to the prices of the secondary market for buying being high.

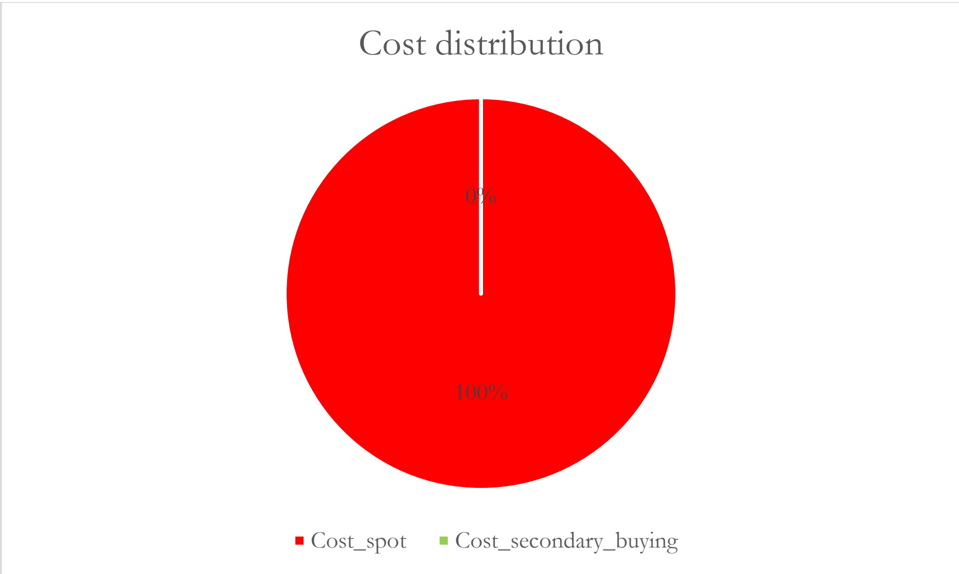

Figure 4-30 Cost distribution for the secondary market case

To have extra information, the prices of that market can be seen here:

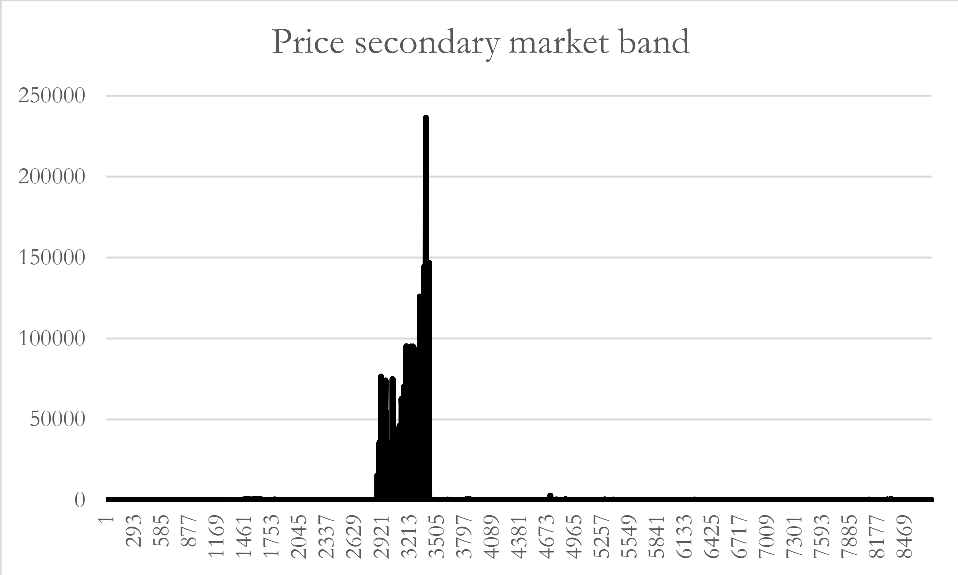

Figure 4-31 Price of the secondary market band

As can be seen, there are rocketing values during the month of May, which may have been affected by other price spikes in other sectors. This is probably a main contribution, but when the chart is zoomed in, it can also be seen that the prices are actually high, reaching average values of 250-300 €/MWh. For the spot price, there is an average of 150-200 €/MWh normally.

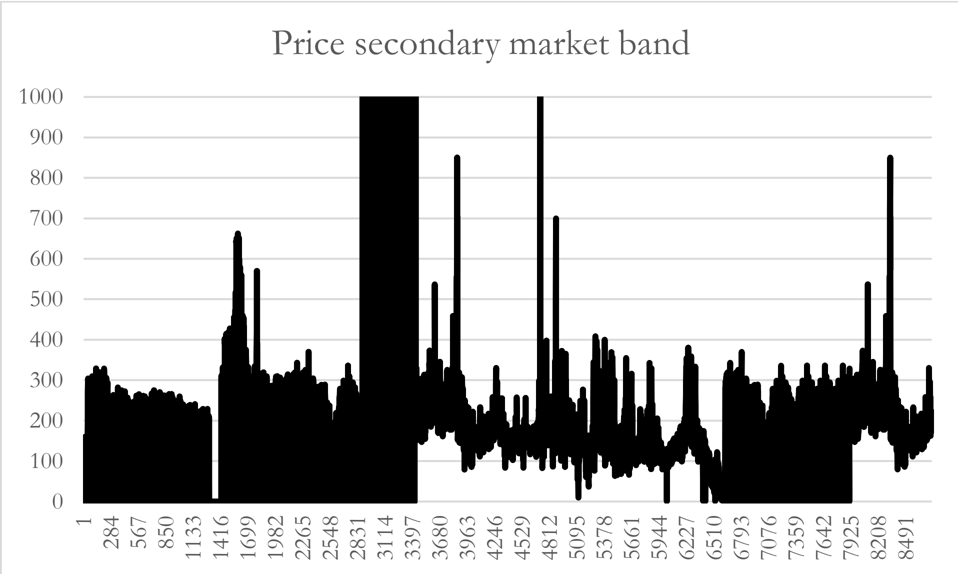

Figure 4-32 Price of the secondary market band zoomed in

On the actual price for selling electricity, the values are similar to the spot price:

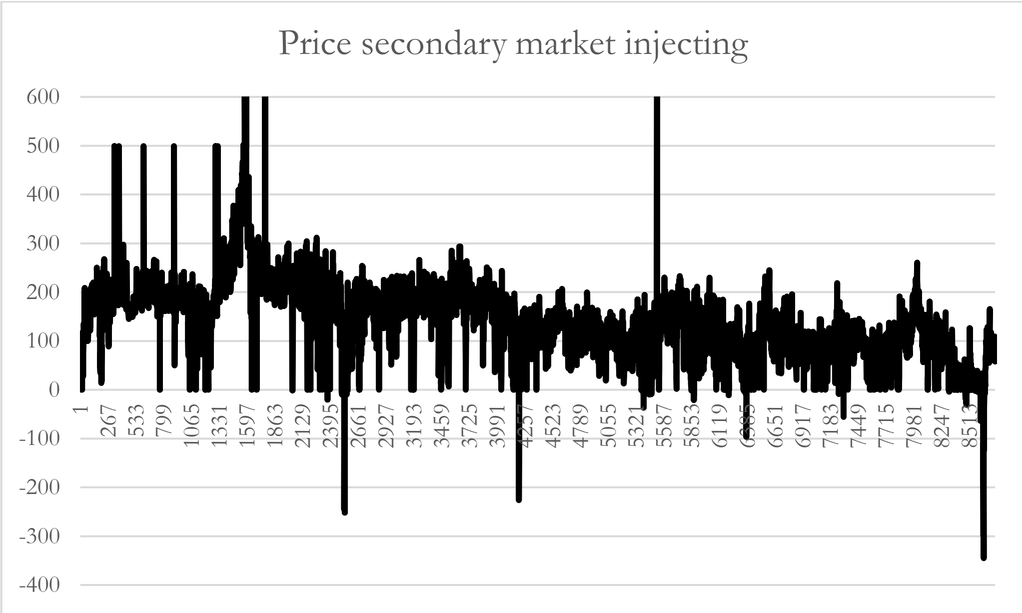

Figure 4-33 Price of the secondary market for injecting

The same applies to the price of the secondary market for purchasing energy:

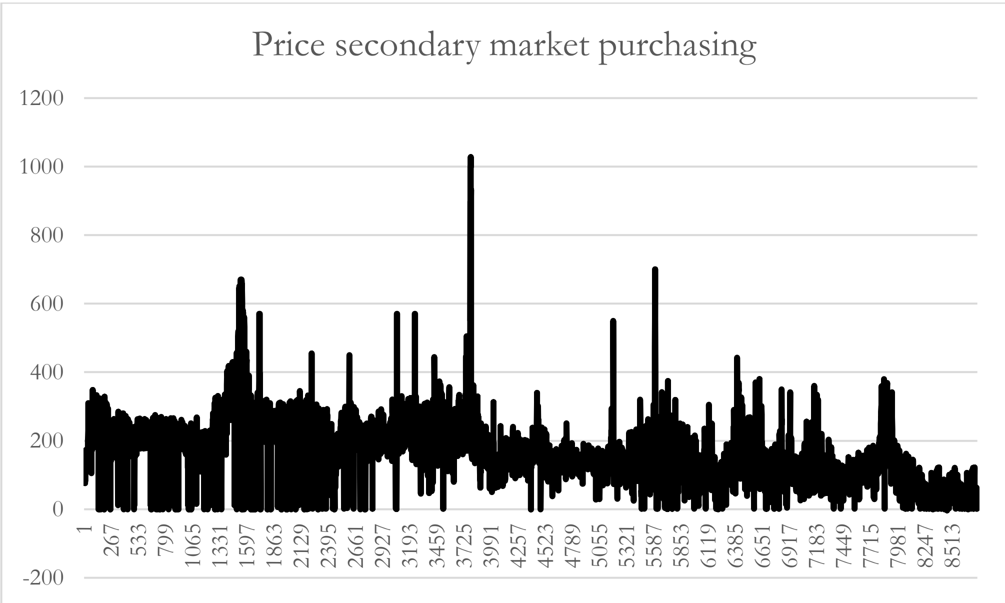

Figure 4-34 Price of the secondary market for purchasing

When analyzing the tertiary market, there are similar price curves there.

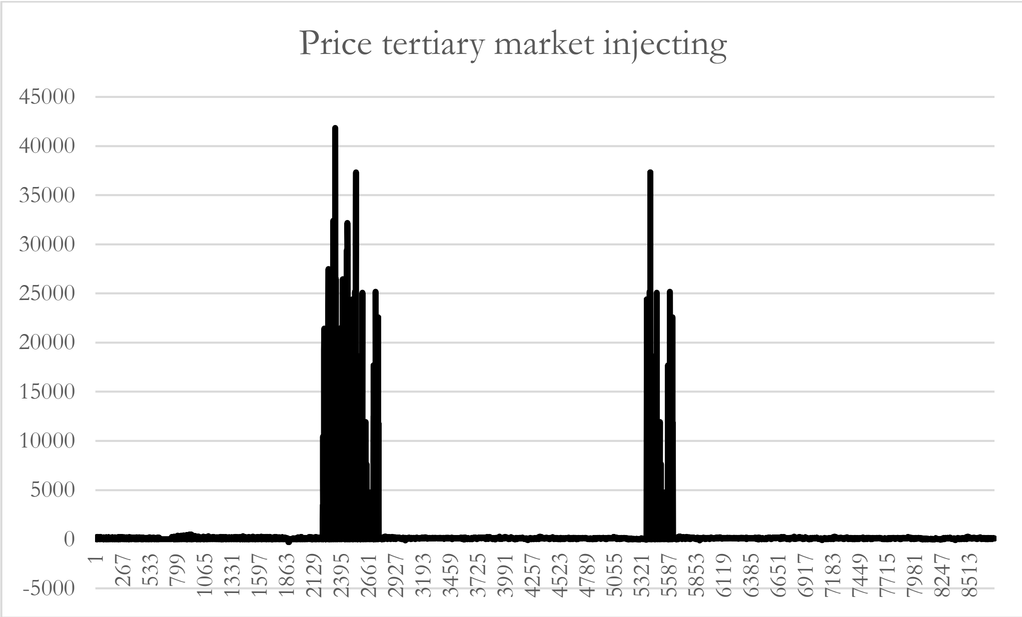

Figure 4-35 Price of the tertiary market for injecting

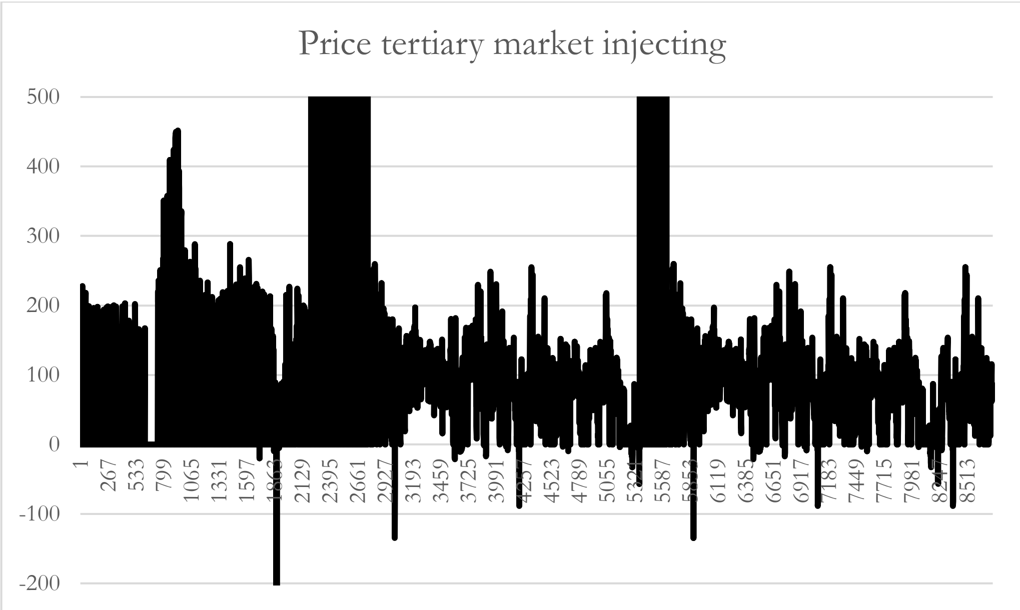

Figure 4-36 Price of the tertiary market for injecting zoomed in

For the purchasing values, the data is the following:

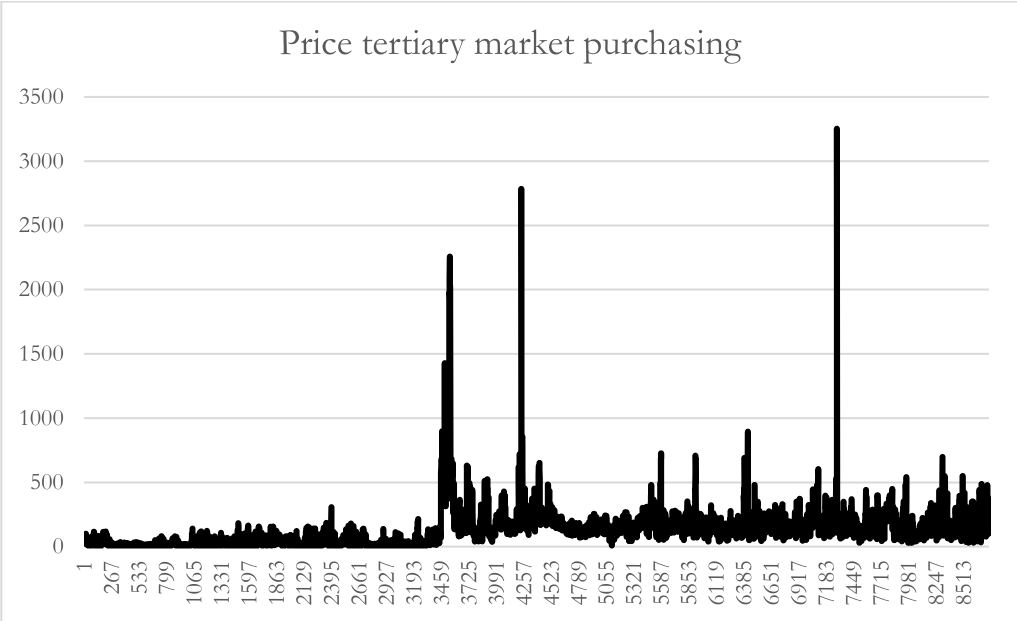

Figure 4-37 Price of the tertiary market for purchasing

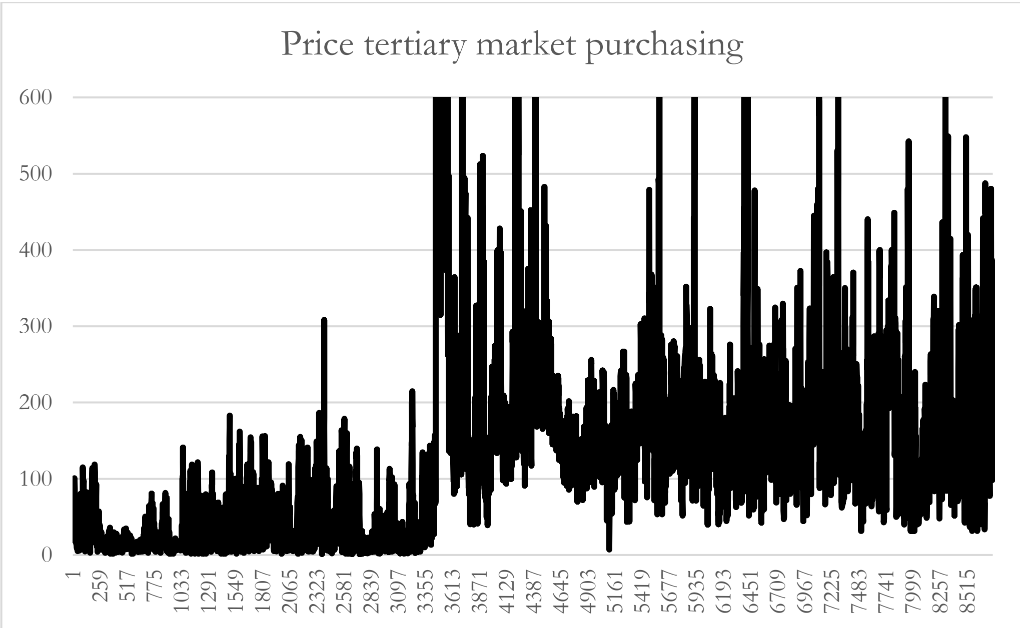

Figure 4-38 Price of the tertiary market for purchasing zoomed in

When it comes to the revenue and cost distribution, now the profit from selling energy in the actual tertiary market increases its share.

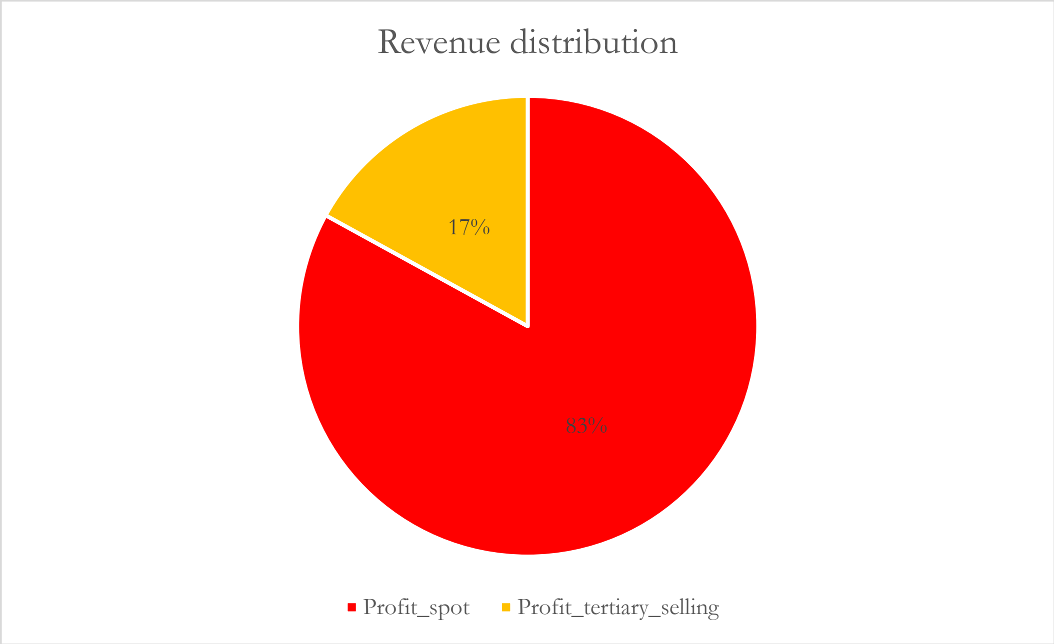

Figure 4-39 Revenue distribution for the tertiary market

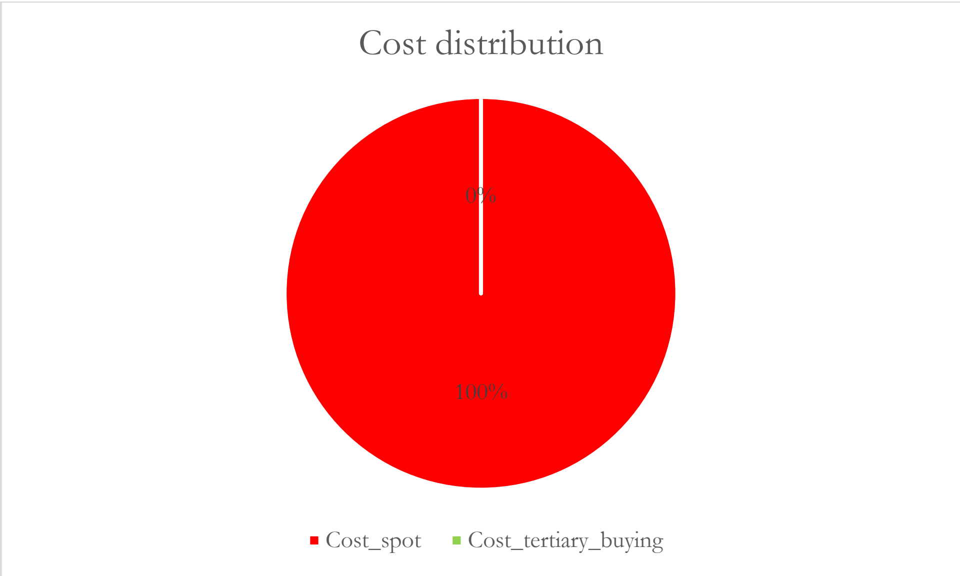

Figure 4-40 Cost distribution for the tertiary market

Likewise, the dispatcher decides not to buy from the tertiary market, with the only electricity purchased coming from the spot market.

4.1.7 Design optimization

After analyzing one by one the specific options and their impacts, it is time to move on to the design optimization, in which the focus will be turned to the bigger picture. The figures won't be based on hourly values, rather on yearly ones. There will be pareto front studies in which trends will be identified and analyzed.

The cases that are presented are the profit and the production optimization. Although the waste and CO_2 optimization have proven to be very relevant for reaching a more sustainable and efficient power plant, the main focus of the thesis is on other KPIs more important for the industry, such as the LCOE or the NPV. That is the reason why it is more relevant to omit them for this part of the study, and to introduce them later on whenever the case when it is needed emerges.

4.1.7.1 Spot market optimizing the profit

On the spot market optimizing the profit from the plant, one of the most important KPIs to be checked is obviously the NPV. It is calculated as follows:

$$NPV = \frac{Cashflow_1}{(1+r)^1} + \frac{Cashflow_2}{(1+r)^2} + \cdots \frac{Cashflow_n}{(1+r)^n} - CAPEX$$

Before showing the results, it is important to mention that this simulation has been conducted with a maximum power that can be injected into the grid of 100 MWe and with a simple sCO_2 cycle (no reheat, recompression…). In addition, in this case the possibility of having BESS has been considered, to get the full picture of what is profitable and what is not. Obviously, the optimization tool has been set with proper boundaries, so that in case it is better to have no BESS the tool can do it. The same applies to the TES, PV, SM (Solar Multiple) and EH.

And after running the optimization code with the genetic algorithm, the results are the following.

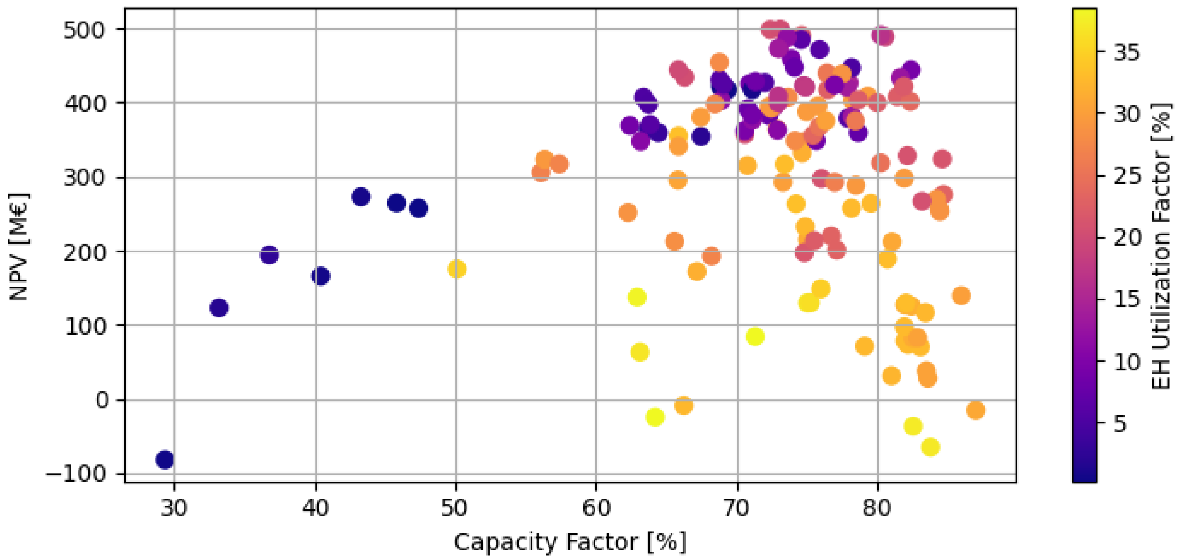

Figure 4-41 NPV vs CF with EH Utilization Factor

First, the pareto front can be clearly seen with a peak or optimum achieved around 73% CF and then going down the higher the CF, which highlights the tradeoff situation, in which the higher the CF doesn't mean the better in terms of NPV.

When it comes to the EH Utilization Factor, the values are scattered and actually, the higher ones correspond to lower NPV. This makes sense because the more you use it the more energy you are diverging from the PV production to the TES, and that means adding many losses on the way, the opposite to just injecting to the grid the PV electricity. On the other hand, buying electricity for the EH is the same case but now paying for that electricity, which although should be at a lower price (the dispatcher optimizes the profit), the losses and other costs make it less profitable.

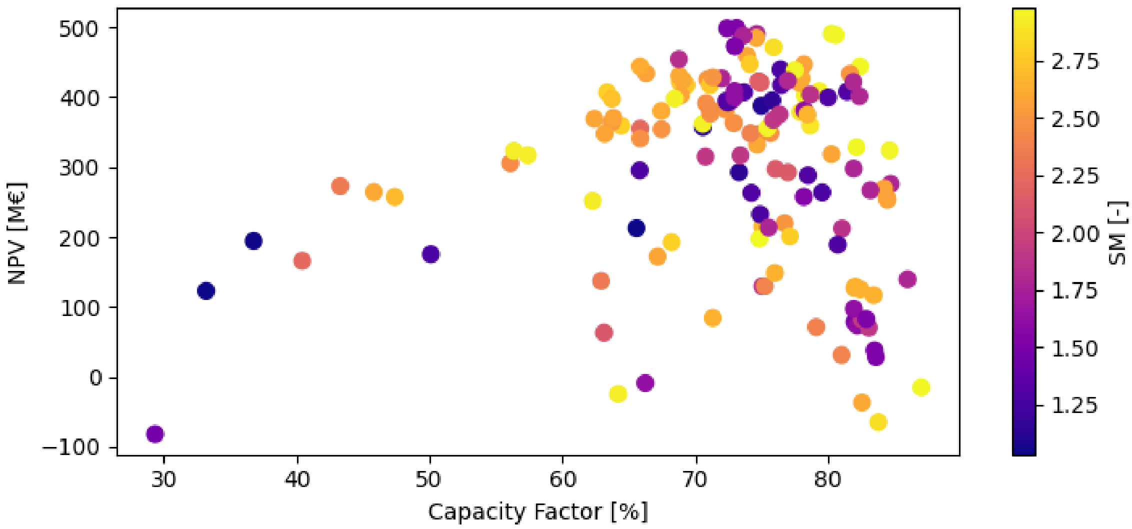

Figure 4-42 NPV vs CF with SM

Another relevant factor to highlight is that the SM values are dispersed along the pareto front, one might find a SM of 2.5 and another of 1.5 very close to each other. That means that the size of the field is not the decisive factor when it comes to optimizing NPV and CF. The contrary can be seen by analyzing the size of the PV capacity.

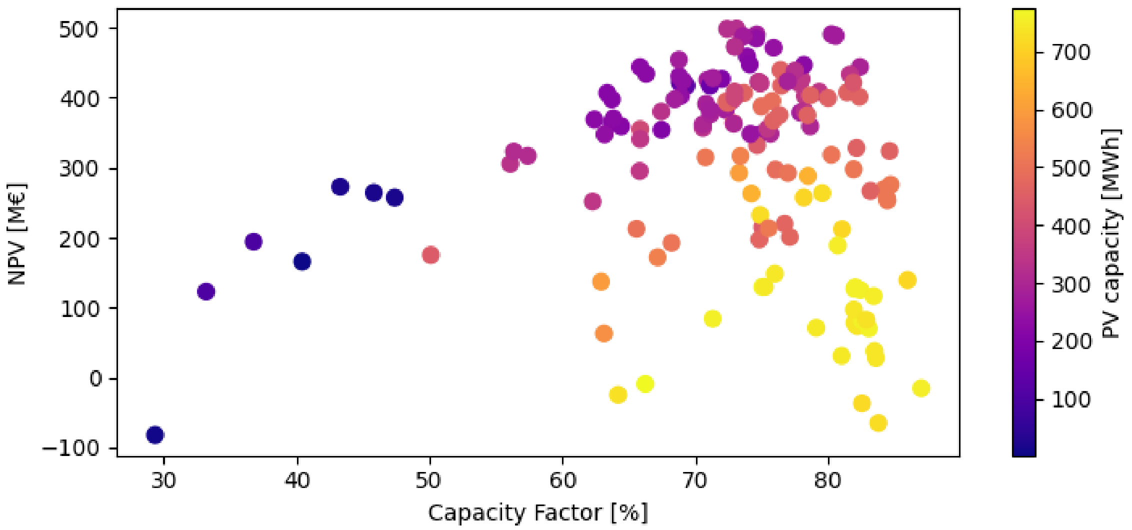

Figure 4-43 NPV vs CF with PV Capacity

The clear optimum for the PV capacity is around 200-300 MWh, which is 2 or 3 times the maximum power that can be injected to the grid. One can be seen that below those values the capacity factor drops significantly to values below 50 %, and above that capacity the plant reaches a limit in the capacity factor and starts to be way more expensive, dropping the NPV.

Therefore, there is a compromise solution in which although the PV part is the cheap one of the hybrid power plant, there is a point after which it is not profitable to install any more capacity.

A similar behavior can be seen when analyzing the PB installed capacity.

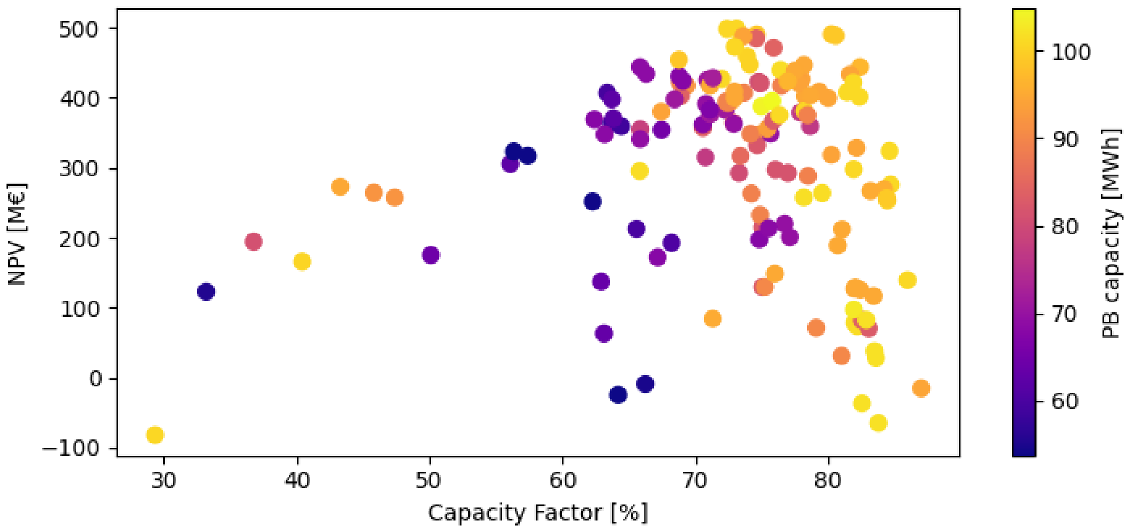

Figure 4-44 NPV vs CF with PB capacity

Since the power that can be injected to the grid is of 100 MWe, it makes sense to have the PB installed capacity (the figure shows gross capacity) as close as possible to that value, so that when having to discharge the TES the power plant can produce the maximum power at nominal rate. Otherwise, in the case of having to generate during the night when there is no PV, the plant would only be able to provide a fraction of the injection limit, which is not very efficient, to have a 100 MWe connection to only be able to use it at some points of the day/year.

Looking now at the storage, both BESS and TES are included in the desired solution and along the pareto front, as can be seen in the next two figures.

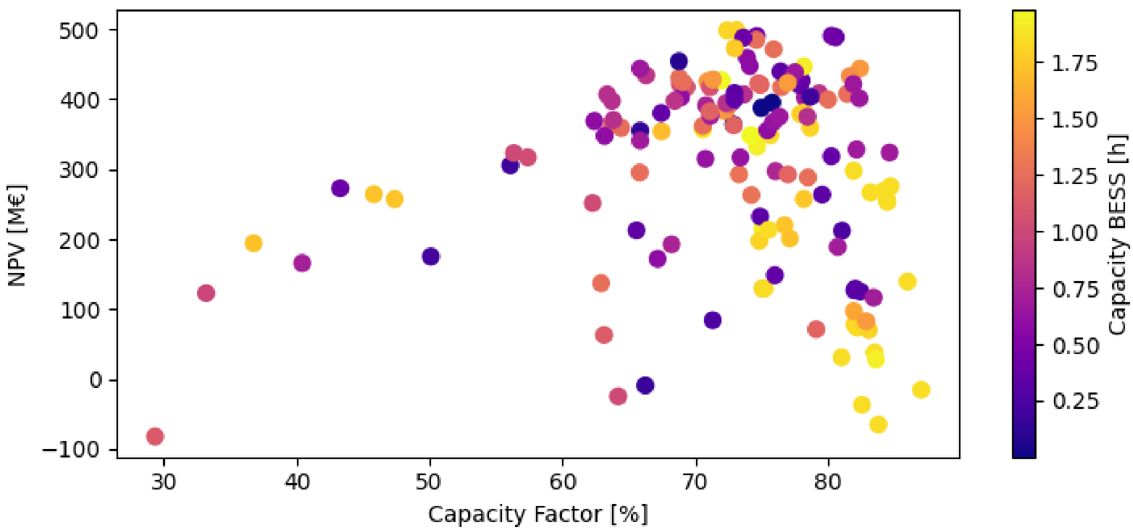

Figure 4-45 NPV vs CF with BESS capacity

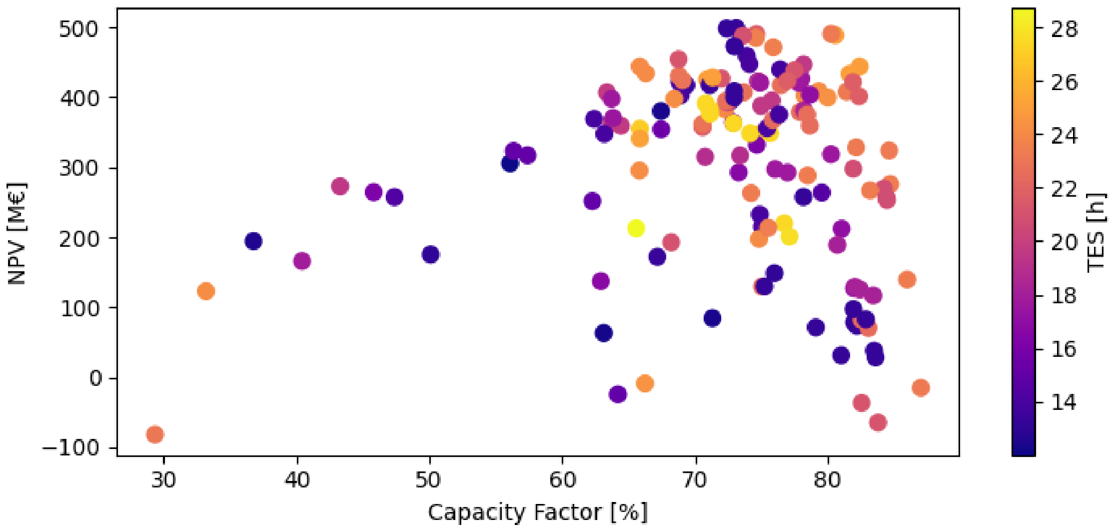

Figure 4-46 NPV vs CF with TES capacity

As can be seen, there is no clear trend for either case. Both storage systems have diverse values along the pareto front, in which one can find an effective design with 14 hours of TES and 2 hours of BESS and then, right next to it, another effective one with 24 hours of TES and 1 hour of BESS.

What is clear, and can be extracted from these charts, is that there is a need for some kind of storage, it adds the required flexibility to be able to effectively use the solar resource. Of course, it helps enormously with the dispatching operation, reducing its inherent intermittency.

To finalize this chapter, it can be seen that there is a clear connection between the LCOE and the NPV, in which the values optimizing one also optimize the other. In the end, although the LCOE only takes into account the energy produced, it is clear that the more you produce the more you can sell and thus, the higher your NPV due to the revenue coming from the grid. The same applies to the CAPEX and OPEX, and the same behavior in regards to them can be expected in both KPIs, due to having them as a negative factor.

The following charts highlight the same that has been mentioned for the NPV, which makes it clear that optimizing one means optimizing the other.

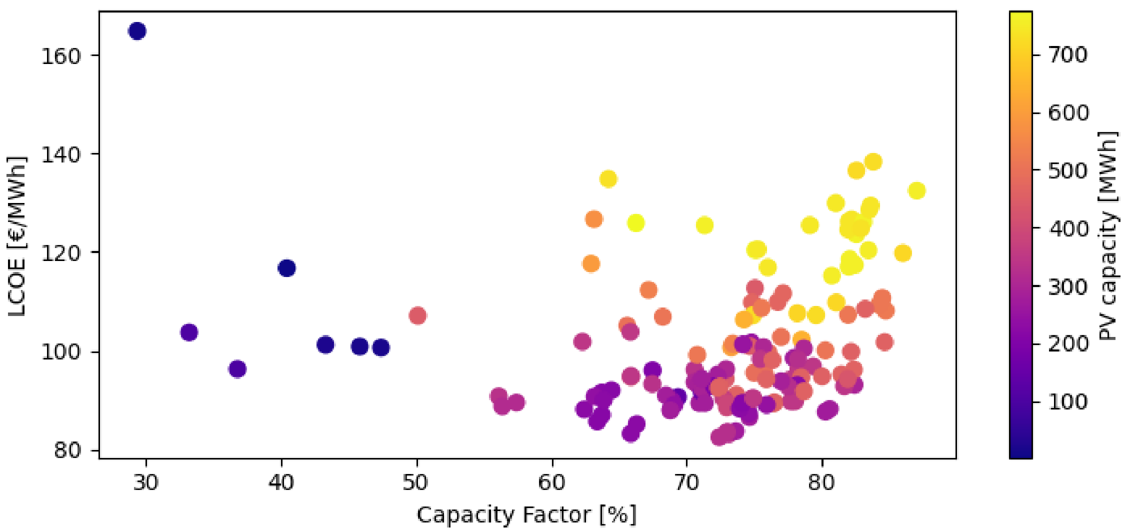

Figure 4-47 LCOE vs CF with PV capacity

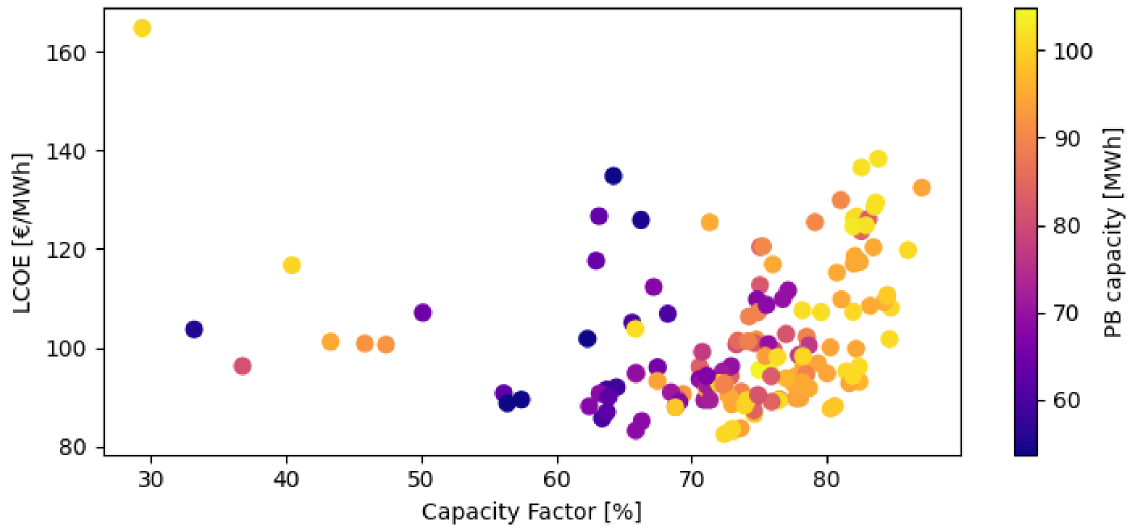

Figure 4-48 LCOE vs CF with PB capacity

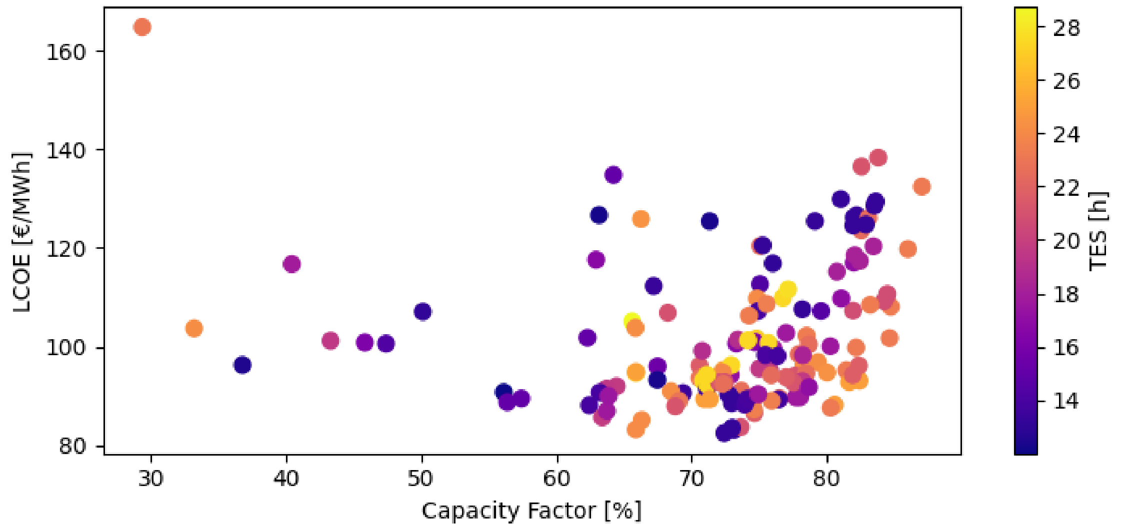

Figure 4-49 LCOE vs CF with TES capacity

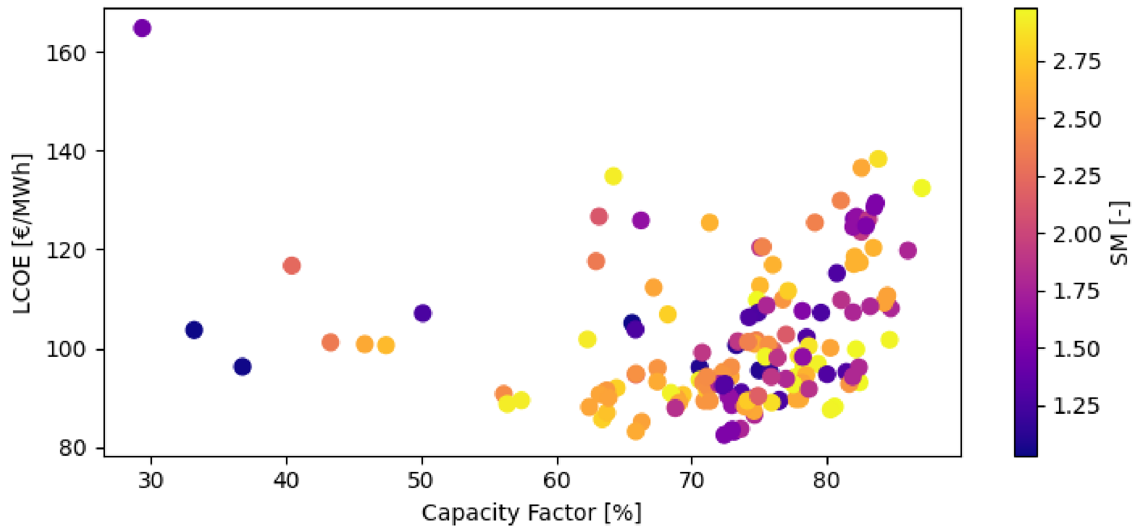

Figure 4-50 LCOE vs CF with SM

As can be seen, the behavior is exactly the same if the figures are compared to the ones with NPV on the vertical axis.

4.1.7.2 Spot market optimizing the production

In this simulation, a similar result can be expected but with lower NPV, since the objective is now to optimize just the production. The LCOE can also be expected to be lower (better), due to producing more or in a more efficient way.

For example, here can be seen the same behavior for the PV and PB installed capacity as before.

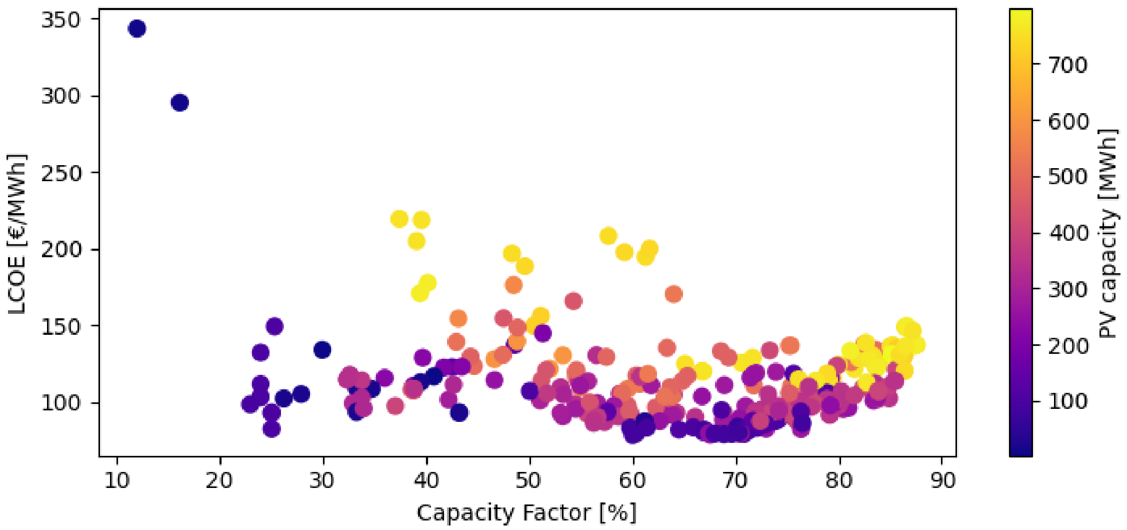

Figure 4-51 LCOE vs CF with PV capacity

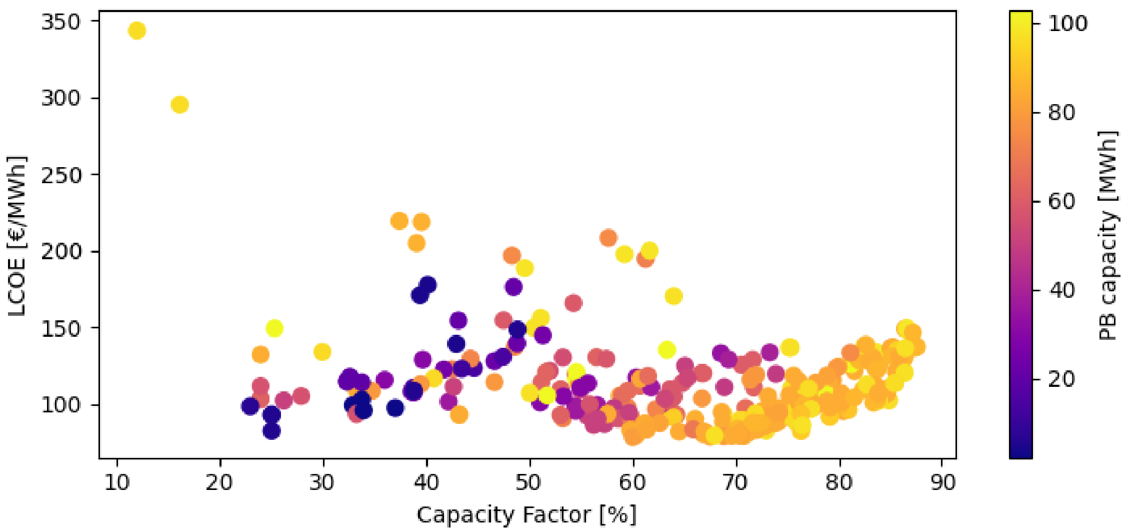

Figure 4-52 LCOE vs CF with PB capacity

The only slight difference is in the fact that the PV capacity has now lower values for the optimum case. This is due to the fact that now there is no need to produce at a precise moment with a precise power, which would require some sort of extra production and storage. Therefore, with this case the hybrid plant only needs to have enough PV installed to ensure all the energy is sent to the grid in the most efficient way, to have more might mean needing to store it and then sending it to the grid, with the consequent losses.

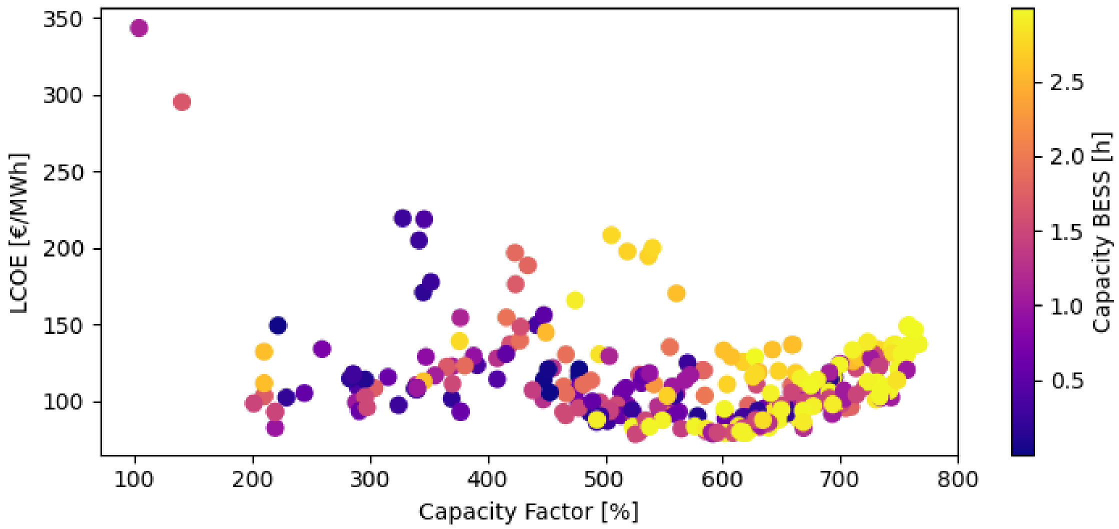

Figure 4-53 LCOE vs CF with BESS capacity

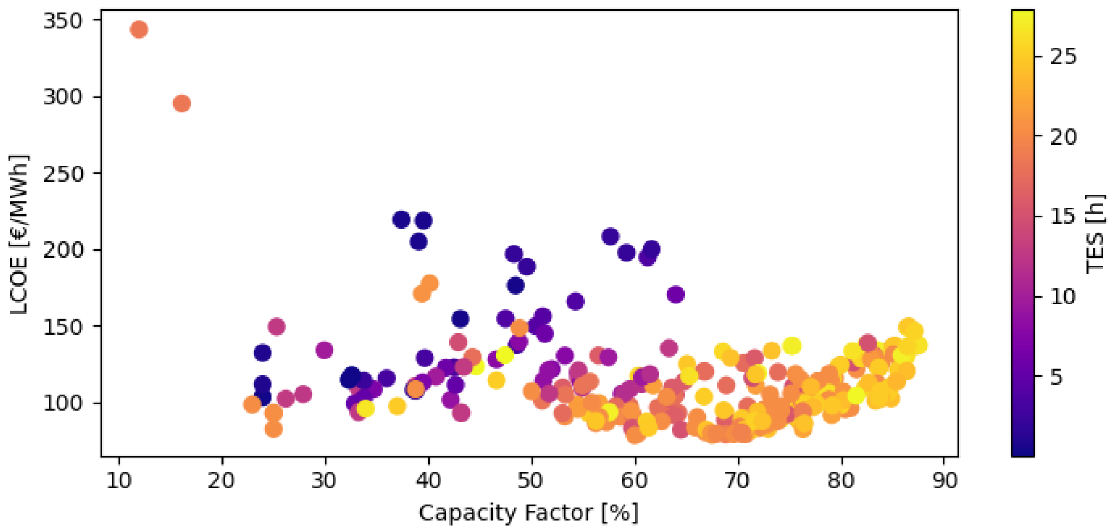

Figure 4-54 LCOE vs CF with TES capacity

Oppositely to what was shown before, now the TES capacity needs to be on the high side of the bounds, always being around 20h of storage for the best cases. A similar behavior is seen in the BESS but not quite the same, because it can be seen that there are cases on the pareto front with either 1.5 or 3 hours of storage. This underlines that the TES is a more cost-efficient storage and a more important part of the hybrid plant. Even though the BESS capacity is higher or lower, the TES stays always high to provide the storage needed for maximizing the production.

Another important fact to highlight is that the SM tends to be high for the pareto front, which means having a bigger field and thus needing to store more of that energy. That can be seen in the next figure.

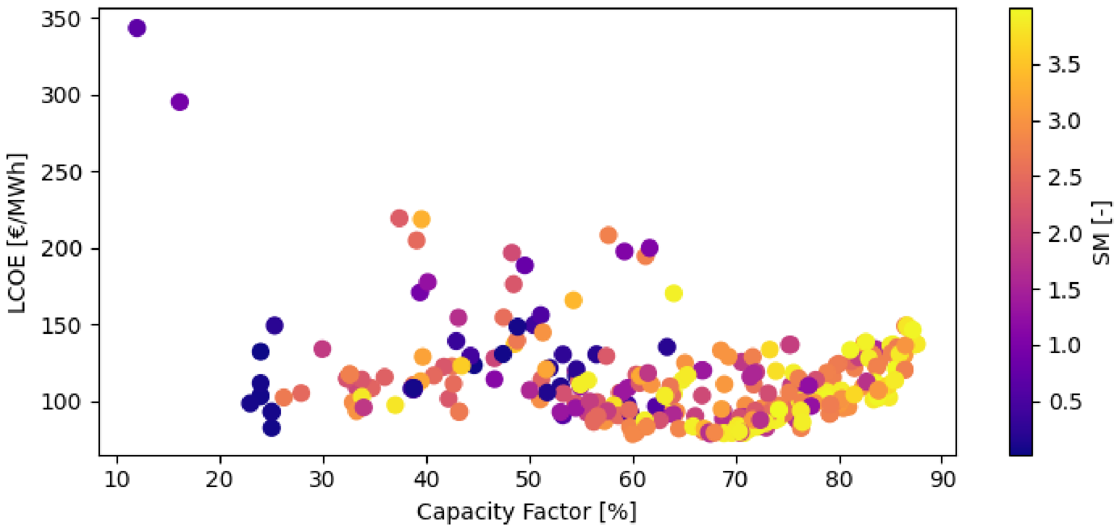

Figure 4-55 LCOE vs CF with SM

To conclude this section, the next figure shows how the EH Utilization Factor becomes low for the pareto front in this case. The reason is clear and that is that the PV installed capacity is on the low side, and knowing that it is not efficient to buy energy for the EH, the only source that remains for powering it is the PV. Consequently, having a relatively small PV field, the EH is not being massively used.

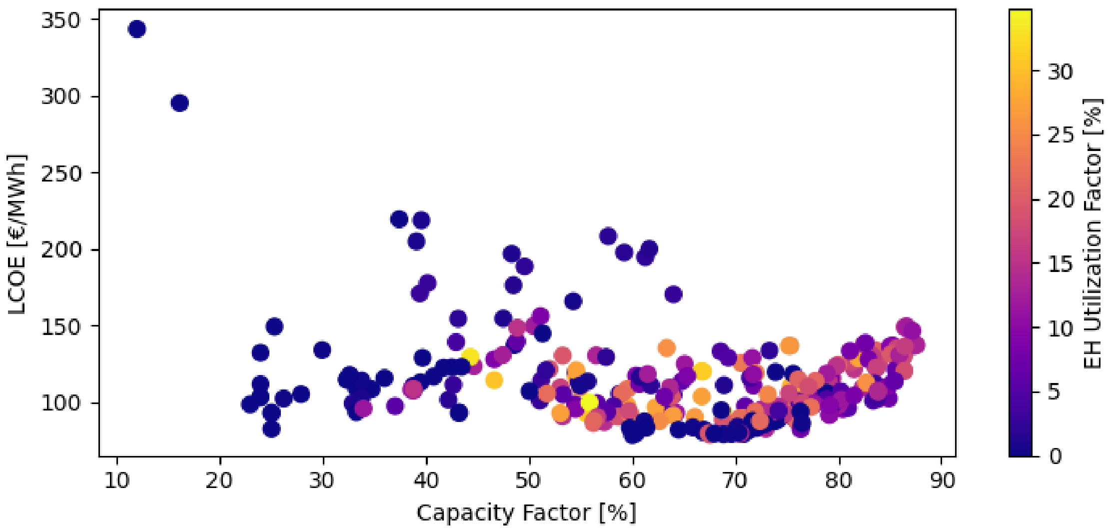

Figure 4-56 LCOE vs CF with EH Utilization Factor

In order to avoid repetition, the NPV charts are not shown for this case.

To conclude this part, here is a comparison table for the optimum values found in both cases, so that a clearer understanding is reached. Otherwise, all the scatter plots only give an idea about the trends.

Variable	Optimizing profit	Optimizing production
AEY [GWh]	640.42	525.96
CF [%]	73 %	60%

LCOE [€/MWh]	**83.14**	**78.34**
EH Utilization Factor [%]	20.38	0.02
Energy Wasted [GWh]	8.5	3.59
CO_2 production [ton CO_2]	36.29	23.02
NPV [Million €]	**499**	**427.6**
SM [-]	1.53	2.86
TES capacity [h]	13.2	20.3
PB gross capacity [MW]	100.67	80.25
PV capacity [MW]	323.6	88.28
BESS capacity [h]	1.815	1.488

Table 9 Comparison between optimization strategies

The first key values to highlight are the NPV and the LCOE, the NPV is clearly higher when optimizing the profit, because the dispatcher focuses on that. For the LCOE, the value is also clearly lower for the production optimization, because what is important for the LCOE is the total energy produced with a defined CAPEX and OPEX, the more the better.

Another important value is the EH Utilization Factor, it is not used for the case optimizing the production because there is no electricity bought and whenever there is extra PV production it goes to the BESS instead of to the EH, it is better in terms of losses.

The Solar Multiple is higher for the case optimizing the production, as well as the TES capacity. The reason is that over dimensioning the field and the TES gives the plant the possibility of produce almost all day long and maximize the resource usage, whereas when optimizing the revenue it is not that profitable to be producing all day long, it is better to do it at precise moments of the day.

Another interesting fact is the PB gross capacity being lower for the case optimizing the production, and that must be because that case reduces CAPEX and OPEX still reaching high production values. The main reason is having a big storage capacity, which can have the energy there for a long time.

To avoid confusion, the optimization tool with the genetic algorithm is optimizing the LCOE and the CF but the dispatcher itself is the tool that optimizes either the profit or the production, and that is done in two steps, as explained before.

4.1.7.3 Secondary market optimizing the profit

Since the solar input is the same and there is no change in the operating variables of the plant, it can be assumed that the case optimizing the production would be exactly the same. Consequently, the only relevant case is the one optimizing the profit, because that is where the Dispatcher has the possibility to have a bigger impact, acting according to the secondary market possibilities.

Indeed, the same analysis was carried out and the results are really promising, with NPV values way above the ones obtained in the spot market. The next figure highlights that, with a similar trend when compared with the one seen before.

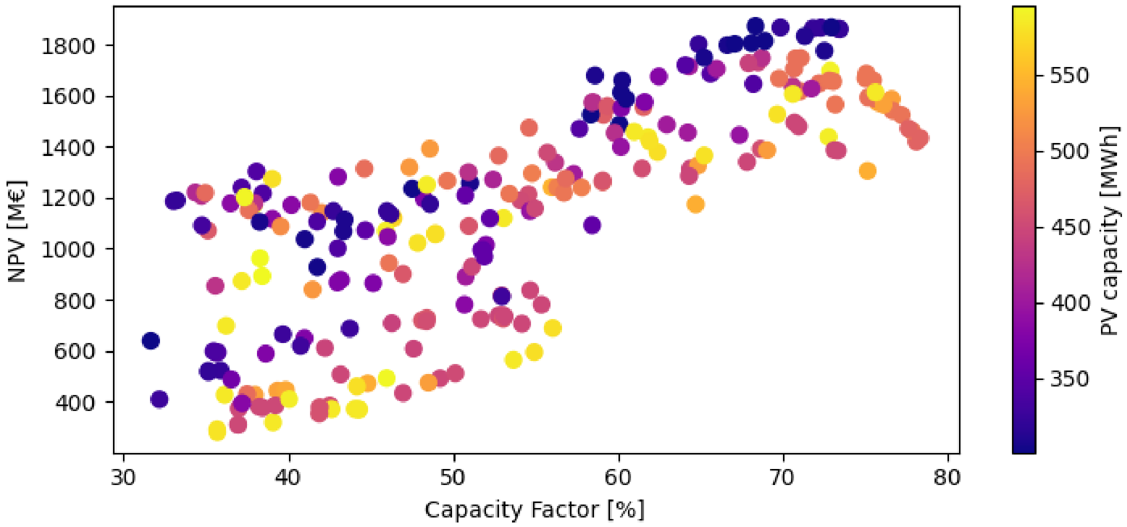

Figure 4-57 NPV vs CF with PV capacity

As can be seen, for optimizing the profit the PV capacity stays again on the lower side of the boundaries. This is due to prioritizing just selling the PV electricity to the grid and not using the EH and minimizing the BESS usage.

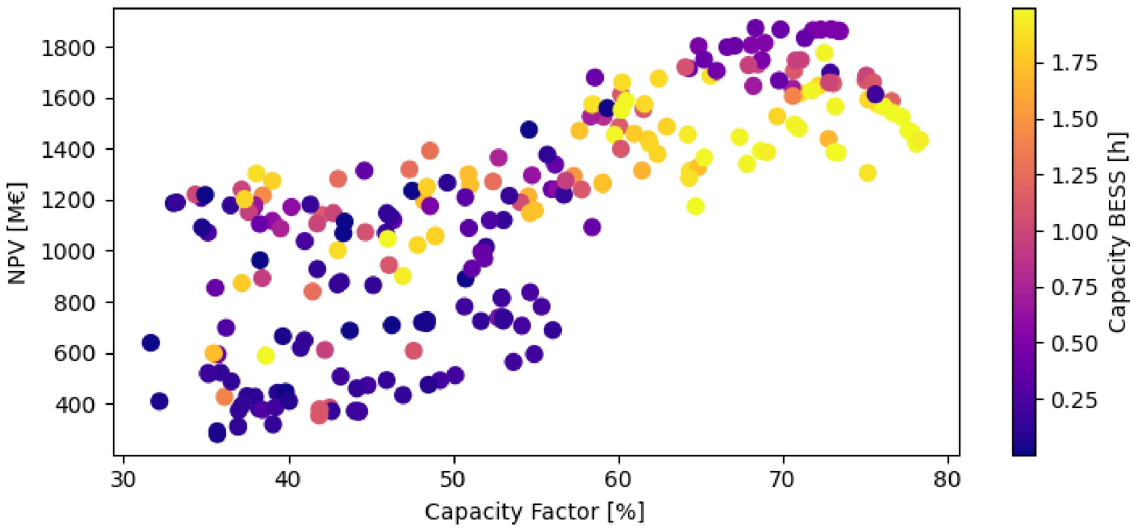

Figure 4-58 NPV vs CF with BESS capacity

As an example, the previous figure highlights the fact that the BESS capacity becomes low, the higher values are creating a lower NPV, and the optimum ones stay on the low side, having just around 1 hour of storage. The same applies to the EH, which is shown in the next figure, having just around a 25% utilization factor.

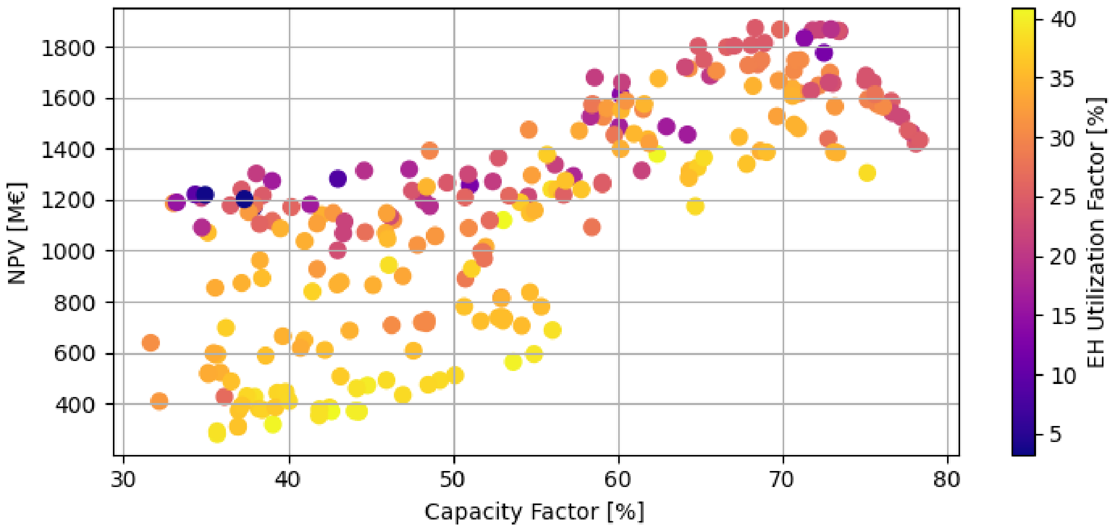

Figure 4-59 NPV vs CF with EH Utilization Factor

Again, the PB capacity tends to stay on the higher side for the same reasons stated previously.

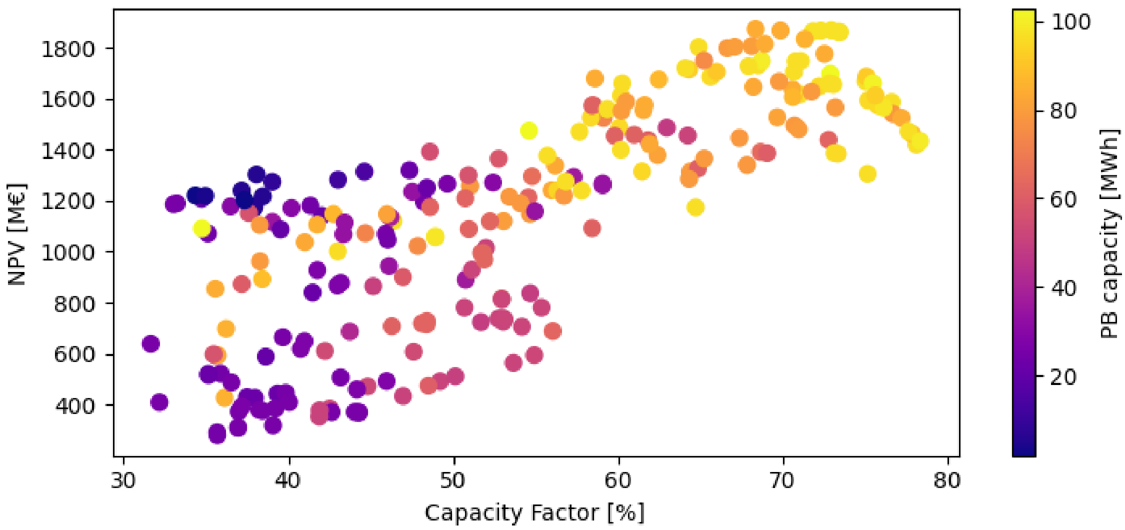

Figure 4-60 NPV vs CF with PB capacity

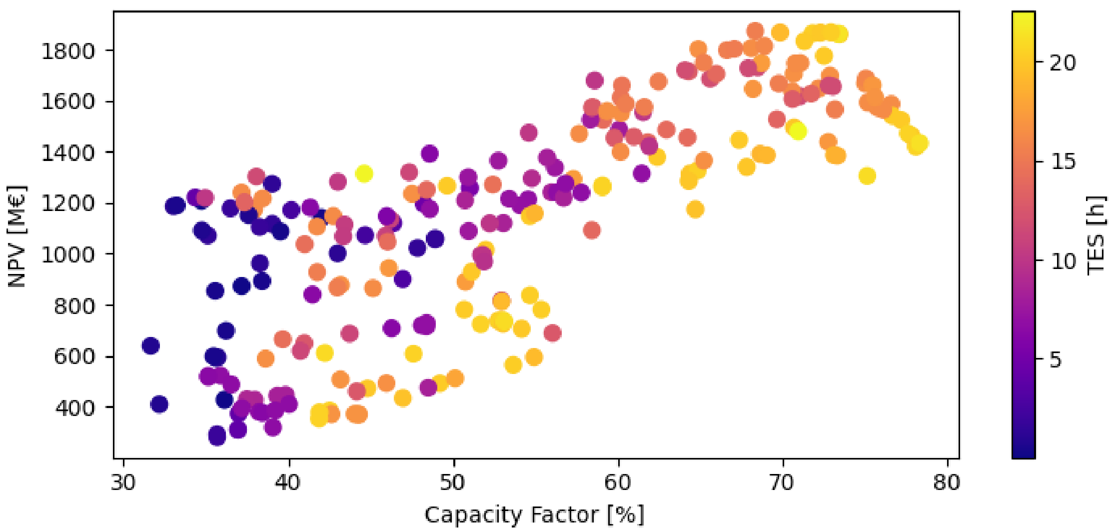

Figure 4-61 NPV vs CF with TES capacity

And a similar behavior is also seen for the TES, staying on the high side due to needing that flexibility to produce whenever is better from a profit perspective.

The most important part comes when analyzing the best absolute values and comparing them with the previous case of the spot market, which is done in the next table.

Variable	Optimizing profit spot market	Optimizing profit secondary market
AEY [GWh]	640.42	598.74
CF [%]	73 %	68.35%
LCOE [€/MWh]	**83.14**	**87.18**
EH Utilization Factor [%]	20.38	24.52
Energy Wasted [GWh]	8.5	155.74
CO_2 production [ton CO_2]	36.29	2.416
NPV [Million €]	**499**	**1873**
SM [-]	1.53	2.2
TES capacity [h]	13.2	15.35
PB gross capacity [MW]	100.67	84.258
PV capacity [MW]	323.6	302.34
BESS capacity [h]	1.815	0.4

Table 10 Comparison between markets

The first clear and most important difference is the NPV, the plant working in the secondary market reaches a value of 1873 million euros of revenue after the 30 years of operation, compared to the 499 in the spot market. It is almost 4 times more NPV, which is obviously super relevant for their techno-economic assessment.

Secondly, the LCOE increases to 87 €/MWh, which is a high value that shows that even though LCOE and NPV are related, participating in the secondary market would mean being less effective in terms of the energy produced for a fixed CAPEX and OPEX. And the reason is obvious, in the secondary market the plant is obligated to produce less than the spot market injection limit, and that undermines its total production.

The third key part is that having to produce less than the injection limit during many days of the year leads to wasting way more energy than in the previous case. The extra energy that is not sold to the grid is not stored because it is just more profitable to waste it, instead of increasing, for example, the BESS size.

The other values are relatively similar to the ones seen in the spot market, as for example the TES size or the SM.

As a conclusion, participating in the secondary market becomes a great revenue source and a really interesting option for these hybrid power plants. It can play a key role in the future integration of the plants to the grid, becoming a win-win situation where the plant benefits from the prices paid in that market and the grid benefits from the service that the hybrid plant can provide.

4.1.7.4 Tertiary market optimizing the profit

When the same analysis is performed for the tertiary market, the results show a similar behavior for all variables again. Starting with the PV and the PB capacities, the trends are the same, with the PV staying on the low side, around 300 MW and the PB on the high side slightly above 100 MW.

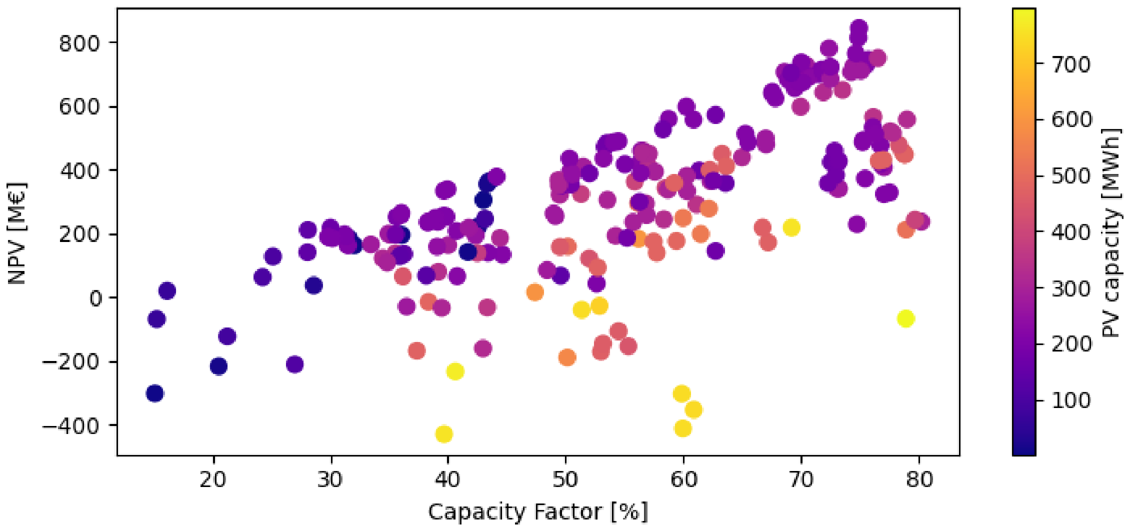

Figure 4-62 NPV vs CF with PV capacity

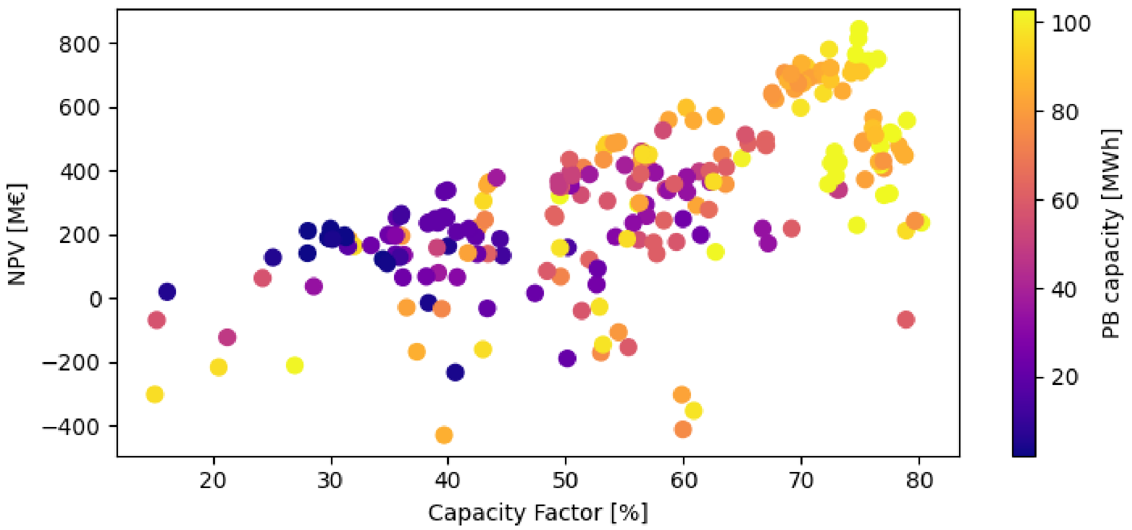

Figure 4-63 NPV vs CF with PB capacity

The storage sizes are taking similar values, with the TES being the most important and bigger one and the BESS staying with a small size.

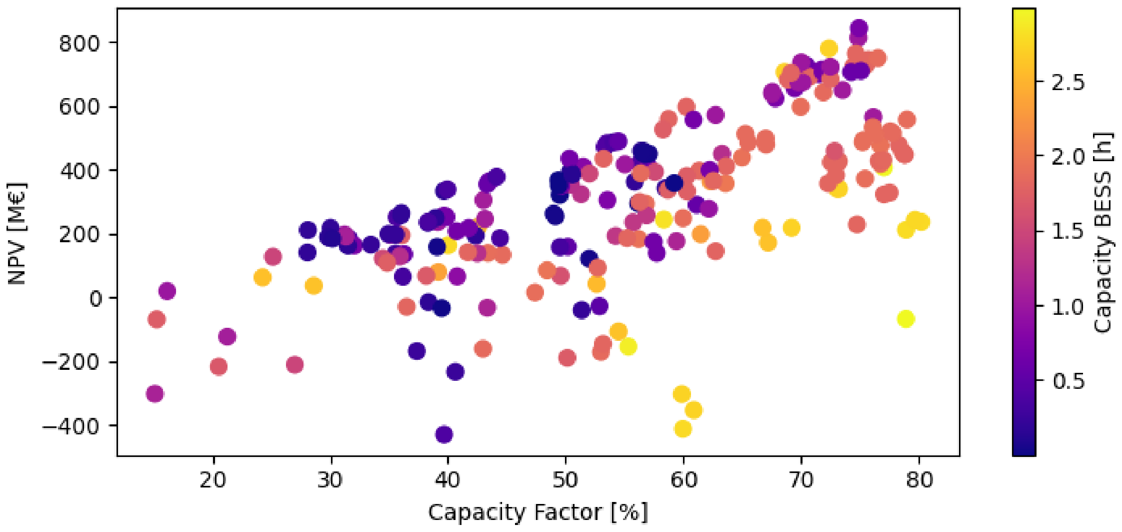

Figure 4-64 NPV vs CF with BESS capacity

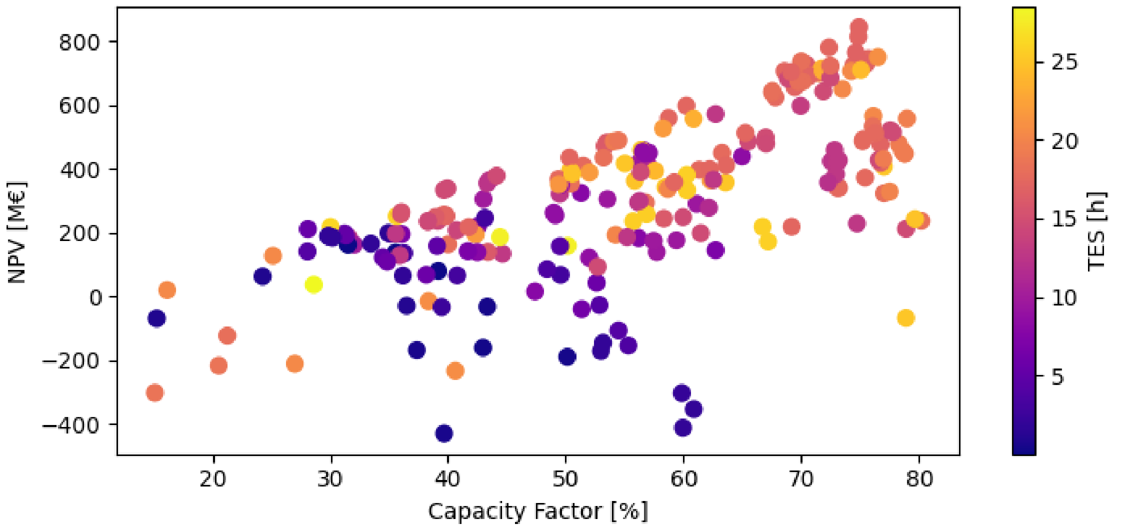

Figure 4-65 NPV vs CF with TES capacity

To conclude, the EH Utilization Factor stays on the low side of the boundaries finding the optimum for values around 15-25%, whereas the SM stays clearly on 2.5-3.

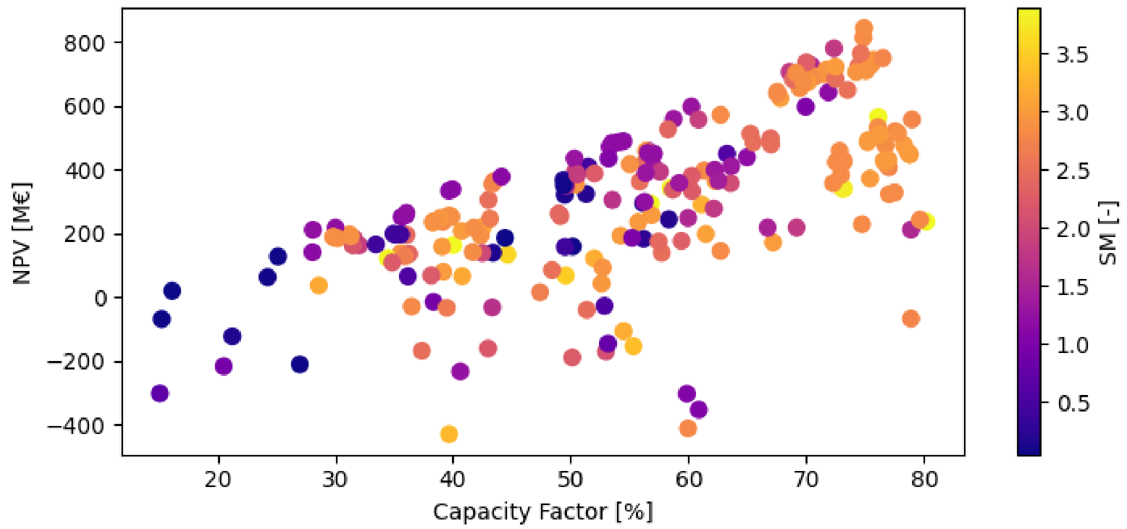

Figure 4-66 NPV vs CF with SM

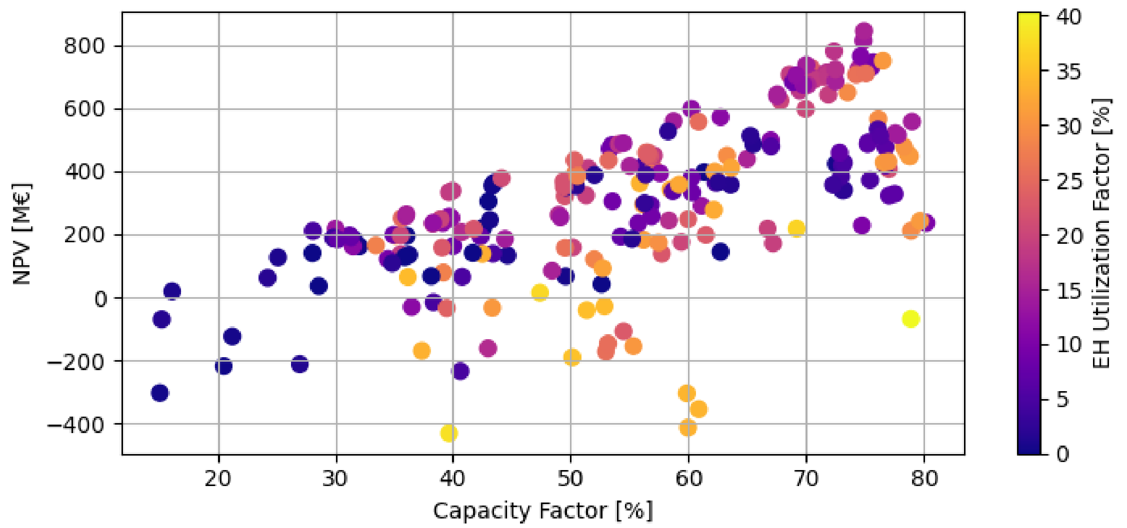

Figure 4-67 NPV vs CF with EH Utilization Factor

When it comes to the absolute values of the optimum, it is important to compare it with the results obtained in the spot and the secondary market. Nonetheless, as forecasted during the single simulation, the tertiary market gives a profit in the middle of the spot and the secondary, which can already be seen in the previous figures. The next table highlights the most important values:

Variable	Optimizing profit spot market	Optimizing profit secondary market	Optimizing profit tertiary market
AEY [GWh]	640.42	598.74	656.19
CF [%]	73 %	68.35%	74.9
LCOE [€/MWh]	**83.14**	**87.18**	**80.63**
EH Utilization Factor [%]	20.38	24.52	15.25

Energy Wasted [GWh]	8.5	155.74	225.33
CO_2 production [ton CO_2]	36.29	2.416	34.39
NPV [Million €]	**499**	**1873**	**843.36**
SM [-]	1.53	2.2	2.85
TES capacity [h]	13.2	15.35	17.07
PB gross capacity [MW]	100.67	84.258	102.87
PV capacity [MW]	323.6	302.34	208.51
BESS capacity [h]	1.815	0.4	0.725

Table 11 Comparison between markets

The most important value to compare here is the NPV, which is almost double the one in the spot market but less than half the one found in the secondary market. Another key difference is the Energy Wasted, which increases a lot for this case, due to the same fact that was mentioned before, the plant can't generate the nominal value during many days because it needs to be prepared for the tertiary market response. The PB stays producing below the nominal and whenever there is the signal from the tertiary market that it needs extra power, the PB increases it.

On the other variables, the values keep taking similar values, with the SM being higher, which corresponds to the shown big energy waste, or the PV capacity going down to avoid losing it due to having a low BESS capacity and having losses with the EH.

In conclusion, all three markets have been studied in detail with general optimizations using the genetic algorithm. The secondary market shows the biggest potential whereas the tertiary has also the potential to increase the revenue of the plant by almost 100 %.

Of course, the analysis has been conducted in a precise location for a precise electricity market with its peculiar behaviors. However, what is indisputable is the potential that a hybrid PV-CSP power plant has for participating in service markets, due to integrating the TES and the EH.

When one thinks about the most common power plants, storing energy at a low cost during a long period of time is almost unattainable for many of them. There are storage banks for that purpose or there is pumped hydro and not many more. This technology could pave the way for the future of the electricity grid, with bigger renewable penetration and thus, bigger intermittency, that leads to needing these services.

5 Conclusion and future steps

5.1 Conclusion

In this thesis, a complete Energy Dispatcher was designed and integrated into the MoSES tool to effectively control the hybrid PV-CSP power plant. The mathematical equations were formulated and integrated successfully using the Pyomo tool, a software package designed for optimization problems. The integration was fully done, even adding new possibilities to the tool itself as buying electricity from the grid, following electricity loads or integrating and controlling BESS.

After the first simulations, it showed very promising results when analysed in detail hour by hour, activating the different components in a perfectly efficient way. The bigger picture with the yearly values also revealed a big impact on KPIs as the energy wasted in the plant, the CO_2 produced, the revenue obtained or the total energy yield.

This Energy Dispatcher thus becomes a very relevant tool for simulating hybrid power plants, with endless applications. To name a few, one can easily select a location and simulate in almost no time many configurations to check what is the optimum according to a defined electricity market, injecting limitation, power block technology… and, obviously, defining what is required to be optimized.

On top of that, the study possibilities are countless, because the Dispatcher was designed from the beginning with total flexibility. If another type of TES is required it can be substituted quickly, if another power block with a higher efficiency is found it can be easily integrated. In addition, even the constraints of the mathematical problem can be activated or deactivated by typing "False" or "True", which opens up the range of options.

The analysis of the electricity markets and the consequent integration of the power plant on them revealed a huge potential for the power plant. The current focus on the spot market or on PPAs only shows a small fraction of the big possibilities that these plants have, specifically with their ability to store energy and dispatch it whenever it is better.

To start with, the tertiary market increasing the NPV by almost 100% and the secondary market multiplying it by more than 3 times. Although this is a specific case, the trend must be highlighted, and that is that these hybrid power plants have a huge possibility and a bright future on the service markets. Especially now that the grid expects a higher renewable penetration and thus, more need for these services with their intermittency and frequent unpredictability.

More technically, when performing a detailed comparison, it was seen that the participation in the regulation markets (secondary and tertiary) normally encompasses lower AEY and more Energy Wasted. That is because the plant is not focused on just producing and trying to sell as much as possible, it has to produce a certain amount at a certain time slots, and that means that some energy will inevitably be lost.

Similarly, the LCOE in the regulation market increases, and that is due to the same reason. Taking a closer look, the LCOE is calculated with the total energy produced and the total cost of the plant, and if the first is decreased due to this regulatory generation, the relative cost of generating that energy becomes higher.

Finally, another key fact to highlight is that the optimal design when participating in the secondary or tertiary markets tends to have higher Solar Multiple and thus, bigger CSP fields, as well as bigger TES sizes. The reason is that since extra flexibility is needed for the production, having more solar resource and more storage capacity become the perfect combination. And they both have to go together, a high solar resource without a big TES would mean wasting energy, and a big TES without a high solar resource would definitely mean a low and ineffective utilization of the storage.

In conclusion, this techno-economic assessment has set two important outcomes. The first one is that it created a tool, the Energy Dispatcher, that pave the way to future research studies. Its flexibility and its endless possibilities emerge as a key fact that multiplies its value. The second outcome is the analysis of the Electricity Market and the power plant effective integration in them.

While already showing its huge potential, it has also laid the groundwork to explore additional design combinations and other ways of participating in the electricity grid.

What becomes indisputable is the fact that these power plants can play a fundamental role in the future global energy mix.

5.2 Future steps

This last chapter is used to highlight some potential future steps identified during the development of this thesis. Although the analyses have shown very relevant and impactful results, there is room for many extra studies and a lot of improvement. Some of these steps, as well as other limitations encountered, are presented here below.

- The plant design was based on a Tower Concentrated Solar Power plant. The reason was that it currently has higher capacity ratios, temperature and efficiency compared to Parabolic Trough. However, due to the innovative characteristic of this study, it might be very beneficial to combine the Parabolic Trough with the Photovoltaic Technology, so that is an analysis that should be carried out.
- On the other hand, the investigation was entirely done in Seville, in Spain. There are many other places with higher solar resource in which these results can be significantly improved, reaching more competitive LCOEs. In addition, since the study is focused on the electricity market and the Dispatcher allows for country selection, it might be the case that a location with less solar resource, but a pricier electricity market shows a better behaviour. This should be analysed, and a comparison should be proposed.
- Having the BESS market under constant development and a hectic growth, it is very relevant to study a variation in the technology used as well as the efficiency values taken in order to assess how much it is impacting the final results. The same should be applied to another incipient technology as the TES, which was only studied for Molten Salts.
- Although the power block has many possibilities when it comes to the complexity, the time and space limitations locked the thesis work to the simplest model. The impact of including a more complex cycle should be investigated, because it has many possibilities of significantly improving the results shown.
- Another key flexible component is the Dispatcher, and its possibilities should be explored more in depth in future works. The number of constraints can be modified according to new discoveries or new plant dispositions/layouts. Even more important, the optimization function is the main part of the optimization tool, and four cases were explored. It goes without saying that this number can be significantly increased to analyse other possibilities as prioritizing the PV production against the CSP, or minimizing the BESS use…
- One last very relevant possibility is the Thermal Energy Storage following a thermal load. The market of Thermal Energy as a service is increasing during the latest years and there are forecasts situating it on a relevant position. Globally, the TES systems are scarce, so this would be another key potential for the power plant. As a comment, since the Dispatcher can have no CSP nor PV, it might be the case that just an Electric Heater with the TES is a viable and very profitable option for entering this other market.
- Due to obvious reasons, a verification and/or validation of the Dispatcher together with the MoSES tool was not carried out. That would require to have a real hybrid power plant with all the data available and study the results for several years. Forecasting a market growth for these plants, this analysis should be performed in future works.

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