Short-Term Operation Planning of a CSP Plant in the Spanish Day-ahead Electricity Market
Viability study of various backup systems

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Degree project in Electric Power Systems
Second Level, Stockholm, Sweden 2014
XR-EE-EPS 2014:006
SHORT-TERM OPERATION PLANNING OF A CSP PLANT IN THE SPANISH DAY-AHEAD ELECTRICITY MARKET

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A Master Thesis with the collaboration of:
Abstract

Solar thermal power or concentrating solar power (CSP) is an emerging renewable energy technology with strong potential to become a competitive source of bulk power in the next decades. The fast growth of this technology in recent years has its origin in special feed-in tariffs and various incentives, which have been significantly reduced due to the economic crisis. However, CSP sustainable development cannot be based only in state incentives and the operation of these power plants in day-ahead electricity markets becomes essential for their successful expansion. Additional improvements such as biomass backup systems and thermal storage tanks could also increase the operational flexibility of this technology favoring its competitiveness in electricity markets.

In this Master Thesis a short-term planning optimization model for a CSP power plant equipped with a fueled backup system has been development. The aim of the model is to derive the optimal operation of a CSP plant in the day-ahead market and to optimize the utilization of the backup system. The proposed model is based on conventional thermal power plants models incorporating the peculiarities of CSP technology through the study of a real power plant. The operation in the spot market during a year has been analyzed for the real case study of Astexol-2, a power plant owned by Elecnor, located in Spain. Additionally, the model has been used to study the potential benefits of a change in the backup fuel system from natural gas to biomass.

The analysis of the model simulation leads to significant improvements. The current operation, using only the solar resource to minimize costs, can be overcome significantly with the profit maximization strategy proposed. The optimal use of the backup system showed in the model allows earlier start-ups, generation during nights and avoids unnecessary shutdowns, which is translated into an optimal use of the solar resource. Profits increase around 10% and generation over 12,5% with a natural gas backup, while the biomass backup provides even better results; 12,5% increase in terms of profits and over 20% in generation.

The advantages of the optimization model are demonstrated through the comparison with the current operation of the power plant. The biomass backup system also leads to improvements in the day-ahead market operation. Adding the social benefits of biomass use and its economical profits, the adaptation of biomass backup system becomes an interesting feature for further research on CSP operation.
Acknowledgement

I would like to show my sincere gratitude to Elecnor and Javier Esquivias, who provided me with the unique opportunity to face this project as a Master Thesis. I would also like to extend this appreciation to all the people from Elecnor who have been involved in the project by providing me with technical data or guidance, and very especially to my tutor, Nadia López.

I could not forget to show my thankfulness to KTH, supporting this project since the very beginning and being the main source of knowledge and information I based this Master Thesis on. And also of course to my tutor, Ilias Dimoulkas, who provided me with constant technical support and very useful advices and who always seemed to be very close to the project despite the distance.

Finally, external support has been essential to accomplish this project, from Usue Pitillas with her thorough grammatical and style advice and continuous personal support to my family and friends, who have always been concerned on my work.
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1. Introduction

1.1 Background

The European Union (EU) recognized in its directive 2001/77/EC that “the promotion of electricity produced from renewable energy sources is a high community priority... for reasons of security and diversification of energy supply, of environmental protection and of social and economic cohesion” [1]. In order to make this promotion effective, the European Commission set the indicative objective that the 12% of 2010 energy consumption has to be provided from renewable energy sources [2] that finally developed in the current target of 20% for 2020.

Among the different renewable energy technologies fostered by the EU and the international community, this project deals with solar thermal technology, also named concentrating solar power (CSP). According to the International Energy Agency (IAE) this “emerging technology (...) holds much promise for countries with plenty sunshine and clear skies” [3]. The IEA also estimates that “by 2050 CPS could provide 11,3% of global electricity” [3] and that it “can be expected to become a competitive source of bulk power in peak and intermediate loads by 2020 in the sunniest countries” [3]. An Müller-Steinhagen article declares “while electricity generation from CSP plants is still more expensive than from wind turbines or photovoltaic panels, its independence from fluctuations and daily variation of wind speed and solar radiation provides it with a higher value” [4]. This independence can be achieved with thermal storage tanks, by back-up/hybridization fuels or by both of them simultaneously.

Within the renewable energy expansion context in the EU, Spain promulgated in 1999 its first national plan for the development of renewable energy setting a target of a 30% of the electricity generation provided from renewable energy sources by 2010 [5]. Spain had liberalized its electricity market in 1997 [6] and by those times it was still immature and required multiple changes in the legislation, which affected the promotion of the renewable energy. New laws and decrees succeeded in establishing a trustworthy environment for the energy sector and the national plan for the development of renewable energy was actualized (Plan de energías renovables 2005-2010 [5]). Since the sector was growing fast, a modification of the economical and juridical regulations became necessary to control some technical aspects that would contribute to the growing of these technologies safeguarding the security of the electrical system and the quality of the service [7]. This occurred with the royal decree-law 661/2007 in May 2007, which lasted, with few modifications, until February 2012. According to that regulation renewable energy sources (RES), biomass and co-generation, referred as special-regime producers, could choose between two favorable ways of participating in the market: a) with a fixed price dependent on the technology and set by the regulatory authority or b) with the spot price plus a fixed premium also dependent on the technology and set in the mentioned decree [7]. As a consequence, this sector grew more and more reaching a 33,2% of the electrical production in 2010.
and overpassing the most optimistic scenarios. Spain became a world reference on wind, photovoltaic and solar thermal technologies.

Under this advantageous economic environment, Elecnor has become a recognized RES producer in the national market as well as in the international scene. With almost 800 MW of wind power installed and participating in projects that counted more than 200 MW of photovoltaic power by 2009 [9], the company decided to enter into the CSP sector with three power plants of 50MW each. One of these power plants, Astexol-2 in Badajoz, west of Spain, is the case study of this project. The plant got its formal pre-assignment in December 2009 under the favorable legislation of 2007 and its finances and operation were calculated for the mentioned situation. After an approximately 300 million euros investment, the plant was first connected to the national power grid in August 2012 meaning a successful result for the company [10].

During 2009 Spanish economy was suffering the effects of the international financial crisis exacerbated by its own peculiarities, and the national renewable energy sector could not avoid the consequences. In coherence with the contraction in the GDP of 2012, the electricity demand decreased to the levels of 2006 (251710 GWh) [8]. This situation was not contemplated in the national plan for the development of renewable energy and created an important imbalance. On top of this fact, the electricity rate shortfall (money owed by the state to the electricity producers due to economical imbalance in the market) became too high and it began to impose a barrier for the suitable development of the electricity sector in general as well as for the renewable energy sector in particular [11].

In the scenario of the debt crisis and the austerity politics a modification in the legislation of the electricity sector was inevitable and came true with the royal decree-law 2/2013 in February 2013 among others. The aim of this law was to decrease the electric system costs and one of its initiatives was to revoke some incentives towards the special-regime producers [12]. In particular, the law retrospectively voided the premium to the spot market giving the power plants the options to either participate freely in the market or to choose the fixed feed-in tariff provided by the system regulator [12]. The feed-in tariff was the option chosen by the majority of producers, but it supposed a small decrease in their profits.

During the winter of 2013, a new economic imbalance was once again created in the electricity sector to erroneous estimations of the demand previsions and unfavorable meteorological conditions [13]. A new royal decree-law [13] was promulgated in July to prepare the legislation for a complete restructuring of the electricity sector in 2014. The new regulation [14] establishes a new reward frame for the special regime producers revoking the feed-in tariff. These special-regime power plants will have to compete in the spot market in the same way as any other power plant, but they will receive an annual fixed incentive regardless the operation to compensate the investment in a state-of-the-art technology [14]. Additionally, and depending on the technology, they can also receive a premium to the operation that is added to the spot price. The new reward parameters are regulated in [32], where RES power plants are classified in different standards depending on their technology and year of construction. According to the new legislation [14] these standards sets a “reasonable profitability” based on the Spanish short-term-bond that will be actualized every three
or six years [14]. For the case of the solar thermal technology studied in this project, the amount of this premium to the operation is set in around 37 €/MWh in comparison with the previous feed-in tariff of almost 300 €/MWh, while the fixed incentive varies from 400000 to 550000 €/MW (installed capacity) per year.

The changes explained above could mean a major regression in the development of the renewable energy sector due to the loss of the profitability of the special-regime producers. The expected added value of these new technologies in the economic and social cohesion that the EU predicated [1] seems to have lost relevance since the economic situation has become more critical in the Spanish society [15]. The diversification of the energy supply and the decrease of the external dependence could be slowed down and the environmental protection objectives could be considerably reduced. Besides it, the EU goal of 20% of energy consumption from RES in 2020 could be at risk. Committed with these causes, Elecnor investigates ways to recover the profitability of its renewable energy power plants so they can contribute to the welfare of the country.

1.2 Problem definition

Astexol-2 is a modern 50MW thermo-solar power plant built with parabolic cylinder mirrors technology that provides clean energy to over 30000 families [10]. This power plant generates electricity in a water steam cycle, where the water is heated in a heat exchanger by a thermal-oil (further on HTF). The heat is mainly provided to the HTF by the solar energy collected in the mirrors field, but the power plant is also equipped with three natural gas boilers that provide extra heating to the HTF under certain conditions. Figure 1.1 shows a simplified block diagram of the power to facilitate the general understanding.

![Diagram of Astexol-2 solar thermal power plant]

Figure 1.1: Simplified block diagram of the Astexol-2 solar thermal power plant
According to the royal decree-law 661/2007 under which Astexol-2 was built, these three boilers were allowed to produce a maximum of 12% or 15% of the total energy generated in the plant, depending on the condition of operation chosen [7]. This limitation implied strong constraints in the optimization of this extra heat resource [16]. After the changes in the legislation of February 2013 [12] when this project was proposed, CSP plants had lost the right to perceive incentives from the part of its generation using the natural gas boilers jeopardizing the profitability of the whole sector. Under the new legislation, the power plant operation in general and the use of this backup boiler resource in particular will be bound to the spot market, so an adaptation to the designed operation conditions must be accomplished.

Besides that, during this project a strategy to increase the profitability of the power plant will be studied. This strategy will consist in the hybridization of the CSP plant with biomass through the adaptation of the natural gas boilers to pellets. This strategy is based on the unlimited possibility for the plant to produce steam according to its demand from the combustion of biomass, increasing in that way the hours of availability of the plant as well as the efficiency of the energy production in the hours of low sun irradiation.

In order to address this problem, a short-term planning model of the power plant will be created to optimize the planning and operation of the system and to estimate the viability of this adaptation strategy. All the different scenarios must be considered in order to have a close approach to reality and to prevent future possible changes. The model will enable Elecnor to study other kind of biomass conversions in the future, such as biogas or solid urban waste.

1.3 Objectives

The main objective of this project is to study how the planning and operation of the 50MW solar thermal power plant will change because of the new legislation conditions and to analyze the impact in the operation of the backup boilers adaptation into biomass (pellets) boilers. The purpose of this study is to analyze if this strategy of adaptation is profitable under the new electricity market regulations.

In order to achieve this objective, a new optimization model of the power plant will be created with special consideration of the critical factors regarding the biomass modification. This short-term planning model will allow estimating the increase in the generation hours and/or in the efficiency of the power plant due to the boilers change. The long-term extrapolation of the short-term planning results will allow a critical analysis of the strengths, weaknesses and opportunities of the adaptation strategy. It will also provide the profitability analysis of this project. The model will also enable future studies of different biomass conversions that will be proposed in this project.

1.4 Overview of the report

This thesis is structured in 5 chapters. After this introduction, chapter 2 describes the solar thermal power field. Short overviews of power plant optimization models under
deregulated environments and about the Spanish electricity sector are also provided in this chapter. Chapter 3 explains the operation features of a solar thermal power plant and develops the MILP short-term planning optimization model in detail. In chapter 4, results of applying the model to the case study of Astexol-2 are shown. From the model parameters calculation to the profitability analysis, passing through the changes in operation of the power plant, this chapter demonstrates the advantages of the model proposed. Finally chapter 5 provides final conclusions and future research fields and improvements.
2. The solar thermal power field

2.1 Solar thermal power technology

Important institutions as the IEA appreciate the importance of solar thermal power plant in the field of renewable energy. “Solar thermal power plants are recognized as suitable technology for bulk electricity generation in the 10-1000MW range” [17]. The basic principle of this technology is to concentrate the direct solar radiation into a fluid to obtain the heat needed to generate electricity through a conventional thermodynamic cycle. Mirrors collect the direct solar radiation focusing it into a heat transfer fluid (HTF), which reaches high temperatures readily. This HTF is responsible for the necessary heat exchange to drive the thermodynamic cycle, either generating overheated steam or heating the gas for a gas turbine cycle or a Stirling engine. The classification of the different solar thermal power technologies is based on the method used for the concentration of the sun irradiation. Linear Fresnel, parabolic trough, solar tower and dish-Stirling technologies are showed in figure 2.1.

![Types of CSP plants](image)

**Figure 2.1** Types of CSP plants [4]

- Line-focusing system: Collectors focus sun radiation onto an absorber pipe to heat the HTF [4]. Depending on the shape of the collectors we can talk about linear Fresnel technology if they are flat or about parabolic trough if they are parabolic.

- Point-focusing central receiver system: a field of heliostats concentrates the sun radiation onto a central receiver situated on the top of a tower where the HFT is heated.
- Dish-Stirling system: a dish-shaped mirror focuses solar radiation into the receiver cavity of a Stirling engine [4].

Table 2.1, provided by Müller-Steinhagen and based on information of the IEA, summarizes the typical performance of these technologies:

<table>
<thead>
<tr>
<th></th>
<th>Parabolic trough</th>
<th>Linear Fresnel</th>
<th>Solar tower</th>
<th>Dish-Stirling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual solar-to-electricity efficiency (%)</strong></td>
<td>15-16</td>
<td>8-10</td>
<td>15-17</td>
<td>20-25</td>
</tr>
<tr>
<td><strong>Water consumption for wet/dry cooling (m³/MWh⁻¹)</strong></td>
<td>3-4/0.2</td>
<td>3-4/0.2</td>
<td>2-3/0.2</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

Table 2.1: Current performance indices of plants based on the four main CSP technologies [4].

One of the peculiarities of CSP is that it can only use the direct component of the solar radiation, in contrast to the solar photovoltaic technology that can use both the direct and the diffuse components. In addition to a high direct irradiance, “concentrating the sun’s rays requires reliably clear skies” [3] and, what matters most is, a low variation of the sunlight over the course of a day [3]. Under changing cloudy skies the intermittence of the direct sun irradiation can cause absence of energy production due to constant heat losses in the solar field [3]. Thus, the most favorable areas for CSP resource are arid or semi-arid regions that typically lay at latitudes from 15° to 40° North or South [3] as it is shown in figure 2.2. Due to the shortage of ideal locations, CSP power plants often need a back-up fuel, a high capacity thermal storage system or both of them to achieve a continuous and efficient operation.

Solar thermal technology also faces some drawbacks. “One of the most critically discussed issues with respect to CSP application is the significant consumption of cooling water for the power plant condensers” [4]. A 50 MW parabolic trough power plant in Spain, like Astexol-2, uses about 0.5 million m³ of water per year [4]. The elevated water consume is rather critical since this technology can be efficiently used in arid and semi-arid regions, where the water is a scarce commodity. Using dry cooling can substantially reduce the water consumption, which enables the desired decrease with a limited impact on the plant efficiency and generating cost [4].
Other downsides of solar thermal power are the land fields required (around 2 hectares per MWe with any storage capacity) and the situation of the ideal locations, often installed far from electricity demands [3]. As demonstrated over the years, distance is a solvable issue. High-voltage direct-current (HVDC) technology is recently used to cover very long distances achieving lower cost and smaller environmental footprint compared to alternating-current transmission lines [3].

On the other hand, there are several positive key aspects that give CSP a high value. Besides the benefits of renewable energy in general, accurately recognized by the EU in its directive 2001/77/EC [1], solar thermal power can avoid the variations of wind power or photovoltaic power contributing to the stability of the power grid. These fluctuations are not only a technical difficulty for the grid regulation that lead to technical limits to their penetration rate, but also mean costs up to 9.5 cents€/kWh for the system [18]. The potential of this technology to contribute to the system regulation is achieved by the back-up/hybridization with fossil fuels or biomass boilers together with a thermal storage system. This combination can allow CSP to provide base load power by storing the excess of heat during hours of high sun irradiation, which will be later used at night or low sun irradiation hours. As it is shown in figure 2.3, the back-up fuel is only used when the storage capacity is empty, offering a larger share of clean electricity and minimizing CO₂ emissions. According to the IEA “CSP offers firm, flexible electrical production capacity to utilities and grid operator while also enabling effective management of a greater share of variable energy from other renewable sources” [3]. “As demonstrated in Spain, connecting CSP plants to some grid sub-stations facilitates a greater share of wind energy” [3] and moreover, “CSP plant backup may also eliminate the need to build fossil-fired ‘peaking’ plants purely to meet the highest loads during a few hours of the day” [3].

![Figure 2.3: Combination of storage and hybridization in a CSP plant to cover a 30 MW demand [3]](image)

Despite the highly promising possibilities of the solar thermal power technology, it still faces the challenge to reduce its rather high costs. Many studies such as the Athene Study or the ECOSTAR Road-Map document [18] analyze the possibilities of this necessary cost reduction. “The most mature technology today is the parabolic trough system that uses thermal oil as a heat transfer medium” [18] which, according to the International Energy Agency, has investment costs in the range of 4.2 to 8.4 $/Watt at present [3]. This data fits perfectly with Astexol-2 investment cost of 300 million euros for its 50MW power plant. Analyzing the distribution of the investment cost of a power plant with similar characteristic under the Spanish sky, it can be
noticed that a 30% of the total amount is spent in the solar field [3]. A thermal storage system like the one previously explained providing 7-h of storage power production can mean less than the 10% of the total investment cost [3] and can provide significant improvements in the operation of the power plant.

According to experts’ estimations, production cost of CSP technology is in the range of 150-200 €/MWh [18]. “Cost reduction is a crucial requirement for electricity generation from these power plants in order to reach cost competitiveness compared to mid-load power from fossil-fired plants” [19]. Conventional fossil plants are immediate competitors of CSP in the mid-load dispatchable generation market, but they achieve to generate in a range of 30-40 €/MWh [18]. Assuming “the potential rise price of the fossil energy and the internalization of associated social cost of carbon emission, (...) the medium-long term competitiveness for CSP is achieved at a level of 50-70 €/MWh” [18]. As it is stated in recent studies, there are two main aspects with similar relevance to reach the desired cost reduction. The first one is the up scaling of the power plants capacity and the volume production effects. While parabolic trough commercial power plants have been built with capacities of 50 MW, “all other technologies are planned for a scale of 15 MW or smaller” [18]. Furthermore, Sargent & Lundy estimations refer to a cost decrease of 14% in parabolic trough technology scaling the plants up to 400 MW and a 17% by volume production effects due to installing 600 MW per year [20]. The second field with a high cost reduction potential is the research and development for innovative technology. Under the broad perspective of R&D, different fields of study might have a strong influence in cost reduction within the next years. Among others, working in the concentrating solar system with new structures and materials, developing more efficient thermal storage systems with lower prices and increased capacity and achieving more efficient thermodynamic cycles due to higher working temperatures, are the most promising and advanced innovation areas. ECOSTAR Road Map Document [18], presents an interesting table that addresses the mentioned research fields and sets development priorities in each of the CSP technologies. For the parabolic trough technology, ECOSTAR [18] gives the highest priority in reducing the cost of the concentrator structure and assembly. After this, developing low cost thermal storage systems and improving the reflectors and absorbers technology are considered as the second stage in the research priority.

Together with the cost reduction possibilities, a complementary strategy to reach competitiveness is to increase the incomes of the power plants. This can be achieved through the biomass hybridization, allowing more generation hours and more full load time availability with a 100% renewable power plant. Hybridization is based on the simple strategy of generating extra heat with biomass boilers to be used when the storage reserve is empty or if there is no storage system. It is particularly useful for CSP plants located in areas where the direct normal sun irradiation is less than ideal, such as the South of Spain [3]. Referring to hybridization, both ECOSTAR Road Map [18] and IEA [3] agreed in the necessity of flexible legal frameworks to favor this option avoiding arbitrary limitations on the hybridization ratios.
2.2 Solar thermal power development and future

The solar thermal power industry for bulk electricity generation made its first steps in the United States during the 1980s with nine power plants with a total capacity of 354MW situated in the Mojave desert in California [4]. The sector grew slowly, and “after several years without new plants of commercial size, concentrating solar power plants are now reentering the market” [19]. By 2010, “solar thermal power plants with a total capacity of 1.3GW are in operation worldwide, with an additional 2.3GW under construction and 31.7GW in advanced planning stage” [4]. Among those 1.3GW, 850MW were installed in Spain and quickly increased up to 2GW of installed capacity in 2012 [8]. This fast growth of the sector has its origin in the Spanish special feed-in tariff for solar electricity, regulated in the Royal Decree-law 661/2007 [7]. The high incentives lead to suppose the rebirth of the CSP technology [19] and placed Spain as the country with the most solar thermal power installed worldwide [4].

The future of CSP lies in achieving the mentioned cost reduction to reach competitiveness. The maturing process of solar thermal technology has still a long way to go through but its results seem to be promising. As stated in the IEA CSP Roadmap, “by 2050, with the appropriated support, CSP could provide a 11.3% of global electricity, with a 9.6% from solar power and a 1.7% from backup fuels (fossil or biomass)” [3]. According to this prevision, the IEA estimates almost 150GW by 2020, with an average capacity factor of 32% [3]. Hybridization and backup will account for the 18% of CSP production [3]. “In the sunniest countries, CSP can be expected to become a competitive source of bulk power in peak and intermediate loads by 2020, and in base loads by 2025-2030” [3]. ECOSTAR Roadmap’s perspectives [18] are not as optimistic as the IEA, but follow a similar route with comparable indications and results.

Both IEA and ECOSTAR agreed in propositions to the governments to favor solar thermal energy and create the desirable scenarios to allow the proper development of this technology. IEA consider the high importance to “support CSP development through long-term oriented, predictable solar-specific incentives” [3]. Spanish legislation changes have meant an important reverse for CSP development due to the retrospective character of the new regulation, causing a lack of investor confidence and a step back for the sector. The optimistic perspective of IEA and ECOSTAR could slow down considerably due to the deceleration of the industry growth. On the other hand, one of the important key actions suggested by the IEA [3] is perfectly applied by the new Spanish regulation, improving the former 2007 decree. This is to “avoid establishing arbitrary limitations on plant size and hybridization ratios (but develop procedures to reward only the electricity deriving from the solar energy captured by the plant, not the portion produced by burning backup fuels)” [3]. It is precisely this aspect of the new regulation what will be exploited in this project by trying to compensate the weakening caused by the uncertainty that was created.

2.3 Power plants optimization modeling in spot markets

Determining whether a power plant will be or will not be generating electricity is a crucial decision for the power plant owner with a great impact on its profits. This
decision is usually named as unit commitment strategy. For the former vertically integrated monopolistic environment, “unit commitment was defined as scheduling generating units to be in service in order to minimize the total production cost of utility” [21]. In those markets, “the system operator, who played also the role of market operator, took into account numerous technical aspects such as transmission constraints, as well as the maintenance of the system security” [22]. That is to say, the system operator acted as a superior agent considering the whole system and imposing the time and amount of electricity that each generation unit had to produce.

In the last decades, electricity markets are suffering a restructure process that “is intended to open the power sector to market forces with the ultimate target of decreasing consumer prices” [23]. “Power exchanges are ‘energy only markets’, since the market operator simply matches supply and demand bids and determines the market clearing price, without taking into account any technical aspects like transmission constraints or capacity payments” [22]. “At any given time and location, the power exchange pays the same price to any producer selling power” [22]. This liberalization of electricity market supposes a drastic change in the objective of the unit commitment strategy. Minimizing total production cost is not the target anymore, but each generation company (GenCo) has now the purpose of maximizing its own profits [21]. At present GenCos must schedule their production, make a short-term planning strategy and place bids each day to optimize its profits in the spot market. This is achieved by solving unit commitment problems, what has been a field of intense research providing “a large variety of models and calculations methods for operation planning of power plants” [24].

“The objective of a short-term planning is to determine detailed plans how to act for the closest future” [24]. “The result is a plan, which for example states how much each power plant should generate during each hour of the planning period” [24]. While the objective tends to be the same for every model, the solution methods proposed can be very different, among to consider: priority list methods, integer programing, dynamic programing, Lagrangian relaxation, Benders decomposition or mixed-integer linear programing (MILP) [21]. Lagrangian relaxation and mixed-integer linear programming are probably the most used methods as well as dynamic programing. “Advances in commercial MILP solvers over the last decade provide an alternative practical solution to large unit commitment problems” [22] and makes MILP the method chosen to solve the short-term planning model during this Master Thesis. “The main advantages of MILP over LR are that 1) it can provide a proven global optimal solution, 2) it provides a more accurate measure of optimality, and 3) it provides enhanced modeling capabilities and adaptability” [22].

The short-term planning decision is always taken under uncertainty. Deterministic models might be used due to the possibility of achieving trustworthy forecast for the model critical factors in the close time. In the day-ahead market bids must be placed in the market one day in advance, when predictions of electricity prices, fuel prices, weather or external conditions can be known with a considerable accuracy providing precise results. The inconvenience of solving the short-term planning optimization problem deterministically is that only one scenario, the most probable, is considered. In order to achieve optimal solutions for all the possible scenarios a stochastic model must be considered. Stochastic models are outlined in the same way as deterministic
models, but parameters that cause uncertainty are considered as stochastic variables. Electricity price, fuel prices or external conditions are modeled with their representative probability function and the result of the optimization will not be a unique decision, but it becomes a probability function as well. In the case of the short-planning problem of a power plant, a probability function with a high average (profits) and low variance (risk) is desired.

Unit commitment strategy was not a determining factor for CSP plants under the fixed feed-in tariff of Spanish regulation. The high subsidies, which widely covered the operation costs, and the independence from market price made the commitment decision only affected by the instantaneous solar resource. Restrictions on the amount of back-up fossil fuel available made “the logic used to determine the amount and timing of fossil burning (...) to be typically evaluated by skilled human judgment, and so is difficult to implement on the computer” [25]. Models, such as [25], have been created to provide detailed state-property predictions for the solar field and the power cycle during solar only operation and its transients [25]. With the aim to implement a hybrid operation easily, SOLERGY model [26] is based on a simple energy balance formulation. Under the new Spanish regulation where CSP power plants will have to compete in the spot market and considering the unlimited possibility to use a backup biomass fuel, the unit commitment problem becomes more necessary. Optimizing the use of the extra heat resource will possibly have a strong impact on the power plant performance and profits. Based on the unit commitment optimization models for thermal power plants [21]-[24] and with the incorporation of the energy balance idea from [26], this project has the aim to create an optimization model for solar thermal power plants equipped with extra heat from fueled boilers. Interaction between the solar and the fuel systems will be considered in order to plan an optimized behavior in the spot market under the external solar conditions.

2.4 Spanish electricity system and market overview

The Spanish electricity sector was a state monopoly until its liberalization in 1997 [6]. After this date, the influence of the state only remains in the planning of the transmission grid expansions and in the regulations of the sector through laws and royal-decrees. The exploitation of the electrical system ceased to be a public company and two private corporations assumed its competencies, one for the economic management and the other for the technical management. Red Eléctrica de España (REE) became the system operator, a natural monopoly in charge of the technical management of the system through transmission and distribution of electricity. Being the only grid owner, REE has the responsibility to ensure the access to the use of the grid to every agent in the sector in accordance with the safety and quality requirements of the regulation. On the other hand, the market operator (OMIE) became responsible for the economic management of the system. The objective of this market operator abandons the theoretical global optimization of the system, to be based on the individual decisions of the economical agents in an organized electricity market. The right of free installation was introduced for the generation companies guaranteeing free competition. A transition opening period of the electricity
distribution market was settled with the target to achieve a completely freedom of choice for all the consumers by the year 2007 [6].

The Spanish electrical system is interconnected with the Portuguese sharing a common economical management, also conducted by OMIE and known as the Iberian Electricity Market. When there are no congestions in the interconnection between both regions, the electricity price is the same for the whole market. In case of congestions, the market splits and prices become different in Spain and Portugal. In 2012, congestions happened for 10% of the year and always meant a higher price in Portugal than in Spain [8].

OMIE manages two separate markets, the day-ahead electricity market where the hourly electricity price is set and the intraday market for generation adjustments. In the day-ahead market producers, consumers and retailers participate placing bids for every hour of the 24-h trading period [25]. Every bid contains an amount of electricity to be sold or bought with a price limit. Some bids may also have other constraints such as block bids conditions, gradient constraints or scheduled shutdowns [25]. Bids have to be sent to the market operator before 12:00 of the previous day [25] who puts in order all the bids (ascending for supply and descending for demand bids) determining a supply and a demand curve as it is shown in figure 2.4. These curves cross in a point (curves orange and blue in the figure) determining a first approximation of the electricity price. Then, the system operator takes into account the bilateral contracts outside the market between generators and consumers and evaluates the technical feasibility of the auction results [25]. In case of unfeasibility due to congestion in transmission lines, security risk or poor quality performance, the system operator reassign the production for some units and set the definite clearing price (cross point between red and yellow curves in the figure) [25]. Generation bids lower than this price and purchase bids above will be accepted and traded at the mentioned clearing price. The intraday market works in a similar way as the day-ahead market, but several auctions are carried out after the closing of the day-ahead market and before the hour considered. These auctions trade a smaller amount of electricity and have the objective of adjusting any possible drifting on the previsions for generation or consumption bids placed in the day-ahead market. This adjustment market allows individual actors of the system to anticipate to their forecast deviations by competing in a free market environment with less uncertainty due to the closer to the real production time.

![Figure 2.4: Supply and demand curve in the Iberian Electricity Market at hour 12, October 18th 2013](image-url)
According to the new regulation of February 2013 [12], RES power plants were not allowed to participate in the day-ahead market and had to accept a fixed regulated price. But under the new modification of the regulation [14], these plants will have to participate in the market and their profits will depend directly on their performance in the market. A RES power plant will be affected by the hourly changes of the pool prices and will have to adapt its generation. This is especially significant for solar thermal power plants, which have the ability to modify their production with the back-up fuel or thermal storage as it has been explained above. It is also important to consider that the high penetration rate of renewable energy technologies in the Spanish market (almost 32% of the demand in 2012 [8]) and the uncontrollable generation of some of these sources intensify the variability of the Iberian electricity market. This variability makes the price forecasting a very difficult and not always successful task.
3. Solar thermal power plant optimization model

3.1 Introduction

According to [23] “in the new competitive electric power generation environment, a fundamental task is to determine the optimal response of a thermal unit to the spot market”. The optimal response is pursued by GenCos with the so-called unit commitment problems. Necessity, objectives and different solution methods available at present for unit commitment problems have been discussed in section 2.3. Even though these problems are small in dimension, they are complex under a mathematical point of view [23]. Modeling electricity generation systems often involves the use of non-differentiable and non-convex functions, exponential functions for the start-up cost as well as many others nonlinear constrains. Nonlinearity leads to inaccuracies in the solution and difficulties in the formulation in addition to more computational burden in the dynamic programming [23]. Mixed-integer linear programming (MILP) overcomes these inconveniences as explained in references [21]-[23] and section 2.3. According to [22], “the main disadvantage of MILP over LP is scalability”. Since the objective of this project deals with the optimization of a single solar thermal power plant, scalability does not mean an obstacle and MILP becomes an ideal choice for our problem.

The model proposed below deals with a solar thermal power plant equipped with a backup boiler under a deregulated market environment. Two systems, the solar field and the boiler, provide the heat to generate electricity in the power plant and can be used either independently or simultaneously. In order to achieve the objective of studying the profitability of the biomass hybridization strategy, the model faces the difficulty of heeding the interaction between both systems. This is done through simplified energy balances as it is explained in detail during this chapter. Solar-heated and fuel-heated systems parameters are independent in the model so that different boilers can be considered with ease.

In the following sections in this chapter a deterministic short-term planning model will be explained based on forecasted electricity prices and solar direct irradiation. The deterministic model will be based on optimization models of conventional thermal power plants [21]-[24], incorporating the peculiarities of the CSP technology. A perfect competition market is assumed in the model, where a GenCo has no influence in electricity prices, i.e. the solar thermal power plant will be considered as a price taker.

3.2 Overview of a hybridized solar thermal power plant operation

With the aim of facilitating the model understanding, an overview of the operation of a hybridized solar thermal power plant is provided. Four different states are considered for the operation of the power plant: on-line (generating electricity), start-up, antifreeze and offline [30]. Each one of these states has its own peculiarities and will be explained bellow.
3.2.1 On-line operation

During the on-line operation the power plant is synchronized with the power grid and electricity power is produced. The power plant generates between its minimal and maximal power capacity, set by the limits of the turbines, similarly as a conventional thermal power plant. The HFT required to produce the steam to run the turbines is heated-up until its operating temperature. The HFT mass flow circulating through the steam generation system at rated temperature determines the amount of steam produced, which in turn, delimits the electricity generated. Two sources of heat are available to reach the operating temperature of the adequate HTF mass flow: the sun irradiation collected in the mirror field and the boilers. As mentioned, these two sources of heat can be used either separately or concomitantly. The heat produced by the solar field is uncontrollable due to the stochastic nature of sun irradiation. This is the main difference between CSP and conventional thermal power plants.

Since the electricity sold has a different reward in the Spanish market (study case) depending on its source [32], sun or fuel, a solar thermal power plant must be equipped with a system to distinguish its origin. According to Spanish legislation [7] and [32], this procedure is based on calculating the electricity generated with the backup system through the fuel consumption during the hours the power plant is synchronized with the grid. The remaining electricity sold is considered to come from the solar field.

The boilers are used as an extra-heat source to complement the heat produced in the solar field. When utilized to generate electricity, boilers can allow: generation during the night, better efficiencies in low sun irradiation hours or continuous generation in variable cloudy days reducing the number of shutdowns of the power plant.

Another peculiarity of the majority of solar thermal power plants is the oversized absorption capacity of the mirror field. At maximum DNI hours the sun collectors gather more energy than can be transferred to the turbines, so that some mirrors have to be unfocused in order to avoid the HTF reaching maximum temperature. This is usually known as dumping [16]. Dumping operation could be avoided stocking up this heat surplus into a storage tank to be used some hours later.

3.2.2 Start-up operation

The objective of the start-up process of the power plant is to achieve the lowest start-up time fulfilling the inherent constraints of every single element of the plant. The initial temperature of the turbines, the steam generation system and the HTF imposes the strongest constraints for the start-up, which in turn, depend on the time the power plant has been offline. The stages that constitute a start-up process are:

1. Heating the HTF until it reaches the steam generation system temperature.
2. Heating the steam generation system having concern for its heating rate limits.
3. First heating of the turbine at low speed.
4. Synchronization of the turbine with the power grid.

5. Second heating of the turbine at high speed generating electricity at minimum power capacity.

As it occurs in the on-line operation, heat required to reach the start-up temperatures following the described process can be obtained from the solar field, the boilers, or both of them at the same time.

3.2.3 Antifreeze operation

The antifreeze operation is meant as a security operation mode to avoid the damage caused by the frozen HTF in the solar collectors. The HTF freezing temperature is approximately 12°C, so the antifreeze mode is necessary for long inactivity periods. For security reasons, it is necessary to start the antifreeze mode before the HTF temperature drops bellows 50°C at any point of the power plant. When the sun irradiation is not enough to ensure a temperature above 50°C with the power plant being of-line, the boilers must be started-up to provide the extra-heat power. HTF is re-circulated through the power plant in the antifreeze mode bypassing the turbines and the steam generation system.

3.2.4 Offline operation

The offline operation is the one that occurs when the power plant is not synchronized with the power grid and it is operating neither the antifreeze mode nor a start-up process. During this operation mode, HTF is re-circulated through the power plant bypassing the turbines and the steam generation system in the same way it happens in the antifreeze mode.

3.3 Problem formulation

A deterministic short-term planning MILP optimization model of a solar thermal power plant is proposed. This model is based on conventional thermal power plant MILP models [21]-[24] incorporating peculiarities of the CSP technology and considering the interaction between the sun and the boiler system through simplified energy balances constraints. Since the model uses one-hour periods energy (MWh/h) and power (MW) can be considered equivalent during the next sections.

3.3.1 List of symbols

The list of the symbols used to describe the model is included bellow. Letter $c$ refers to costs of the system. Letter $P$ refers to power production while letter $H$ refers to heat production. $E$ parameters take into account energy requirements, while $SU$ relates with start-up limitations. Greek letters are either forecasted values ($\lambda$ and $\psi$) or efficiencies ($\alpha$ and $\eta$). Finally binary variables $u$ and $v$ relate with the status of the power plant and the boiler respectively. In order to consider the different purposes the boiler can be used for, three different binary variables regulate its commitment: $v_{gen}$ when the boiler is used to generate electricity, $v_{start}$ for starting-up and $v_{af}$ for the antifreeze mode. Concurrently, two variables are used for the power plant commitment, $u$ for its on-line operation and $u_{af}$ for the antifreeze mode. Start-up or
stop orders at the beginning of a time period are considered for both the boiler and the power plant with the super index + and - respectively.

**Sets**

- $T$: set of the intervals of the planning period [1-48]
- $T^*$: set of the intervals of the planning period including hour 0
- $NS$: number of steps of the discrete function that regulates the energy needed for the start-up

**Indices**

- $t$: time interval index (hour)
- $i$: time interval for offline hours

**Constants**

- $\lambda_{el,t}$: forecasted electricity price during hour $t$ in €/MWh
- $\lambda_{sun}$: premium for the electricity generated through sun in €/MWh
- $\lambda_{bio}$: premium for the electricity generated through biomass in €/MWh
- $\lambda_{CO2}$: tax for the CO$_2$ emissions in €/MWh
- $\psi_{s}$: forecasted solar direct irradiation during hour $t$ in MWh/h
- $c_{off}$: fixed operation cost of the power plant when it is offline in €/h
- $c_{af}$: fixed operation cost of the antifreeze mode of the power plant in €/h
- $c_{start}$: fixed cost of the power plant start-up in €
- $b_{start}$: boiler start-up cost in €
- $\alpha$: solar absorption capacity of the mirror field
- $P$: maximum power production of the power plant in MWh/h
- $P$: minimum power production of the power plant in MWh/h
- $H$: maximum heat production of the boiler in MWh$_{th}$/h
- $H$: minimum heat production of the boiler in MWh$_{th}$/h
- $E_{start,i}$: energy needed for the start-up after $i$ hours offline in MWh$_{th}$/h
- $E_{af}$: energy needed for the antifreeze mode in MWh$_{th}$/h
- $SU_{1,i}$: start-up minimal power limit of the power plant after $i$ hours offline for the first on-line hour in MWh
- $SU_{2,i}$: start-up minimal power limit of the power plant after $i$ hours offline for the second on-line hour in MWh
- $SU_{1,i}$: start-up maximal power limit of the power plant after $i$ hours offline for the first on-line hour in MWh
- $SU_{1,i}$: start-up maximal power limit of the power plant after $i$ hours offline for the second on-line hour in MWh
- $toff_{max}$: maximum number of hours the power plant can be offline until the antifreeze mode starts
- $toff_{0}$: number of hours the power plant has been offline at hour 0
- $u_{0}$: status of the power plant at hour 0: 1 commitment, 0 uncommitment
- $u_{af,0}$: status of the power plant at hour 0: 1 commitment, 0 uncommitment
- $v_{gen,0}$: status of the boiler at hour 0: 1 commitment, 0 uncommitment
- $v_{start,0}$: status of the boiler at hour 0: 1 commitment, 0 uncommitment
- $v_{af,0}$: status of the boiler at hour 0: 1 commitment, 0 uncommitment

**Variables**

- $P_{fuel,t}$: power output from the boiler at hour $t$ in MWh/h
- $P_{sun,t}$: power output from the sun at hour $t$ in MWh/h
- $H_{sun,t}$: heat provided by the solar field for generation at hour $t$ in MWh$_{th}$/h
- $H_{gen,t}$: heat provided by the boiler for generation at hour $t$ in MWh$_{th}$/h
- $H_{start,t}$: heat provided by the boiler for the start-up at hour $t$ in MWh$_{th}$/h
- $H_{af,t}$: heat provided by the boiler for the antifreeze mode at hour $t$ in MWh$_{th}$/h
- $toff_{i}$: number of hours the power plant has been offline in hour $t$
- $u_{t}$: 0/1 variable that is equal to 1 if the plant is online during hour $t$
\[ u_i = \begin{cases} 0/1 \text{ variable that is equal to 1 if the plant starts-up at the beginning of hour } t \end{cases} \]

\[ u_i' = \begin{cases} 0/1 \text{ variable that is equal to 1 if the plant starts-up at the beginning of hour } t \text{ after } i \text{ hours off line} \end{cases} \]

\[ u_i = \begin{cases} 0/1 \text{ variable that is equal to 1 if the plant shuts down at the beginning of hour } t \end{cases} \]

\[ u_{af,t} = \begin{cases} 0/1 \text{ variable that is equal to 1 if the plant is running in the antifreeze mode during hour } t \end{cases} \]

\[ v_{gen,t} = \begin{cases} 0/1 \text{ variable that is equal to 1 if the boiler is used for electricity generation during hour } t \end{cases} \]

\[ v_{start,t} = \begin{cases} 0/1 \text{ variable that is equal to 1 if the boiler is used for the start-up during hour } t \end{cases} \]

\[ v_{af,t} = \begin{cases} 0/1 \text{ variable that is equal to 1 if the boiler is used for the antifreeze mode during hour } t \end{cases} \]

\[ v_f = \begin{cases} 0/1 \text{ variable that is equal to 1 if the boiler is shut off at the beginning of hour } t \end{cases} \]

\[ v_s = \begin{cases} 0/1 \text{ auxiliary dumping variable used to calculate the off-time counter} \end{cases} \]

### 3.3.2 Objective function

The goal of the model is to maximize the profits of the operation and so it is considered through the objective function. The function is formulated as ‘profits equal to incomes minus costs’.

Incomes of the power plant are obtained selling the electricity generated to the spot market. Premiums for the electricity generated through the sun or the biomass can be easily considered by adding the fixed amount of the premium to the forecasted spot price. If fossil fuel is used in the boiler and the market imposes fees for CO₂ emissions (\(\lambda_{CO₂}\)), the fee could also be considered by subtracting the fixed quantity to the forecasted spot price. Power plant also incurs several costs, which depend on the operation modes that plant goes through. These costs are explained in the following subsections. Objective function is presented in 3.1

\[ \sum_{i=1}^{n} \left( \lambda_{s,i} + \lambda_{sun} \right) P_{sun,i} + \left( \lambda_{af,i} + \lambda_{fuel} \right) P_{fuel,i} - \cos t_{offline} - \cos t_{start} - \cos t_{antifreeze} - \cos t_{fuel} - \cos t_{b,off} - \cos t_{CO₂} \] (3.1)

### 3.3.3 Electricity production

As explained, electricity production can come from the two available sources of heat: sun and fuel. Regardless of where the heat comes from, the electricity production depends on the efficiency of the thermodynamic cycle that transforms heat into steam and steam into electricity when the power plant is on-line. This process of energy conversion is modeled with the function \(\eta\), which is calculated through a regression technique considering the relation between enthalpy of the HTF at the beginning of the heat exchangers and the net power production. These data were provided from a real solar thermal power plant (Astexol-2, Elecnor [29]) and shows linear approximation with a square correlation coefficient (\(R^2\)) of 0.9996 (see appendix A).

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1 The term \(\lambda_{sun}\) is only included in 3.1 if the biomass backup system is considered, otherwise it takes the value 0.

Cost of CO₂ emissions are only considered for a fossil fueled backup system, otherwise it takes the value 0.
\[ P = \eta_1 + \eta_2 H_t \] \hspace{1cm} (3.2)

Constant \( \eta_1 \), which is negative, is related with the power plant electricity auto consumption and with the lower efficiency when generating at low capacity. As explained in section 1.1, power is sold at different prices depended on the source of the heat used to produce this power. Therefore power produced by sun, \( P_{\text{sun},t} \), and by the backup fuel boiler, \( P_{\text{fuel},t} \), are considered separately in the model. This separation can only be approximated and the following approximation technique is based on the instructions of the Spanish law according to which \( P_{\text{fuel},t} \) is calculated from the fuel consumption and then \( P_{\text{sun},t} \) is the difference between the total power production and the \( P_{\text{fuel},t} \).

Usable heat from the sun for generation each hour, \( H_{\text{sun},t} \), is calculated with the forecasted direct sun irradiation, \( \psi_t \), multiplied by the mirror field heat absorption capacity factor, \( \alpha \). \( \psi_t \) is calculated with SAM\(^2\), a program that corrects the direct sun irradiation measured in the solar station with the solar position among other factors. This corrected direct solar irradiation makes the heat absorption capacity linear for every moment of the day and year (see Appendix A). Heat provided in the solar field is not equal to the product of \( \alpha \psi_t \) in order to allow the dumping operation explained in subsection 3.2.1

\[ H_{\text{sun},t} \leq \alpha \psi_t \] \hspace{1cm} (3.3)

Then, the power generation is calculated in 3.4 through the function \( \eta \).

\[ P_{\text{sun},t} = \eta_1 u_t + \eta_2 H_{\text{sun},t} \forall t \in T \] \hspace{1cm} (3.4)

\( P_{\text{fuel},t} \) is calculated by 3.5 or 3.6 where \( H_{\text{gen},t} \) is the heat provided by the boiler and is a function of the fuel consumption. Which one is used depends on the value of \( \alpha \psi_t \). When it is low 3.5 is used. Instead if it is higher than a specific limit 3.6 is used. This limit is the amount of heat in the HTF after which power generation begins.

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\(^2\) “The System Advisor Model (SAM) is a performance and economic model designed to facilitate decision making for people involved in the renewable energy industry, ranging from project managers and engineers to incentive program designers, technology developers, and researchers” from:

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The difference between $P_{\text{sun},t}$ and $P_{\text{fuel},t}$ is that while the former depends on the solar conditions that are given parameters, the later depends on the heat from the boiler that is an optimization variable and hence, can be controlled by the power plant operator.

3.3.4 Offline cost of the power plant

CSP power plants incurs in cost while offline. This is due to the necessity of pumping the HTF through the plant to prevent it from freezing, running auxiliary systems and the control center among others. This is considered in 3.7, where a fixed cost is estimated as offline cost for every hour the power plant is neither on-line nor operating antifreeze mode.

$$\text{cost}_{\text{offline}} = c_{\text{off}} \left(1 - u_t - u_{\text{af},t}\right) \forall t \in T$$

3.3.5 Variable cost of the power plant

Variable cost of the power plant is mainly related with the fuel consumption of the backup system and is determined with the function $\text{cost}_{\text{fuel}}$. This gives the cost of the fuel consumed in the boiler when $H_{\text{gen},t}$ MWh/h of heat are transferred to the HTF for electricity generation. Depending on the type of boiler this function can be approximated either by a linear or a non-convex function. Both formulations are proposed in the model.

Linear formulation:

$$\text{cost}_{\text{fuel}} = b_{\text{fuel}} H_{\text{gen},t} \forall t \in T$$

The MILP formulation of a non-convex function implies more complexity and some other symbols must be defined:
\[
\text{cost}_{\text{fuel}} = \sum_{n=1}^{NL} B_n h_{\text{gen},n,t} \\
H_{\text{gen},t} = H V_{\text{gen},t} + \sum_{n=1}^{NL} h_{\text{gen},n,t} \\
\left( \overline{B}_1 - H \right) w_{\text{gen,1},t} \leq h_{\text{gen,1},t} \leq \left( \overline{B}_1 - H \right) w_{\text{gen,1},t} \\
\left( \overline{B}_n - \overline{B}_{n-1} \right) w_{\text{gen,n},t} \leq h_{\text{gen,n},t} \leq \left( \overline{B}_n - \overline{B}_{n-1} \right) w_{\text{gen,n},t} \quad \forall t \in T \quad (3.9) \\
0 \leq h_{\text{gen,n},t} \leq \left( \overline{H} - \overline{B}_{NL-1} \right) w_{\text{gen,NL-1},t}
\]

This piece-wise approximation of the non-convex function is made taking into account \( NL \) concatenated linear segments, each one with a slope of \( B_n \) and an upper limit of \( \overline{B}_n \). Each segment corresponds to a generation of \( h_{\text{gen,n},t} \) MWh/h and auxiliary binary variables \( w_{\text{gen,n},t} \) are used to ensure that every segment \( n \) comes after the previous one, \( n-1 \). A more detailed explanation of the piece-wise linear approximation is described in [21]-[23]. In favor of the clarity and due to a good correspondence with the available data, only the linear formulation will be considered further on.

3.3.6 Time offline counter

The operation of a solar thermal power plant to generate electricity, to start-up or to operate in the antifreeze mode implies the transfer of heat to the HTF and then, to power island (turbines and steam generation system). Therefore, offline operation is the only mode in which there is a reduction of the heat content in the system. The loss of heat is a critical factor for the operation of a CSP plant since start-up and antifreeze operation depend on the temperature of the HTF among other elements. Consequently, the time offline counter becomes necessary in our model.

An offline counter is included in this model based on the paper written by Arroyo and Conejos [23] including the peculiarities of the antifreeze operation, a significant characteristic of CSP plants. The proposed counter increases the variable \( toff \), each hour the power plant has been offline until it reaches the value \( toff_{\text{max}} \) where the antifreeze mode has to start. If \( toff_{\text{max}} \) is reached, the counter will remain in this value, since the antifreeze mode ensures heat contribution to the HTF to maintain a safety temperature. When the power plant is commitment and generating electricity, \( toff \) will become zero.

These constraints could be implemented using the logic operators if, and, or, etc. that are accepted in optimization software like GAMS. The main inconvenience for the use of them is the occurrence of the undesirable non-linearity. An alternative linear solution using the power plant commitment binary variables \( u_t \) and \( u_{\text{off},t} \) is showed bellow.
\[(t_{off, t-1} + 1) - u_{off, t} - \left( (t_{off, max} + 1) u_t \right) \leq t_{off} \leq \left( (t_{off, t-1} + 1) \right) \forall t \in T \] (3.10)

First line of constraints ensures that the counter increases while offline and remains in \( t_{off, max} \) while antifreeze operation. Second line states the limits of the counter; zero when the power plant is online and \( t_{off, max} \) otherwise.

### 3.3.7 Start-up operation and cost

As explained in 3.2.2, the start-up process consists of heating-up the HTF and the equipment until they reach operating conditions taking into consideration the heat-rate limits. The minimum heating time of equipment and thus, the energy (heat) needed to reach the required temperatures is directly related to the initial temperature of the HTF, turbines and steam generation system (SGS). These temperatures are, in turn; related to the time the power plant has been offline. The previous argumentation conducts to the conclusion that the heat needed to start-up the power plant depends on the time the power plant has been offline, \( t_{off} \). A similar approach to the one used here is considered in [23] for conventional thermal power plant start-up cost. This heat requirement can be calculated with empirical data of the power plant or with theoretical approximations creating the heat to start-up function, depending on the offline time. This function is exponential according to the empirical data of the case study and it is linearized in this model as a stair-wise approximation. This approximation considers \( NS \) steps (one step per offline hour), each one with a value \( E_{start, i} \) (energy needed to start-up after \( i \) hours offline).

The energy to start-up the plant can come from the mirror field or the boiler. The heat available from the sun \( (\alpha \psi_i) \) is transferred to the HTF constantly, even when the power plant is offline. This solar resource allows storing heat in the HTF during the offline hours and, in turn, reduces the energy requirement for the start-up. The other source of heat to achieve generation conditions provides from the boiler, \( H_{start, t} \). In favor of a flexible use of the boiler, its utilization as a source of heat for the start-up is allowed for several hours before the start-up decision is made. These ahead-hours allow storing heat in the HTF until there is enough heat to start-up the power plant, in the same way as it happened with the sun irradiation. As for electricity generation, the solar resource for start-up is an uncontrollable parameter while the heat contribution from the boiler is the variable to optimize and it is used and desired by the power plant operator. The following energy balance expresses this interaction between the solar and the fueled systems for the start-up decision.
\[
\sum_{i=1}^{NS} \left( E_{\text{start},i} - \sum_{t=t-\text{off}}^{t} (\alpha y_t) u_{i,t}^+ \right) \leq H_{\text{start},1} + H_{\text{start},3} + H_{\text{start},5} + H_{\text{start},7} + H_{\text{start},9}
\]

\[
v_{\text{start},1} - v_{\text{start},3-1} \geq \left( u_{i,1}^+ - 1 \right) + \left( v_{\text{start},1} - \frac{H_{\text{start},1}}{H} \right)
\]

\[
v_{\text{start},3-2} - v_{\text{start},3-1} \geq \left( u_{i,2}^+ - 1 \right) + \left( v_{\text{start},2} - \frac{H_{\text{start},2}}{H} \right)
\]

\[
v_{\text{start},3-4} - v_{\text{start},3-3} \geq \left( u_{i,3}^+ - 1 \right) + \left( v_{\text{start},3} - \frac{H_{\text{start},3}}{H} \right)
\]

\[
v_{\text{start},3-4} - v_{\text{start},3-3} \geq \left( u_{i,4}^+ - 1 \right) + \left( v_{\text{start},4} - \frac{H_{\text{start},4}}{H} \right)
\]

\[\forall t \in T^* \quad (3.11)\]

First equation in 3.11 implies that if at hour \( t \) there is enough heat available to start-up the power plant, then the start-up decision will be taken at the beginning of hour \( t \) and the start-up process will be accomplished. This heat available, as mentioned, is the heat coming from either the sun irradiation or the boiler and accumulated in the HTF during the previous hours in addition to the heat available in the sun and boiler during hour \( t \). Last four equations in 3.11 are meant to impose that the use of the boiler is higher the closer it is to the start-up process in order to avoid losses in the heat accumulation.

Parameter \( E_{\text{start},i} \) represents the energy requirement to start-up the power plant after \( i \) hours offline. Each \( E_{\text{start},i} \) parameter needs to be related to its corresponding binary variable \( u_{i,t}^+ \), which registers a start-up order at the beginning of hour \( t \) after \( i \) hours offline. This relationship is done with a dumping auxiliary variable, \( y_t \), through the four constraints shown bellow, as it is explained in [23]:

\[
\sum_{i=1}^{NS} u_{i,t}^+ = u_t^+
\]

\[
t_{\text{off},i} = \sum_{i=1}^{NS} i u_{i,t}^+ + y_t
\]

\[
y_t \leq t_{\text{off},\text{max}} \left( u_{i,NS}^+ - u_t^+ + 1 \right)
\]

\[
y_t \geq N S u_{i,NS}^+
\]

First constraint ensures that when a start-up order has been given at hour \( t \) (\( u_t^+ = 1 \)) only one \( u_{i,t}^+ \) variable is chosen. Second constraint relates properly the variables \( u_{i,t}^+ \) with the offline counter while third and fourth set the limits of the auxiliary variable \( y_t \).

Finally, the variable cost of a start-up process is taken into consideration with the linear function \( \text{cost}_{\text{start}} \). This function has a fixed term, \( c_{\text{start},i} \), representing the fixed start-up cost due to the HFT pumps among other auxiliary systems needed in the start-up plus a variable term, \( \text{cost}_{\text{fuel},i} \), depending on the heat provided from the boiler, \( H_{\text{start},t} \). This second term is analogous to the variable cost of the power plant (3.8) that
also considers the fuel consumption in the boiler to transmit heat to the HFT but using \( H_{start,t} \) instead of \( H_{gen,t} \).

\[
cost_{start} = c_{start}u^+_t + cost_{fuel,start} = c_{start}u^+_t + b_{fuel} H_{start,t} \quad \forall t \in T
\] (3.13)

On the other hand, the start-up process of the boiler is faster than one for the power plant and its dependence with the offline time of the power plant is not as significant as it is for the whole plant. Therefore, considering the boiler start-up cost in the objective function as a fixed amount of money for every start-up, \( c_{b,start} \) is a good approximation for our purpose according to the data provided in the case study.

\[
cost_{b,start} = c_{b,start}u^+_t
\] (3.14)

### 3.3.7 Antifreeze operation and cost

The antifreeze operation ensures that the HFT never reaches its freezing temperature, which would cause damages to the solar collectors. During the antifreeze operation heat is provided to the HFT. Under real operation, a solar thermal power plant will only begin the antifreeze mode whenever one of its HTF thermal sensors drops bellows a safety limit. An approximation of the antifreeze operation decision is proposed in this model avoiding more extra-complexity. In the same way as explained for the start-up, the only source of reduction in the HTF heat content is the offline operation of the power plant. There exits risk to achieve the HTF freezing temperature only after a certain number of offline hours, \( toff_{max} \). This number of offline hours is not frequently reached due to the warm and arid location of CSP power plants but it can be calculated by extrapolating the cooling curve of the HTF or by empirical experience.

The linear formulation of the antifreeze mode commitment condition is expressed in 3.15:

\[
\begin{align*}
    &u_{af,t} > \frac{toff_t}{toff_{max}} - 1 \\
    &u_{af,t} \leq \frac{toff_t}{toff_{max}} \\
\end{align*}
\quad \forall t \in T
\] (3.15)

Which means that if \( toff_t \) becomes equal to \( toff_{max} \) then the power plant operates in antifreeze mode \( (u_{af} = 1) \).

Once the antifreeze mode begins, either the solar field or the boilers must provide heat to the HTF, \( E_{af} \), to maintain it at a safety temperature. An energy balance constraint defines the interaction between the solar and the fueled backup system in a similar way as it was proposed above for the start-up:
\[
\begin{align*}
\left( E_{af} - \alpha \psi_t \right) u_{af,t} &\leq H_{af,t} \\
H_{af,t} &\geq 0
\end{align*}
\forall t \in T 
\tag{3.16}
\]

The heat provided by the boiler during the antifreeze mode, \( H_{af,t} \), must be higher or equal than the difference between the total heat needed, \( E_{af} \), and the heat provided in the solar field, \( \alpha \psi_t \), for every hour when the antifreeze mode operates.

Antifreeze operation cost, \( cost_{af} \), likewise start-up cost, are modeled as a linear function with an independent term, \( c_{af} \), representing the fixed cost of the operation, and a variable term, \( cost_{fuel,af} \), depending on the heat provided by the boiler, \( H_{af,t} \). \( cost_{fuel,af} \) is in this case the same function presented in 3.8 and but using \( H_{af,t} \) instead of \( H_{gen,t} \).

\[
\begin{align*}
\text{cost}_{af} &= c_{af} u_{af,t} + \text{cost}_{fuel,af} = c_{af} u_{af,t} + b_{fuel} H_{af,t} 
\end{align*}
\tag{3.17}
\]

Since the antifreeze mode is an operation mode that in reality occurs automatically when any of the thermal sensors drops below a certain threshold, it could seem not necessary to include it in the short-term planning of the power plant. The purpose of including it in this model is to try to prevent this circumstance from happening. This model formulation can lead to scenarios where some hours of solar irradiation are used together with the backup system to generate power under conditions when it would not be profitable by its own. This generation could become the optimal solution since the use of the backup system for antifreeze operation during the following hours would imply more losses than the generation.

3.3.8 Generation limits

Generation limits express the maximum and minimum generation capacity of the power plant when it is online and ensure that there is no generation when it is offline. These limits are not constant due to technical restrictions when starting-up the power plant. Generally, generation limits can be written as follows:

\[
\begin{align*}
\underline{p}_t &\leq P_{\text{min},t} + P_{\text{fuel},t} \leq \overline{p}_t
\end{align*}
\forall t \in T 
\]

\( \underline{p}_t \) and \( \overline{p}_t \) set the minimum and maximum generation limits respectively each hour bearing in mind if the power plant operation is under a start-up process or not. As mentioned in 3.2.2, a start-up process has several stages that allow different generation capacities. During the steps where the HTF and the equipment are heated until the operating temperature, generation is not technically feasible. The synchronization of the turbine with the power grid does not allow generation, but the second heating of the turbine implies generation at minimum capacity for several minutes. The duration of each stage changes with the time the power plant has been offline. An example of a generation curve during a start-up process is shown below to provide a better understanding.
Figure 3.1: Start-up generation curve after 13 hours offline

Generation curves for every start-up process (every hour offline until antifreeze mode) are included in the model through parameters $SU_{1,i}$ and $SU_{2,i}$, where $i$ refers to the number of hours offline before the start-up. These parameters have the mission of restricting the generation capacity of the power plant when it is under a start-up process. Since these processes can last for more than one hour, sub-indices 1 and 2 refer to the first and second hours after the start-up order. With the purpose of describing the generation curve correctly and allowing the whole range of possible situations, the start-up limitations ($SU$) are considered with a maximal and a minimal limits, $\overline{SU}_i$ and $\underline{SU}_i$ respectively. The minimal limitation is needed to ensure that once the turbine has been synchronized with the power grid, it has enough energy available to complete its second heating at minimal capacity. The certainty that there will be enough heat in the system to accomplish the steps previous to the second heating of the turbine is achieved due to the $E_{start,i}$ parameter described in subsection 3.3.7. Upper limit provides the maximum energy the power plant can generate each hour after the start-up order and until the online operation, taking into account the second heating limitation and the ramp-up to maximum power. The values of the four $SU$ parameters that describe the curve plotted in figure 3.1 are presented to clarify their meaning:

\[
\begin{align*}
SU_{13}^1 &= 0 \text{MWh/h} \\
\overline{SU}_{13} &= 0 \text{MWh/h} \\
SU_{13}^2 &= 5,5 \text{MWh/h} \\
\overline{SU}_{13} &= 5,5 \cdot \frac{7}{60} + 49,5 \cdot \frac{8}{60} + 55 \cdot \frac{45}{60} = 45,19 \text{MWh/h}
\end{align*}
\]

After thirteen hours offline, upper and lower limits during the first hour of start-up are zero since, according to figure 3.1, the second heating of the turbine begins 60 minutes after the start-up order. During the second hour, the lower limit is the
minimum capacity of the power plant, required during the second heating and extended during this second hour when the power plant has to be on-line. The maximum limit in the second hour is calculated as: 1) the minimum time of the second heating multiplied by the power available during this step, 2) plus the ramp to maximum power and 3) plus the maximum time the power plant could operate at maximum power during this second starting-up hour.

It is also important to note that the process of heating the HTF does not begin when the start-up order is given. As it has been explained in 3.3.7, all the solar energy available and the use of the boiler for some hours ahead contribute to storage heat in the HTF even during the offline operation in order to reduce the heat requirement for the start-up process. Considering this contribution dynamically in our model would cause a considerable increase in the complexity and it does not provide a significant improvement since the time to reach the required HTF temperature is one of the least determining factors in the start-up process. The solution proposed instead takes into account heat storage in the HTF the hours previous to the start-up plus a fixed time (5 minutes) after the start-up order when the HTF flow and temperature is modified to start-up conditions. This time is an approximation that depends on the working conditions of the power plant and must be adapted with the operational experience to reach an optimal accuracy.

Summarizing, data needed to obtain a complete description of the start-up process and decision in this model is presented in table 3.1.

<table>
<thead>
<tr>
<th>Explanation</th>
<th>Name</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of hours the power plant has been offline</td>
<td>$t_{off}$</td>
<td>1, 2, ... , i, ... , $t_{off, max}$</td>
</tr>
<tr>
<td>Energy needed for the start-up after $t_{off}$ hours</td>
<td>$E_{start,i}$</td>
<td>$E_{start,1}$, $E_{start,2}$, ... , $E_{start,i}$, ... , $E_{start,t_{off, max}}$</td>
</tr>
<tr>
<td>1st hour of start-up</td>
<td>Minimal power requirement</td>
<td>$SU_{1,i}$</td>
</tr>
<tr>
<td>Maximal power limit</td>
<td>$SU_{1,i}$</td>
<td>$SU_{1,1}$, $SU_{1,2}$, ... , $SU_{1,i}$, ... , $SU_{1,t_{off, max}}$</td>
</tr>
<tr>
<td>2nd hour of start-up</td>
<td>Minimal power requirement</td>
<td>$SU_{2,i}$</td>
</tr>
<tr>
<td>Maximal power limit</td>
<td>$SU_{2,i}$</td>
<td>$SU_{2,1}$, $SU_{2,2}$, ... , $SU_{2,i}$, ... , $SU_{2,t_{off, max}}$</td>
</tr>
</tbody>
</table>

Table 3-1: Data needed to describe the start-up

Considering the start-up constraints explained above, the generation limits of the power plant are finally expressed as:

$$P_{sun,i} + P_{fuel,i} \geq \sum_{j=1}^{NS} (SU_{1,i} u_{ij}^* + SU_{2,i} u_{ij+1}^*) + P\left(u_t - u_t^* - u_{t+1}^*\right) \quad \forall t \in T \quad (3.18)$$

$$P_{sun,i} + P_{fuel,i} \geq \sum_{j=1}^{NS} (SU_{1,i} u_{ij}^* + SU_{2,i} u_{ij+1}^*) + P\left(u_t - u_t^* - u_{t+1}^*\right)$$

For both lower and upper generation limits equations set the start-up limits, $SU$, during the two hours after a start-up order, and the minimum and maximum capacities of the power plant otherwise. Binary variables disposition ensure that the generation is zero when the power plant is offline.

Finally, heating capacity limits of the boiler must also be considered on its three operation modes. Boilers nearly always have maximum and minimum limitations due to the maximum and minimum amount of fuel permitted at correct operation.

Short-term operation planning of a CSP plant in the Spanish day-ahead electricity market
Evidently, these limits set the heat generation variable to zero in each mode when the boiler is not used.

\[
\begin{align*}
H^{v}_{\text{gen},t} & \leq H_{\text{gen},t} \leq \bar{H}^{v}_{\text{gen},t} \\
H^{v}_{\text{start},t} & \leq H_{\text{start},t} \leq \bar{H}^{v}_{\text{start},t} \\
H^{v}_{\text{af},t} & \leq H_{\text{af},t} \leq \bar{H}^{v}_{\text{af},t}
\end{align*}
\ \forall t \in T \tag{3.19}
\]

### 3.3.9 Commitment constraints

MILP optimization problems require a careful study of the binary variables logic to describe the correct operation of the power plant.

Three restrictions allow the correct operation of the power plant: 1) If the power plant changes its commitment status, \(u_t\), between two consecutive time periods it is because either a start-up \((u^+_t)\) or a stop \((u^-_t)\) order is given at the beginning of the time period \(t\). 2) A start-up order cannot be given at the same time period as a stop order and vice versa. 3) The on-line operation \((u_t=1)\) and the antifreeze mode operation \((u_{af,t}=1)\) cannot occur simultaneously. These restrictions are expressed as follows:

\[
\begin{align*}
&u_t - u_{t-1} = u^+_t - u^-_t \\
u^+_t + u^-_t \leq 1 \\
u_t + u_{af,t} \leq 1
\end{align*}
\ \forall t \in T^* \tag{3.20}
\]

The boiler operation modes also require three constraints to be defined correctly. These are analogous to the power plant constraints but include the three different operation modes of the boiler: generation \((v_{\text{gen},t})\), start-up \((v_{\text{start},t})\) and antifreeze \((v_{\text{af},t})\).

\[
\begin{align*}
(v_{\text{gen},t} + v_{\text{start},t} + v_{\text{af},t}) - (v_{\text{gen},t-1} + v_{\text{start},t-1} + v_{\text{af},t-1}) &= v^+_t - v^-_t \\
v^+_t + v^-_t \leq 1 \\
v_{\text{gen},t} + v_{\text{start},t} + v_{\text{af},t} \leq 1
\end{align*}
\ \forall t \in T^* \tag{3.21}
\]

The first equation states if the boiler starts or stops. A start-up order of the boiler will only be given when it is uncommitted in all its operation modes during the previous hour, \(t-1\), but it is committed in any of its operation modes during \(t\). The other way around occurs with stop orders. The second equation means that the boiler cannot start and stop at the same time while the last expression only allows one operation mode of the boiler to be active every time period.

Three additional commitment equations set the logical of the interaction between the solar and the fueled backup system:

---

**Short-term operation planning of a CSP plant in the Spanish day-ahead electricity market**
The first one allows the correct use of the boiler only when the antifreeze mode is being operated. The next one allows the flexibility required in (3.7) for the use of the boiler during the start-up processes. And finally, the last one makes the generation with the boiler only possible when the power plant is online.

### 3.3.10 Change of the boiler

As justified during this chapter, the model proposed considers the solar system and the fueled system parameters independently in order to enable different types of boilers to be used as a backup of the solar thermal power plant. Only four parameters need to be changed to describe correctly the fueled system with its corresponding boiler or group of boilers. These parameters are:

1. Boiler maximum heating capacity in MW → $P$
2. Boiler minimum heating capacity in MW → $H$
3. Boiler start-up cost → $c_{b,\text{start}}$
4. Boiler variable cost, related with its fuel consumption to provide a certain amount of heat and with the fuel price → $b_{\text{fuel}}$.

The most determining factor among the mentioned ones is the boiler variable cost function, which, as explained in this chapter, can be considered either linear or non-linear.
4. Case study: Astexol-2 under new market regulations

4.1 Introduction

As explained in the first chapter of this thesis, Astexol-2 is a solar thermal power plant built between 2010 and 2012 in Badajoz, western Spain, whose profitability has been jeopardized due to regulation changes in the sector. At present, the power plant is equipped with a backup system of three natural gas boilers untapped for the sake of cost reduction. The power plant was operating in solar-only mode with a feed-in tariff for every MWh generated through the sun. Currently, they are still operating in the solar-only mode to minimize the costs. With the new regulation, the power plant operates in the spot market receiving an additional incentive for its renewable energy production.

Elecnor, aiming to achieve a more advantageous realignment to the new market conditions, conceived a biomass hybridization strategy consisting of the adaptation of the current natural gas boilers to pellets boilers. This would allow a 100% renewable energy generation, avoid the taxes for CO₂ emissions and probably imply a higher reward due to the change in the power plant regulation standard (see [32]).

The viability of the biomass hybridization will be studied through the model described in chapter 3 demonstrating its utility. The deterministic MILP model will be used to simulate the power plant operation during one standardized year. Comparison between the use of the backup systems to maximize profits and the solar-only operation (no use of boilers to minimize cost) will demonstrate the potential of the short-term planning optimization model. Comparison between the simulations with the natural gas boilers system and with the modified pellet boilers will provide an average measure of the benefits of this strategy. Extrapolation of these results to the long-term will allow a deeper study of the investment profitability. Furthermore, the analysis of the results will show the changes in the CSP plant operation due to changes in the regulations and in the use of the backup boiler system.

Results showed since the beginning a good fitting with the power plant performance and the results could be considered reliable as will be further justified in 4.3. Furthermore, the analysis of the results supposed a constant improvement process in the model proposed in chapter 3, since some inconveniences showed that a few constraints needed to be modified or added. The model showed in chapter 3 is, however, the result of this continuous improvement process.

4.2 General model input calculation

Elecnor provided construction and operational information in order to make a precise adjustment of the model parameters to the CSP plant Astexol-2. Exact calculations cannot be provided due to confidentiality, but a general description of how every parameter has been calculated is provided during this chapter and summarized in appendix A.
The mirror-collectors supplier provided a document [28] dealing with the solar field capacity to transfer heat to the HTF. This report presents a corrected sun irradiation measure that software (SAM) applies to the measured data taking into consideration the angle of incident and the sun position. The value obtained with this procedure is the value used as direct sun irradiation in the model, $\psi_t$. Considering this corrected direct normal irradiation (DNI) measure, a table relating the sun irradiation with the energy contribution to the HTF was provided. Through a simple linear regression technique a function was calculated showing an almost perfect correspondence. The independent term of the linear function was twelve orders of magnitude lower than the slope and therefore disregarded, remaining only the solar absorption capacity of the solar field, $\alpha$, with the value of the mentioned slope (see appendix A).

The mass and energy balances of the power plant were provided for several turbine loads [29] and used to calculate the heat to electricity function and the fuel consumption of the natural gas boiler. Heat to electricity function was calculated through linear regression subtracting the power plant auto-consumption at every load obtaining a correlation square factor higher than 0.99. A problem appeared since the independent term of the function became negative. A negative value of $\eta_1$ means a negative value of the electricity production through the sun, $P_{sun,t}$, for low sun irradiation values (see equation 3.2) which cannot be feasible. Solution was found introducing a threshold for the function that makes $P_{sun,t}$ equal to zero when the sun irradiation is lower than the calculated value. In practice, this implies that the solar field is not able to produce enough heat for electricity production if sun irradiation is not higher than this threshold.

Parameters describing the startup process (table 3.1) are calculated in detail in appendix B. $SU$ parameters to follow every start-up curve are determined adding the heat-rate limitations of the steam generation system to the heating and synchronization times of the turbine and its ramp limits [30]. Cooling curves of the turbine depending on the offline time were estimated through empirical data of the real power plant performance. Three different curves were considered to model the cooling process: one for the first 6 offline hours (hot start-up), another one for the second 6 hours (warm start-up) and a last one from the 13th offline hour and further (cold start-up). $E_{start,t}$ energy needed to start-up after $i$ hours offline, was ascertained with real data of the power plant operation. With the power plant operating in the solar-only mode, energy contribution of the solar field to the HTF was considered during different startup processes after different offline hours. Results were extrapolated to obtain a function that was discretized into $t_{off, max}$ intervals corresponding to the every $E_{start,i}$ parameter. Particularly, Elecnor provided 5 different start-up processes to calculate the curve. Due to the importance of this parameter, a better tuning of the function could have been adequate to improve the results with a higher number of cases to estimate the function. The correlation in this case resulted in a factor 0.98. However, the company did not provide more information. Finally, start-up fixed cost, $c_{start}$, is calculated through operational data of the power plant as an average of the start-up process provided by Elecnor.

Antifreeze mode operation parameters were also calculated through empirical data of the power plant. While the energy needed in antifreeze mode, $E_{af}$, was determined in order to maintain a constant and secure temperature of the HTF, the time to start
the antifreeze mode was estimated with a considerable safety margin. Anyhow, antifreeze mode in Astexol-2 is a rare event since it has only been necessary for few hours during the last year due to the favorable weather conditions of its location.

Maximum and minimum limits of both the natural gas boiler and the power plant are set as the rated values in [30].

4.3 Yearly simulation

4.3.1 Background description

The deterministic MILP model proposed in 3.3 has been used to simulate the power plant behavior according to the new legislation [14], [32]. Model aims to maximize the profits from selling power to the day-ahead market with an efficient use of the boilers. Three different operation frameworks are compared in the same solar irradiation and price scenarios:

A) Solar-only mode. Following a cost minimization strategy, this mode is currently in use in Astexol-2. Operation in this mode constrains the boilers to be used only for the antifreeze mode.

B) Natural gas boilers. A profit maximization strategy is applied to the actual infrastructure of the power plant, where three natural gas boilers are freely used to optimize the power plant behavior in the spot market.

C) Pellet boilers. An adaptation of the current natural gas boilers to pellet boilers is considered. Pellet boilers are also freely used to maximize profits with the additional convenience of a lower ecological impact and the state incentive to the use of biomass.

The results analysis begins with a short-term planning comparison between the three operation modes in order to show the changes in the planning and operation of the power plant. This comparison is done in a daily and weekly basis with some particular days chosen from the one-year simulation due to its significance. After that, a summary of the monthly results through the year allows studying the seasonality and the general impact on the power plant performance, both technical and economical.

The working process has been very useful to identify sources of improvement in the model proposed. Inconsistencies with the toff counter, the threshold required in equation 3.2, or necessity to extend the time period to 48 hours to a correct optimization can be examples of improvements during the results analysis. Another important enhancement was vital to increase the flexibility of the use of the boiler. This is the possibility to use the boiler for the start-up not only the hour when the start-up decision is taken, but since some hours before. The number of hours ahead is calculated so that the most energy demanding start-up process could be complete without any solar contribution.

The necessity of using a 48 hours planning horizon is justified because the operation decision of the boiler during the night depends on next morning solar irradiation and electricity prices as will be described during this chapter. However, bids only must be
placed in the day-ahead market 24 hours in advance, so that among the 48 hours simulation, the 24 first hours will be our model output. For next day operation, simulation will be considered again taking into account another 48 hours period with the following 24 hours. A 24 hours model could be also used simulating from midday of one to until the midday of the next day, where the night performance of the boiler is considered. The only drawback of this second solution is that bids must be placed for a natural day period (from 0:00 till 24:00) in the Spanish day-ahead market.

4.3.2 Inputs

Apart from the general inputs explained above, specific inputs used for this case study are solar irradiation and electricity price. When using the model for short-term planning, these parameters will be estimated and will imply the source of uncertainty.

In our simulation, standardized direct solar irradiation data has been used in favor of the generality of the results. Elecnor calculates this standardized solar year with data from the meteorological stations of the power plant and some others in the surrounding area. It is the same data used when Elecnor made the economic analysis of the power plant before building it.

Electricity price used is the daily market price of 2013. The fast growth of the renewable energy sector during the last years and its effect in the spot prices makes the price evolution from 2008 to 2012 significant enough to not consider taking averages prices. Furthermore, the stoppage of the new power plant licenses set in the Royal Decree of January 2012 [11] has implied a great decrease in the construction of new power production plants for 2013. This means the Spanish power system will not change over the next years due to the actual overcapacity installed.

The premium for the use of renewable energy to generate electricity has been set according to the preliminary bill published by the Spanish Ministry of Industry [32]. The reward of the solar energy in cases (A) and (B) has been set with the IT-01002 standard of the mentioned document [32], which leads to suppose a 37,375 €/MWh premium for generation. For the biomass hybridization (C), the standard considered is IT-01015, which increases the fixed incentive and uses the premium for generation considered in IT-01002 for the solar energy and in IT-01134 (0 €/MWh) for the biomass generation.

The data used to represent the boiler system is the nominal data and the fuel consumption curve found in the power plant documents for the natural gas boiler. Natural gas price was considered through the monthly contracts signed by Elecnor with the gas supplier. In the case of the pellet boiler, Elecnor set the target of achieving a boiler system with the same power capacity while data of fuel consumption was calculated from other industrial pellet boilers with similar characteristics. Pellet price was taken from PIX pellet Nordic FOEX on December 17th 2013 [31].

4.3.3 Results: Changes in operation

The use of the optimization model in the day-ahead market brings several changes in the power plant operation in comparison with the current situation, case (A). The flexible use of the boilers to maximize profits in the day-ahead market either for start-up heat apportions or for generation is detailed in this subsection.
When the boiler is used to provide heat for the power plant start-up process it means a cost, which might be recovered through the earlier start-up. To decide exactly when the power plant must start, suppose the main difference with the current operation mode. In case (A), with the boilers unavailable for the start-up, the sun irradiation guides the start-up process. The power plant will only generate electricity when the heat apportion of the solar field could achieve a complete start-up process. As it can be seen in figure 4.1, the use of the fueled system can imply a change in the power plant start-up operation. In figures 4.1-4.3, the graph on the top shows total power production sold to the pool in MWh for the three cases: (A) red dotted, (B) blue dashed and (C) green continuous line during two consecutive days. At the same time, the graph on the bottom represents the heat production of the boilers to achieve the power plant performance on the top. As it was explained in chapter 3, this heat contribution of the backup system is the power plant operator decision to optimize the generation. The pellet boiler is represented by green-dashed for start-up mode and green-continuous for generation mode while the gas boiler is blue-dotted for start-up and blue-dotdashed for generation.

![Graph showing total production and heat contributions of the boilers.](image)

**Figure 4.1** Power production and use of the boiler. Two consecutive days in January

As an example of this situation, figure 4.1 shows two consecutive days of January, with low solar resource. During the first day, solar-only operation allows a first generating hour at 13:00 selling about 30 MWh due to technical restrictions in the start-up, explained in chapter 3. For this same day, our model shows improvements if any fueled system is used for start-up. With the natural gas boilers, currently installed in the power plant, generation can begin at 12:00 generating also about 30MWh for this hour, but increasing the generation at 13:00 until maximum capacity. This is achieved by heating the HTF with the boiler during the 3 hours previous to the start-up: 5, 44 and 44 MWh\text{thermal} respectively. The model provides even better results for the biomass back-up system, where a 5-hour thermal contribution to the start-up leads to suppose generation from 11:00, about 45 MWh at 12:00 and also full capacity
at 13:00. For the three cases, the power plant will shut down at 18:00 and remain offline for the whole night.

During the second day presented in figure 4.1, a very similar use of the pellet boiler is considered to help with the cold start-up (more than 12 hours offline). However, under this day conditions, the contribution of the natural gas boiler for the start-up is not profitable, and the model predicts the same operation for (A) and (B). This means that the cost of the gas needed in the boiler cannot be recovered through an increase in the solar generation. The situation described, among others similar, happens because of either low sun irradiation conditions after the start-up, low electricity prices for these hours or a mixture of both factors.

The fueled systems improving start-up process are the optimal solution of the model during many days all along the year. On the other hand, there are some other days when the utilization of none of the boilers is profitable and the system operates as in the solar-only mode. While figure 4.1 shows different operations according to the boiler used, figure 4.2 shows two days in August where the solution for gas and pellets is the same.

![Figure 4.2](image)

**Figure 4.2** Power production and use of the boilers. Two consecutive days in August

The first day presented in figure 4.2 shows the same use of both back-up systems for the start-up achieving one extra hour of generation in comparison with the solar-only mode. Heat production for the start-up (warm start-up, between 6 and 12 hours offline) are in this case lower than in the winter case, meaning only two hours, about 20 MWh\(_{\text{thermal}}\) for the first one and 44 MWh\(_{\text{thermal}}\) for the second one. The reason of this difference is the longer days and shorter nights of the summer, which implies less offline hours for the power plant and, consequently, lower energy requirements for the start-up.

The graph shows another big variation in the power plant operation and it is related with the use of the boilers for generation. As it can be seen in 4.2, the solar-only
operation implies a shutdown of the power plant at 20:00 coinciding with the last hour of solar resource. On the other hand, according to the model both boilers system will be used to generated electricity at minimum capacity after the sunset. With the gas boiler, generation will last for 4 hours, and then the power plant will disconnect from the grid. The boiler will then be used next day at 6:00 in start-up mode in addition to the solar irradiation to achieve generation two hours ahead than the “no boiler” case. Generation at night with the boiler has here the purpose of decreasing the offline hours, reducing in that way the energy requirement for the start-up (hot start-up, 6 or less offline hours). Nevertheless, technical start-up requirements constrain generation for this first hour to 3 MWh. For the case of the pellet boiler, generation at minimum capacity will last during the whole night and the solar resource will be entirely used for generation during the next day. A continuous generation implies that the power plant start-up process can be avoided, evading the HTF and SGS heating-rates as well as the heating and synchronization of the turbine.

During the night of the second day the model shows generation with the back-up system only for the biomass, and not for the natural gas. According to the model, continuous generation is achieved in the model for cases (B) and (C) during one or more days in a row for numerous times in the year. This situation is more often for short nights, since the cost of keeping the boiler at work is lower and can be more easily recovered during the next day. High prices at night or the next morning also favor continuous operation. A solar resource enough to allow generation for the first solar hour is also very important to take advantage of this circumstance.

![Power production and use of the boilers. Two days in September](image)

Another improvement in the operation of the power plant is shown in figure 4.3. Similarly to the two previous figures, we can see the use of both boilers for start-up during the first day, where 3 hours of heat production with the back-up system mean two extra hours of generation in comparison with (A). The significant difference in this graph can be found at the end of the first day. For cases (A) and (B), generation is
stopped at 17:00, two hours before the sunset, due to a very low sun irradiation hour from 17:00 to 18:00. On the other hand, the model shows that generation at minimum capacity during this hour through the pellet boiler can allow taking advantage of the last hour of solar resource, wasted in the other two cases. As it has been explained in chapter 2, CSP technology works only with direct sun irradiation, which can be almost completely obstructed by clouds. These momentary obstructions are the cause of short stops that not only decrease the exploitation of the solar resource but also are inadvisable for the turbines. Fast starts and stops of the turbines shorten its lifetime according to the manufacturers.

An example of these avoidable short stops is shown in the second day of figure 4.3. Contribution of both fueled systems for the start-up is also presented for this second day, increasing the solar generation in one hour, but during this day both boilers are also used to avoid the power plant disconnection at 17:00. If we observe carefully, the solar only operation implies a stop at 17:00 to reconnect the power plant from 18:00 to 19:00. Due to the technical start-up limitations, the electricity production during this reconnection is restricted to minimum capacity, so solar potential is wasted in comparison with (B) and (C). In (B) and (C) the boilers are used during this cloudy period to keep the power plant producing at minimum capacity, and the last hour of solar irradiation allows a generation over 20 MWh optimizing the whole solar irradiation potential.

With the aim to provide a more general vision of the benefits of the optimization model in the power plant operation, figure 4.4 shows the results of a week in November. The graph on the top shows the solar irradiation in the left y-axe (yellow dotted line) and the electricity prices (blue continuous line) in the right one. The graph on the bottom shows total production of the solar-only operation mode (red dotted line) and of the pellet boiler (green continuous line). Natural gas boiler is removed from this graph with the purpose of the facilitating the understanding and due to similar results with the pellet boiler.

First three days on the week shows continuous generation for the pellets boiler. During those days the high and stable solar irradiation is completely used for generation since the very first hour in the morning. The electricity prices show a typical pattern for the Spanish winter days, where prices decrease at night and increase early in the morning. As it can be observed, the electricity prices are already high for the first solar hours due to the winter late sunrise, fact that favors the continuous generation in spite of low prices at night.

Thursday and Friday in figure 4.4 are cloudy days, with low and variable solar resource. However, prices remain high and the use of the boiler for start-up is profitable according to the model, meaning an increase of generation of two hours each day. Saturday is presented as a cloudy or rainy day, where no sun irradiation is available and thus, no electricity production is worthwhile. Sunday is again a sunny and stable day, with the decrease in the electricity price at night. High prices in the morning make the use of the boiler ideal to help with the cold start-up process after more than 24 hours offline optimizing the favorable solar resource available during the day.
Finally, to conclude this subsection, figure 4.5 shows a graph analogous to 4.4 but in this case for a summer week in July. Summer days are characterized by its short nights and high solar resource since the first hours of the morning due to the high position of the sun.

In the same way as it happened in November, a correct use of the pellet boiler increases generation through earlier start-ups or generation at night. A rare event occurs on Wednesday when the electricity price decrease in the morning. This fact, in addition of the cloudy period after the second solar hour makes the use of the boiler unprofitable nevertheless the favorable summer conditions.
This week has also been chosen to show the small gap between the decision of generating the whole night or using the boiler for an earlier start-up. Short summer nights are not enough to ensure a continuous generation with the pellet boiler as it is shown in figure 4.5. The value of solar irradiation during the first hours and electricity price at night and in the morning have a great impact on the decision, and it is the mixture of both circumstances what is considered in the model to maximize profits. Comparison between figures 4.4 and 4.5 shows that while continuous generation is the optimal solution for some days in the week of November, some generation hours with the boiler during the night in order to achieve a hot start-up next morning are better in the week of July instead of the complete night of generation.

4.3.4 Results: Overall yearly results

In the previous subsection most relevant changes in the operation of the power plant have been studied. A yearly simulation of power plant’s operation shows a significant impact on its performance, which is explained below.

![Figure 4.6 Monthly generation of the power plant](image)

Figure 4.6 shows the monthly generation of power plant in the three mentioned cases throughout the year. The dependence with the solar resource is clear. Generation increases along the winter, as days become longer and solar resource higher, reaching its maximum generation in the summer months. The decrease in generation during autumn is faster than the increase during the winter and spring since it is a wet season with a higher concentration of cloudy and rainy days with no direct sun irradiation.

Figure 4.6 shows the utility of the optimization model during all the year. The optimal use of the fueled backup systems increases generation each month. Comparison between pellet boiler and natural gas boiler also demonstrate the benefits of the hybridization strategy proposed by Elecnor, achieving a higher generation each month as well.
Figure 4.7 Monthly profits of the power plant

The monthly profit distribution of figure 4.7 shows the expected similar seasonality to the generation distribution. Exceptions happen in March and April, when electricity prices in Spain are typically very low due to high wind and hydropower penetration in the generation mixture. Electricity prices become zero for these months during several hours a day or even complete days, meaning that the increase in generation is not directly translated to an increase in profits. It can also be noticed that the profit differences between the three scenarios studied is smaller than the generation differences. The explanation to this fact resides in that the increase in generation occurs due to the use of the boilers, which means an extra cost for the power plant reducing thus, the profits.

In order to see more clearly the economic impact of the optimal use of the natural gas boiler and the biomass hybridization strategy in comparison with the current operation mode, figure 4.8 shows the accumulated difference of profit during the year. Profits of the current solar-only operation in the day-ahead market are estimated with the model in $7,848,387\,€$. The optimal operation of the natural gas boilers, which are already installed in the power plant and ready for its utilization, can imply a 10.18% increase in the power plant profits under the new legislation. This perceptual increase means $799,007\,€$, including the taxes to the CO₂ emissions. The improvement achieved by the investment in a pellet boiler leads to suppose $210,225\,€$ over the profit of the case b) (2.43%). Comparing with the current operation of the power plant, profit would increase by a 12.86% reaching a total annual results close to 9 million euros ($8,857,620\,€$).

Finally, table 4.1 summarizes the yearly total results for the three different operation modes studied in terms of profits, total generation and use of the boilers. Analyzing
global results, higher increases in generation than in profits can be noticed, as mentioned before. While generation increases 8,41% with the pellet boiler in comparison with the natural gas, profits only show an augmentation of a 2,43%. The use of the pellet boiler for generation is near three times higher than the gas boiler, but the impact of the boiler generation over the total generation in not very significant (2,7%). The use of the pellet boiler for start-up increases 59,66%, but again the repercussion on the profits seems to be small. Biomass boiler would be considerably more utilized in the power plan operation according to the model. However, its economic impact will be very limited.

<table>
<thead>
<tr>
<th></th>
<th>No boiler</th>
<th>Natural gas</th>
<th>Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Profits</strong></td>
<td>Total (€)</td>
<td>7.848.387,20</td>
<td>8.647.394,88</td>
</tr>
<tr>
<td></td>
<td>Difference (€)</td>
<td>-</td>
<td>799.007,68</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>-</td>
<td>10,18%</td>
</tr>
<tr>
<td><strong>Total generation</strong></td>
<td>Total (MWh)</td>
<td>106.829,36</td>
<td>120.354,60</td>
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<tr>
<td></td>
<td>Difference (MWh)</td>
<td>-</td>
<td>13.525,24</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>-</td>
<td>12,66%</td>
</tr>
<tr>
<td><strong>Boiler for generation</strong></td>
<td>Thermal (MWh&lt;sub&gt;thermal&lt;/sub&gt;)</td>
<td>-</td>
<td>4.065,65</td>
</tr>
<tr>
<td></td>
<td>Electricity (MWh)</td>
<td>-</td>
<td>940,00</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Boiler for start-up</strong></td>
<td>Thermal (MWh&lt;sub&gt;thermal&lt;/sub&gt;)</td>
<td>-</td>
<td>12.319,19</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Table 4-1 Total year results |

4.3.5 Discussion

Results presented in the previous two subsections provide a demonstration of benefits of the optimization model from the daily operation to the yearly consequences.

Figures 4.1-4.3 present the most relevant situations that lead to operational changes in the power plant. These changes are occasioned by the appropriated use of the
backup systems and imply an optimization of the available solar resource increasing the total electricity production and thus, the incomes. The exploitation of the backup system is presented in three different ways: by heat generation in the start-up process, by generation at night (either to reduce the start-up heat requirement or to achieve continuous generation) and by generation during short cloudy periods avoiding disconnections. The use of the boilers in any case means a cost for the power plant due to the fuel consumption, and this cost must be recovered through the extra incomes achieved.

The complexity of the system leads to a difficult decision about when and how to use these backup boilers. The shorter a night is, the cheaper would it be to keep the boiler working to achieve continuous generation at minimum capacity. But at the same time, short nights imply few offline hours and consequently low heat requirements for the start-up, which would lead to small heat production (low fuel consumption) with the boiler. On the other hand, long nights would imply more fuel consumption at night but also more fuel consumption to complete the cold start-up energy requirement.

Parameters referring to the start-up, both the energy needed and the start-up power limitations are determining for the operation decision. These parameters have been calculated through a mixture of empirical and theoretical data of the power plant. Elecnor provided five different real start-up situations, which have been used to extrapolate the curves and to test the model. Under these situations, model results coincide with reality as it was expected. Due to the importance of the start-up, more situations would have probably been needed to a more accurate tuning of the parameter. However, the company did not provide more information and the results show a good correspondence.

As seen in figures 4.4 and 4.5, the factors that tip the scales between one operation decision and the other are complex in any situation. Electricity prices at night are important to determine how much of the fuel consumption at night can be recovered if the backup system is used to generate at night. However, the amount of extra solar generation that can be achieved has a stronger impact on the decision due to the premium added to the spot price. This additional solar generation is very influenced by the direct solar irradiation during the first hours of the morning. High enough irradiation to reach full capacity the second or third solar hour would allow a big difference with the current operation mode (A), when the first solar hours are used to start-up the power plant and hence, the solar energy cannot be sold. Electricity price during these prime generation hours is also very relevant for the optimization model, since it sets the price paid for this extra electricity and therefore, the potential increase of incomes that should compensate the additional costs.

The choice to generate or not during a short cloudy period is based on the same reasoning exposed above. In this case, the setback occasioned to the turbines because many stop-starts has not been considered in the model due to a decision of the company. Anyways, it could be easily incorporated to the model by adding the fictitious cost of a power plant stop, cost\(_{\text{stop}}\). This is the reason why binary variable \(u_t\) remains in the model formulation.

These complex features of the decision problem make the optimization model proposed a great help in the power plant planning and operation. It achieves
significant improvements in comparison to the solar-only operation, although it does increase the complexity of the operation. Main obstacles appear in the forecast of solar irradiation and electricity price. As it has been explained, decision equilibrium between how to operate the power plant is complicated. Wrong estimations of solar resource for the next two days could imply either over or under use of the backup systems diverging from the optimal solution. Additionally, direct solar irradiation is a very difficult parameter to forecast since it depends on the clouds position every moment and it is a field under extensive research nowadays.

The favorable point is that for either clear or completely covered days, the predictions improve significantly, and the location of the CSP power plant tends to be in arid regions with stable meteorological conditions. Astexol-2 is situated in one of the places with the best direct solar irradiation resource of Spain, and evidence can be found since there are many other CSP power plants in the area [33]. This fact decreases the number of cloudy and unstable days for the model, when its deterministic results are less trustworthy. For unfavorable days, experience and judgment of the power plant operator will still be needed to do a correct interpretation of the solution, either avoiding risk or managing the volatile conditions.

Both solar irradiation and electricity prices have a stochastic nature, which has not been taken into account in this deterministic model. Making our model stochastic would have a positive impact in the results, since the risk associated to the volatility of these parameters would be taken into account in our optimization problem.

Under a global point of view, the use of this optimization model has the potential to increase the clean electricity production as well as the profits for the company. Both impacts have been demonstrated through figures 4.6-4.8. However, economical profits of the power plant under the new regulation must be contextualized. Results showed above deals with the profits of the operation in the spot market and costs considered are always marginal cost of the operation. According to the new legislation, there is an additional state incentive to compensate the fixed costs of the investment in a state-of-the-art technology. This incentive is independent of the operation and will be received always the power plant overcomes a minimum production, easily achieved with the solar-only mode in Astexol-2. The total amount of the fixed reward to the investment for Astexol-2 (standard IT-01002) is set in 20.004.600 € a year, which means more than twice the potential profits of the power plant operation.

Regarding to the biomass hybridization strategy, its environmental impact is clearly positive since the power plant will contribute to reduce CO2 emissions. It is also very important to mention that biomass (pellets) is produced in Spain and its use would favor the young national pellet industry. At the same time, it would decrease the energy dependency of the fossil fuel exporting countries, in alignment to the EU policies [1].

As it has been mentioned before and according to table 4.1, the global results show an important increase in the use of the pellet boiler for start-up and generation in comparison with the natural gas boiler. Consequently, its operation would become more difficult and the higher complexity of biomass boilers would also slow-down the learning process of the new power plant operation proposed. On the other hand, the almost 3000% augmentation in the backup generation would result in more days of
continuous generation and hence, less stops of the power plant and less start-up process, which are the main cause of troubles in the daily operation. Another drawback of this higher utilization of the biomass boiler is related with its maintenance. While natural gas boilers need no maintenance, the dirty smoke from the biomass would cause several scheduled stops of the pellets boilers for cleaning. However, the impact of the maintenance can be reduced because Astexol-2 has a system of three boilers (1/3 power each) in parallel. During the time that one of the boilers is under maintenance, the other two could be perfectly used.

Considering only the economical point of view, the hybridization strategy would have a very limited economic impact in the power plant operation by its own, in contrast with the technical disadvantages. This impact has the potential to become larger with the years, since natural gas price historically increases much faster than pellets price, as it will be shown in next section. Certainly, the mentioned drawbacks could be somehow overcome and the social and environmental benefits are under no doubt. The strongest source of profit increase of this strategy could come from the new legislation. If the administration allows the change of the power plant reward standard from IT-01002 (fueled backup) to IT-01015 (biomass hybridization), the reward frame would change. The operational point of view studied in this Master Thesis would have no differences, since the premium for biomass generation will be 0 €/MWh. But the fixed incentive previously mentioned would increase up to 27.845.900 € (39%). Nevertheless, this option is not further developed in favor of a conservative perspective and due to the difficulties with the Spanish administration that it would cause.

Finally, and to justify the reliability of the model, Elecnor provided its total production estimation for the standardized year in two situations. The former, without the use of the boiler and the latter with a 12% of generation provided with the natural gas boiler according to 2007 feed-in tariff [7]. The first case is comparable with the case (A) simulated in this thesis and results show a very good correspondence to the model. Due to confidentiality, exact values cannot be provided but difference between both simulations is lower than 2%. The second case is not comparable to any of our simulation, but since in case (B) the same boilers are used less than the 12% of Elecnor simulation, results are expected to show a lower total generation just as it happens. Consequently, and in addition to the conformity of the company with the results showed, the model can be considered reliable according the objectives of this project.

4.4 Economic analysis of an investment in pellet boiler adaptation

After discussing the general considerations about the impact of the biomass hybridization strategy in the power plant, results of the yearly simulation will be used to perform a more detailed economic feasibility study of this strategy. Since the natural gas boilers are already installed and ready to use, the benefits in the change of the backup fuel will be analyzed in this section in comparison with the optimal use of the gas backup boilers provided by the model simulation, i.e. case c) will be contrasted with case (B). This analysis aims to set the limits of the maximal feasible investment in the hybridization strategy.
The starting point of the analysis [38] will be the annual profits of the model simulation for one year in each case, \( R_0 \) and \( R'_0 \). The ideal evolution of these parameters through the time should be considered by running the one-year simulation for every year studied, adjusting the electricity and fuel prices with its forecasted growth rate. This would be a very time consuming process and for the purpose of this section, a simplification is carried out.

In the approximation, the annual profits considered after \( n \) years, \( R_n \), increases proportionally to the electricity price, \( e \), since you will sell the electricity at a higher price. At the same time, this annual cash flow is reduced inversely proportional to the increase in fuel price, since a more expensive fuel will decrease the profits. Both factors are considered together through the equivalent inflation rate for our cash flow as it can be seen in equation 4.1. Analyzing 4.1 we regard that if electricity price increases faster than fuel price (\( e > g \)), this factor, \( r \), will be positive and the profits will increase every year. On the other hand, if fuel price increases faster (\( g > e \)) the impact will be negative for our cash flow. Evidently, the relationship between fuel and electricity prices with profits is not as simple in the model. We have proved in section 4.3 that the use of the boiler does not depend only on the price, and that the increase in the use of the backup is not proportional with the increase in profits. Nevertheless, this approximation can be good enough to give a first idea of the maximal investment since the increments in prices are rather small.

\[
r = \frac{e - g'}{1 + g'}
\]

(4.1)

Including also the effects of the taxes \( (t) \) and the rate of return \( (i) \) in our profits (more detailed equations in Appendix D), the evolution of the cash flow for the natural gas boiler and for the pellets boiler is finally estimated. Since the natural gas boilers are already installed in the power plant and they do not need any additional investment to be operated, the net profit of the biomass hybridization strategy will be the difference between the profits of the pellet backup and the profit of the gas backup through the years.

Additionally, annual maintenance cost for the hybridization strategy is considered in the investment analysis, since it is one of the main drawbacks for the pellets boilers. Therefore, a maintenance cost, \( FC_n \), is subtracted to \( R_n \) to study the investment feasibility. This cost is calculated as a percentage of the real cost of the boiler \( (m) \), and it is actualized every year including the inflation \( (g) \), and the expected rate of return, \( (i) \). The investment of the company \( (ICO) \), is divided in a direct contribution from the company \( (\alpha) \) plus a loan from the bank \( (\beta) \) with annual interest \( (i') \).

The financial parameters used for the analysis are summarized in table 4.2. The company provides the information about the bank’s interest rate \( (i') \), the desired rate of return \( (i) \) and the payback time. Inflation is estimated in 1.5% for the following years, based on the European Central Bank forecast [36]. Growth rate of pellets price is considered to increase at the same rate as inflation while natural gas increase faster, at 2.5% according to European Commission [36]. The Spanish electricity price growth rate is considered to increase under inflation, at 0.5%. The tendency was decreasing at
around -5,0% in the last two years due to restructuring of the sector and decrease of
the demand. However, new regulation of the sector and improvements of the Spanish
economy let us estimate a recovered stability of the electricity prices. The wide share
of renewable energy penetration in the Spanish grid softens the effect of the increase
in fossil fuel prices, main source of general inflation. Finally, the structure of the
investment chosen has been 40% of own contribution and 60% of loan in accordance
with Elecnor.

Alternative macro-economic scenarios to the one proposed here can be easily
studied through the equations provided in Appendix D. By simple inspection, it can be
proved that the most influential parameters for the final results are growth rate of fuel
and electricity prices, which are also the most difficult to forecast due to its natural
volatility.

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
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<tbody>
<tr>
<td>Interest rate</td>
<td>$i'$ 8,00%</td>
</tr>
<tr>
<td>Rate of return</td>
<td>$i$ 12,00%</td>
</tr>
<tr>
<td>Taxes</td>
<td>$t$ 36,00%</td>
</tr>
<tr>
<td>Inflation</td>
<td>$g$ 1,50%</td>
</tr>
<tr>
<td>Growth rate fuel price (pellets)</td>
<td>$g'$ 1,50%</td>
</tr>
<tr>
<td>Growth rate fuel price (NG)</td>
<td>$g''$ 2,50%</td>
</tr>
<tr>
<td>Growth rate of el price</td>
<td>$e$ 0,50%</td>
</tr>
<tr>
<td>Payback time</td>
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</tr>
<tr>
<td>Fraction of own contribution</td>
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</tr>
<tr>
<td>Fraction of loan</td>
<td>$\beta$ 60,00%</td>
</tr>
<tr>
<td>Maintenance cost factor</td>
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</tr>
<tr>
<td>Initial profits for pellets</td>
<td>$R_o$ 8.857.620 €</td>
</tr>
<tr>
<td>Initial profits for natural gas</td>
<td>$R_o'$ 8.647.394 €</td>
</tr>
<tr>
<td>Initial cost</td>
<td>$IC_o$ 1.983.527 €</td>
</tr>
</tbody>
</table>

*Table 4.2 Investment feasibility study parameters*

For the payback time desired by the company ($n=12$) the net profits (profits of pellet
minus profits of natural gas and minus operation cost) should be equal to the
actualized investment, so equation 4.2 is proposed. Solving this equation, the initial
investment cost ($ICo$) can be finally calculated. This value, 1.983.527 €, also shown in
table 4.2, is the budget for our hybridization strategy to be feasible according to the
technical data provided by the optimization model and the financial estimations
explained above.

$$R_{12}^{pellets} - R_{12}^{gas} - FC_{12} = I_{12} \quad (4.2)$$

The budget calculated is insufficient either to acquire three small pellet boilers
equivalent to the three installed natural gas boilers or to purchase one big pellet boiler
with the same total thermal power according to the company estimations. This leads
the company to study the adaptation of the natural gas boilers to pellets for the
biomass hybridization. Such an adaptation will be studied taking into account the
model proposed in this project and this estimated budget. Regarding the boiler adaptation, three main alternatives appear:

- An auxiliary combustion chamber for pellets could be added at the bottom of the boiler and the flame directed to its current position.
- Pulverization of pellets can be performed, similarly to coal pulverization. This modified fuel, which has an easier burning, can be used in an adapted burner providing better technical features.
- Gasification of pellets can be done in a special equipment to obtain biogas, which can then be utilized in the current boilers with no additional adaptations.

Elecnor will study these modifications in detail under a technical and economical point of view to make the final decision. The most feasible one will be finally included in the proposed model with a detailed calculation of its parameters to actualize the results and provide a final assessment of the company’s investment decision. However, the parameters referring to the boiler used during the calculation in this master thesis are not expected to change drastically since they are already based on real pellet boilers and prices. Final power capacity of the boiler will probably decreases due to the changes, which can be solved by adding more flexibility in the use of the boiler, i.e. allowing a use of the boiler during more hours ahead to the start-up. This implies a more complex operation, but it is not expected to be a limiting factor while the decrease of the thermal capacity remains around a 35%.

As a conclusion, the evolution of the investment cash flow is shown in figure 4.9. It can be noticed that after 20 years, still within the operating expected time of the power plant, the company could earn almost 5 times the initial investment, which is around 9,8 millions €. In the long term context, the profits of this investment after 20 years seems to be rather small in comparison with the total profits of the operation plus the fixed estate incentive mentioned in the previous section. Just the fixed incentive for one year regardless operation is over 20 millions €, twice as much as the investment profits in 20 years.

Figure 4.9 Investment feasibility study
Closure

5.1 Summary

This project has faced the viability study of changes in planning and operation of a solar thermal power plant due to changes in Spanish legislation. The uncertain economic environment established in the Spanish renewable energy sector since 2012 due to constant changes in the regulation has led the companies to operate in a way to minimize the operational risks. The announcement of a retrospective withdrawal of the feed-in tariff reward system in 2013 increased the incertitude of the whole sector. In particular the CSP technology, still in its first steps of development, saw its profitability jeopardized. The new legislation, where renewable energy power plants have to operate in the spot market, implies new requirements to optimize their operation.

Elecnor, in order to recover the profitability, conceived a biomass hybridization strategy, consisting in changing the current backup boiler system from natural gas to pellets. This could mean higher incentives from the state in addition to achieve a 100% renewable generation and avoid CO$_2$ taxes. The feasibility study of this hybridization strategy is studied in this project under the new sector regulation.

A MILP short-term planning deterministic model for a solar thermal power plant equipped with a backup boiler system has been created in this thesis to address the problem explained. This model aims to schedule the use of the backup system to optimize the performance of the power plant in the day-ahead market increasing the profits. The model considers the parameters referring to the backup system independently in order to allow the study of changes in planning and operation with the current gas boiler and with the pellets boiler desired in the hybridization strategy.

This model has been tested with real data provided by the company showing consistent results. The model has then been used to simulate the operation for one year in three different cases, which allow a realistic feasibility study of the hybridization strategy. Scenarios studied are:

a) No use of the boiler: current operation of the power plant to minimize cost.

b) Optimal use of the gas boilers: optimal operation with the already installed gas boilers.

c) Pellet boilers: optimal operation of the desired biomass hybridization strategy.

5.2 General conclusions and recommendations

Solar thermal technology has a great potential of development in the next decades according to IEA [3] and ECOSTAR [18] but it still has many challenges to overcome. As it has been discussed in chapter 2, competitiveness of CSP plants will be reached after decreases in the investment costs and through the innovation and development of the engineering and materials. However, since the electricity markets have been involved
in liberalization processes, the future of this technology will also be unavoidably tied to the operation in the spot market. Feed-in tariffs, which made possible its fast growing, cannot be the basis of its sustainable development. The study of the optimal operation of CSP power plants in the deregulated markets will also be an important field of research to achieve the desired competitiveness in the next decades.

Solar thermal technology has a significant advantage in comparison with other RES technologies such as photovoltaic or wind power for the operation in the spot market; it can control generation and avoid fluctuations. This is possible because CSP plants can be equipped with a backup system and/or with a thermal storage system, which can provide an extra heat resource. The extra heat resource can then be used as desired by the power plant operator to optimize the operation and profits in the spot markets. Short-term planning optimization models for CSP plants, as the one proposed in this project, will be helpful to achieve competitiveness in the deregulated markets. It will also help to move from the previous operation under feed-in tariffs to the new market conditions, as it has happened in Spain with the power plant studied in this thesis.

Probably the main inconvenience for the use of short-term planning models with solar thermal technology is the difficulty in making accurate forecasts for the direct sun irradiation. While forecasts models provide reliable predictions for some couples of hours ahead, the 24-48 hour forecasts needed for the operation in the spot market are only trustworthy for clear and stable sunny days. The development of direct sun irradiation prediction models is a field under extensive research. This research should go together with the CSP short-term planning models favoring the mentioned competitiveness objectives.

This project has aimed to be a little contribution to the solar thermal power development, and consequently to the renewable energy sector. Benefits of renewable energy in general are widely recognized by the international institutions, as it can be demonstrated in the EU 2001/77/EC directive [1]. In addition to these recognized social benefits, CSP technology can contribute to the stability of the power grid, increasing the integration share of other non-dispatchable RES technologies in the grid. This special feature enhances the effect of this still immature technology in the RES sector.

5.3 Conclusions from the case study

During this project, the model proposed has been used to simulate the performance of a real 50 MW solar thermal power plant, Astexol-2, located in Spain. Parameters used in the model have been calculated through a mixture of theoretical data from the design documents of the power plant and empirical data from the operation. This fact makes the model proposed applicable to any other parabolic trough CSP plant equipped with any kind of backup boiler system.

The analysis of the changes in operation occasioned by the use of the short-term planning optimization model in the day-ahead market shows important improvements to the current situation. As it has been discussed in chapter 4, the correct use of the
backup system is translated into an increase in profits and generation. This increase is achieved by earlier start-ups due to the use of the backup boilers to pre-heat the power plant and reach generation conditions earlier, but also by generation at night through the backup system. Generation at night can avoid the shut down of the power plant, which leads to take advantage of sun irradiation since the first hour in the morning. In general, the optimization model allows a better exploitation of the solar resource thanks to the backup boilers, which also means an increase in profits.

The comparison of the three cases studied allows a wide vision of the strengths and weaknesses of the hybridization strategy. The implementation of a pellet backup boiler will increase generation significantly, but the increase in profits will not be as high. This occurs because the augmentation in generation is caused by a more extensive use of the backup system in comparison with the currently installed natural gas boilers. The higher utilization implies, at the same time, a more difficult operation and a slower learning curve for the new boilers. Biomass boilers are in general more difficult to operate and require periodical maintenance.

On the other hand, the hybridization strategy will allow a 100% renewable power plant, decreasing the consumption of fossil fuels. Since the Spanish pellet market could assume the requirements of this power plant, this strategy would also help to decrease the dependence in foreign energy in alignment to the EU policies [1]. Volatility of natural gas prices in Spain and its dependence with political affairs makes the use of pellet more predictable in the long term. Moreover, price growth rate of natural gas has been higher than pellets in the last years [31] and this tendency is expected to continue. For the operation of the power plant, this will mean a bigger difference in favor of the pellets every year.

These prices evolutions together with other macro-economic parameters have been considered in the investment feasibility study in section 4.4. The results show the long-term evolution of the investment. Even though the economic impact in the operation with the biomass hybridization is not enough to acquire a completely new biomass boiler system, it seems to be sufficient to accomplish a boiler adaptation for burning pellets. However, a further study must be done to evaluate the technical feasibility of these modifications.

The impact of the model could vary from one location to another, since different solar resource and electricity prices will alter the results of the model. Nevertheless, the analysis of the results shows that the backup system contributes the increase of profits and generation in both winter and summer and in days with good and bad solar resource. This fact underlines the importance of the short-term planning model for the operation in the spot market for any CSP power plant. However, the feasibility analysis of the biomass hybridization must be done carefully in each situation. It depends on many factors and advantages are not clearly over the disadvantages yet, so a global conclusion about hybridization of CSP power plants with biomass backup boilers cannot be determined with generality.
5.4 Future studies

This project provides a tool to be used as a first approximation of the short-term planning problem in a solar thermal power plant with backup boilers in the day-ahead electricity market. The use of this tool in the real operation of the power plant will need a constant update of the model parameters, especially the parameters referring the start-up process. This constant tuning of the model parameters can be easily done following the documents provided by the company for the parameters calculation, and should aim to a constant improvement of the equations to be as close as possible to the real behavior of the power plant.

There are two main sources of improvements in the model to address the short-term planning problem completely. The former is to develop the deterministic model proposed into a stochastic model. This stochastic model, despite of a higher complexity, would allow introducing the risk resulting from the sun and price forecast uncertainty as an objective variable to optimize. The latter is to take into consideration in the model the different regulation markets where the power plant can operate, e.g. the intraday market or the balancing market. Since direct solar irradiation forecast is much more reliable some hours in advance than 24-48 hours ahead, operation in the secondary markets could be more precise and correct the deviations observed from the operation in the day-ahead market. This would be considered through a multi-stage optimization model with the same base as the model proposed here.

Finally, another interesting improvement to the model would be to include the option of thermal storage. This has been considered at the beginning of the project but rejected by the company, since its strategy was only focused in the biomass hybridization. However, the study of thermal storage systems is a field under extensive research at present, e.g. Powell and Edgar [34] investigates the dynamic modeling and control of the thermal storage system while the optimal operation of a solar-thermal power plant with energy storage and electricity buy-back from the grid is studied in [35].
References


Solar field performance report, **Confidential.**

Elecnor, “Balance de Materia y Energía”, **Confidential.**

Elecnor, “Manual de operación de la planta”, **Confidential.**


[38] Kaldelis I, Spyropoulos G, Kavvadias K. “Computational Applications of Renewable Energy Sources” (in Greek)
## APPENDIX A: SUMMARY OF DATA CALCULATION

### Description of the model parameters calculation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Data</th>
<th>Unit</th>
<th>Explanation</th>
<th>Calculation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_t$</td>
<td>Electricity price forecast</td>
<td>€/MWh</td>
<td>A forecast of the electricity spot price in the day-ahead market for each hour of the following day.</td>
<td>Hourly electricity price of the day-ahead market of 2013 based on OMIE (<a href="http://www.omie.com">www.omie.com</a>)</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{sun}$</td>
<td>Solar thermal premium</td>
<td>€/MWh</td>
<td>Value added to the spot price for the electricity produced through the sun in order to make this technology competitive in the market.</td>
<td>From the draft of the new RES power plant retribution law. February 2014</td>
<td>37.375</td>
</tr>
<tr>
<td>$\lambda_{bio}$</td>
<td>Biomass premium</td>
<td>€/MWh</td>
<td>Value added to the spot price for the electricity produced through the biomass in order to make this technology competitive in the market.</td>
<td>From the draft of the new RES power plant retribution law. February 2014</td>
<td>0</td>
</tr>
<tr>
<td>$\lambda_{CO2}$</td>
<td>CO$_2$ emission tax</td>
<td>€/MWh</td>
<td>Cost of CO$_2$ emissions per MWh of natural gas measured in LHV</td>
<td>Data form Elecnor monthly report about prices evolution</td>
<td>1.2</td>
</tr>
<tr>
<td>$c_{off}$</td>
<td>Fixed off-line operation cost</td>
<td>€/h</td>
<td>Operation cost of the power plant to keep the needed systems working when it is off-line. This energy is bought from the power grid.</td>
<td>Calculated as an average of empirical data from the power plant operation.</td>
<td>42.5</td>
</tr>
<tr>
<td>$c_{of}$</td>
<td>Fixed operation cost in antifreeze mode</td>
<td>€/h</td>
<td>Operation cost of the power plant to keep the needed systems working when it is operating in the antifreeze mode. This energy is bought from the power grid.</td>
<td>Calculated as an average of empirical data from the power plant operation.</td>
<td>142.5</td>
</tr>
</tbody>
</table>
| $cost_{fuel}$ | Variable cost function | €/h | Function that calculates the variable costs of the power plant operation associated with the fuel consumption in the boiler. $B(G_{t,gen}) = b_1 + b_2 \cdot G_{t,gen}$ | Calculated through the power plant energy balances provided by Elecnor as the amount of fuel needed to provide $G_{t,gen}$ MWh/h of heat and multiplied by the fuel price. Results can be approximate the function as linear without loss of accuracy | GAS $b_{fuel} = 56.351$  
BIO $b_{fuel} = 43.1519$ |
| $c_{start}$ | Fixed cost of the power plant start-up | € | Value of the fixed electricity consumption during a start-up process | Calculated as an average of empirical data from the power plant operation provided by Elecnor. | 177.5 |
| $C_{b,start}$ | Fixed cost of the start-up of the boiler | € | Fixed cost that the boiler incurs when it starts-up | Calculated as the total fuel consumption until the burner can begin operation (provided by the manufacturer) multiplied by the fuel price. | GAS 103.25  
BIO 172 |
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi_t$</td>
<td>Forecasted solar DNI</td>
<td>W/m²</td>
<td>Prediction of energy received on collectors plane every hour of the day.</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Mirror field absorption capacity</td>
<td>MWh/(W/m²h)</td>
<td>Factor that gives the percentage of the solar DNI that the mirror field is able to transmit to the HFT.</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Heat to electricity function</td>
<td>MWh/h</td>
<td>Linear function that relates the heat produced either in the solar field or in the boiler with the electricity sold to the power grid. This function is related with the efficiency of the thermodynamic cycle and includes the auto-consumption of the power plant when it is on-line.</td>
</tr>
<tr>
<td>$H$</td>
<td>Maximum production of the boiler</td>
<td>MWh/h</td>
<td>Maximum heat produced by the boiler.</td>
</tr>
<tr>
<td>$H_{\text{min}}$</td>
<td>Minimum produced by the boiler</td>
<td>MWh/h</td>
<td>Minimum heat produced by the boiler.</td>
</tr>
<tr>
<td>$E_{\text{start},i}$</td>
<td>Discrete interval of the start-up energy needed for the start-up after $i$ hours off-line</td>
<td>MWh</td>
<td>Energy needed to start-up the power plant after $i$ hours off line. It is calculated as the energy needed to heat up the HTF, the steam generator system and synchronize the turbine. (Second heating of the turbine not included).</td>
</tr>
<tr>
<td>$E_{\text{af},i}$</td>
<td>Energy needed for the antifreeze mode</td>
<td>MWh/h</td>
<td>Energy needed for keeping the HFT above 50ºC.</td>
</tr>
<tr>
<td>$t_{\text{off}_{\text{max}}}$</td>
<td>Maximum time offline until antifreeze</td>
<td>h</td>
<td>It is the maximum number of hours the power plant can be offline until either the antifreeze mode starts or the power plant starts-up.</td>
</tr>
<tr>
<td>$SU_{x,i}$</td>
<td>Start-up ramp limits</td>
<td>MWh/h</td>
<td>Parameters used to follow the start-up curves of the different start-up process after $i$ hours off line during the time that the start-up process last.</td>
</tr>
<tr>
<td>$p$</td>
<td>Maximum power output</td>
<td>MWh/h</td>
<td>Maximum power output of the power plant.</td>
</tr>
<tr>
<td>$p_{\text{min}}$</td>
<td>Minimal power output</td>
<td>MWh/h</td>
<td>Minimum power output of the power plant.</td>
</tr>
</tbody>
</table>

Data of an standardized solar-year in Astexol-2, provided by Elecnor

Calculated through theoretical data provided by the solar field supplier (figure 2)

Calculated through the energy balances of the power plant operation provided by Elecnor (figure 1)

$\eta(\ldots) = \eta_1 + \eta_2 \cdot H$,

$\eta_1 = -4.5174$

$\eta_2 = 0.3983$

Boiler specifications provided by the manufacturer.

Boiler specifications provided by the manufacturer.

GAS 44

BIO 44

GAS 5

BIO 5

See APPENDIX B

Empirical data of the energy needed to start-up the power plant during different days with different off-line hours are used to estimate the function and to split it in $i$ intervals for each off-line hour.

1.5

Approximated through empirical operation. Very rare operation due to weather conditions in the power plant location

72

See excel in APPENDIX B

Nominal value of the power plant

50

Nominal value of the power plant

3.76
**Figure 1** Heat to electricity function

**Figure 2** Calculation of the solar absorption factor of the mirror field
APPENDIX B: START-UP DATA CALCULATION

Calculation of start-up parameters:

Figure 3 shows the results of performing a regression with Excel to interpolate the data of 5 different start-up process.

![Graph showing heat requirement for start-up vs hours offline]

**Figure 3** Heat requirement for start-up after \( t \) hours offline

Next table shows the calculation of the SU parameters based on the time restriction
<table>
<thead>
<tr>
<th>Time offline</th>
<th>Time to heat HTF</th>
<th>Time to heat SGS</th>
<th>Time to heat steam</th>
<th>Min temp of turbine</th>
<th>1st heating time of turbine</th>
<th>Synch time of turbine</th>
<th>2nd heating time of turbine</th>
<th>Time to max power with no generation</th>
<th>Generating time %</th>
<th>Generating time 1st hour</th>
<th>SU1min</th>
<th>SU1max</th>
<th>SU2min</th>
<th>SU2max</th>
<th>Estart</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>min</td>
<td>min</td>
<td>min</td>
<td>°C</td>
<td>min</td>
<td>min</td>
<td>min</td>
<td>min</td>
<td>min</td>
<td>min</td>
<td>MW</td>
<td>MW</td>
<td>MW</td>
<td>MW</td>
<td>Ext</td>
</tr>
<tr>
<td>1</td>
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<td>6</td>
<td>7</td>
<td>19</td>
<td>341.07</td>
<td>15</td>
<td>5</td>
<td>0</td>
<td>52</td>
<td>52</td>
<td>60</td>
<td>8</td>
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<tr>
<td>2</td>
<td>120</td>
<td>6</td>
<td>7</td>
<td>19</td>
<td>322.29</td>
<td>15</td>
<td>5</td>
<td>0</td>
<td>52</td>
<td>52</td>
<td>60</td>
<td>8</td>
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<tr>
<td>3</td>
<td>180</td>
<td>6</td>
<td>7</td>
<td>19</td>
<td>313.15</td>
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<td>52</td>
<td>52</td>
<td>60</td>
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<td>4</td>
<td>240</td>
<td>6</td>
<td>7</td>
<td>19</td>
<td>306.80</td>
<td>15</td>
<td>5</td>
<td>0</td>
<td>52</td>
<td>52</td>
<td>60</td>
<td>8</td>
<td>OFF4</td>
<td></td>
<td>0.50</td>
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<tr>
<td>5</td>
<td>300</td>
<td>6</td>
<td>7</td>
<td>19</td>
<td>298.59</td>
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<td>60</td>
<td>8</td>
<td>OFF5</td>
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<td>0.50</td>
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<tr>
<td>6</td>
<td>360</td>
<td>6</td>
<td>7</td>
<td>19</td>
<td>290.53</td>
<td>15</td>
<td>5</td>
<td>0</td>
<td>52</td>
<td>52</td>
<td>60</td>
<td>8</td>
<td>OFF6</td>
<td></td>
<td>0.50</td>
</tr>
</tbody>
</table>

**HFT heating rate** 4 °C/min

<table>
<thead>
<tr>
<th>Pmin</th>
<th>3,73</th>
<th>50,00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pmax</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramp to Pmax</td>
<td></td>
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</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>51</td>
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</tr>
<tr>
<td>70</td>
<td>4200</td>
<td>6</td>
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<td>4260</td>
<td>6</td>
</tr>
<tr>
<td>72</td>
<td>4320</td>
<td>6</td>
</tr>
</tbody>
</table>
APPENDIX C: GAMS CODE

Gams code used to perform the simulations

$ONText
CSP power plant with a fueled backup boiler in the spot market
$OFFText

Sets
  t hour /H1*H48/  
  i off-line hours /OFF1*OFF72/  
  aux auxiliary set for equation startup1 /1*72/  
;
*Model data

$CALL GDXXRW.EXE sunpred.xlsx par=sun rng=A1:B48 Rdim=1 Cdim=0
Parameter sun(t);
$GDXIN sunpred.gdx
$LOAD sun
$GDXIN
display sun;

$CALL GDXXRW.EXE pricepred.xlsx par=lambda rng=A1:B48 Rdim=1 Cdim=0
Parameter lambda(t);
$GDXIN pricepred.gdx
$LOAD lambda
$GDXIN
display lambda;

Parameters
  lambdasun premium for electricity generated with sun /XX/
  lambdabio premium for electricity generated with biomass /XX/
  lambdac02 premium for electricity generated with biomass /XX/
  eta1 independent term of the 'heat to electricity efficiency' function /XX/
  eta2 slope of the 'heat to electricity efficiency' function /XX/
  A fixed operation cost of the power plant when off-line /XX/
  Aaf1 fixed operation cost of the antifreeze mode /XX/
  b1 independent term of the fuel consumption function /XX/
  b2 slope of the fuel consumption function /XX/
  c1 fixed cost of the power plant start-up /XX/
  D boiler start-up cost /XX/
  alpha solar absorption capacity of the mirror field /XX/
  Gmax maximum thermal production with the boiler /XX/
  Gmin minimum thermal production with the boiler /XX/
  Gminop minimum thermal production to generate electricity with the boiler
  Is(i) energy needed for start-up after i hours off-line
  /OFF1 XX, OFF2 XX, ..., OFF71 XX, OFF72 XX/
  Iaf energy needed for the antifreeze mode /XX/
  toffmax maximum number of hours the power plant can be off-line until af
  /XX/
  SUmin1(i) minimal start-up requirement in first hour
  /OFF1 XX, OFF2 XX, ..., OFF71 XX, OFF72 XX/
  SUmin2(i) minimal start-up requirement in second hour
  /OFF1 XX, OFF2 XX, ..., OFF71 XX, OFF72 XX/
  SUmax1(i) maximal start-up limit in first hour
  /OFF1 XX, OFF2 XX, ..., OFF71 XX, OFF72 XX/
SUmax2(i) maximal start-up limit in second hour

Pmax maximum power output of the power plant
Pmin minimum power output of the power plant
u0 status of the power plant at hour 0
uaf0 status of the power plant at hour 0
toff0 number of hours the power plant has been off-line at hour 0
vgen0 status of the boiler at hour 0
vstart0 status of the boiler at hour 0
vaf0 status of the boiler at hour 0
NS number of steps of the discrete function that regulates the startup

Gminop = (Pmin-eta1b)/(eta2*alpha)

*functions
Positive variables
   b(t) variable cost function
   c(t) startup cost function
   aaf(t) antifreeze mode cost function
;
*optimization variable
Free variable
   z maximization variable
;
*model variables
Positive variables
   G(t) power output from the boiler at hour t
   Ggen(t) heat provided from the boiler for generation at hour t
   Gstart(t) heat provided from the boiler for start-up at hour t
   Gaf(t) heat provided from the boiler for antifreeze mode at hour t
   S(t) power output from the sun at hour t
   toff(t) number of hours the power plant has been off-line at hour t
   y(t) auxiliary variable for the toff counter
;
Binary variables
   u(t) unit commitment of the power plant at hour t
   us(t) start-up order of the power plant at hour t
   uss(t,i) start-up order of the power plant at hour t after i hours off-line
   ustop(t) shutdown order of the power plant
   uaf(t) antifreeze mode commitment at hour t
   vgen(t) boiler commitment for generating electricity at hour t
   vstart(t) boiler commitment for the start-up at hour t
   vaf(t) boiler commitment for the antifreeze mode at hour t
   vs(t) start-up order of the boiler at hour t
   vstop(t) shutdown order of the boiler at hour t
;
Equation
   objfunc objective function;
   objfunc .. z =e= sum(t, (lambda(t)+lambdasun)*S(t) +
   (lambda(t)+lambdabio)*G(t) - lambdaCO2*(Ggen(t)+Gstart(t)+Gaf(t)) - A*(1-
   u(t)-uaf(t)) - b(t) - c(t) - D*vs(t) - aaf(t));
Equations

sunprod(t) total electricity available from the sun
boilerprod(t) total electricity available from the boiler
variablecost(t) variable cost of the power plant
startup1(t) energy balance of the start-up process
startup2(t) toff startup type
startup3(t) relation with the toff counter
startup4(t) relation with the toff counter
startup5(t) relation with the toff counter
startup6(t) regulates the priority in the use of the boiler for start-up
startup7(t) regulates the priority in the use of the boiler for start-up
startup8(t) regulates the priority in the use of the boiler for start-up
startup9(t) regulates the priority in the use of the boiler for start-up
startup10(t) regulates the priority in the use of the boiler for start-up
startupcost(t) startup cost of the power plant
toffcounter1(t) toff counter equation
toffcounter2(t) toff counter equation
toffcounter3(t) toff counter equation
antifreeze1(t) equation that forces to start the antifreeze mode
antifreeze2(t) equation that forces to start the antifreeze mode
antifreezecost(t) antifeeze mode cost of the power plant
genlimits1(t) lower generation limit of the power plant
ngenlimits2(t) upper generation limit of the power plant
boilerlimit1(t) maximum limit of the boiler for generation
boilerlimit2(t) minimum limit of the boiler for generation
boilerlimit3(t) maximum limit of the boiler for start-up
boilerlimit4(t) minimum limit of the boiler for start-up
boilerlimit5(t) maximum limit of the boiler for antifreeze mode
boilerlimit6(t) minimum limit of the boiler for antifreeze mode
commitment1(t) logic equation of the power plant commitment
commitment2(t) logic equation of the boiler commitment
commitment3(t) logic equation of the boiler commitment
commitment4(t) logic equation of the power plant commitment
commitment5(t) logic equation of the boiler commitment
commitment6(t) logic equation of the power plant commitment
commitment7(t) logic equation of the power plant commitment
commitment8(t) logic equation of the boiler start-up
commitment9(t) logic equation of the boiler generation

suntime(t) = \eta_1 s(t) (sun(t) > G_{min\_opp}) + u(t) \eta_2 \alpha s(t) (sun(t) > G_{min\_opp});
boiler(t) = \eta_1 b(t) (sun(t) > G_{min\_opp}) + \eta_2 G_{gen} (t);
variablecost(t) = b(t) = b_1 v(t) + b_2 G_{gen} (t);
toffcounter1(t) = (toff(t) + toff_0 (ord(t) = 1) + 1) \cdot u(t) - (toff_{max} + 1) \cdot u(t) = toff(t);
toffcounter2(t) = toff(t) = (toff(t) + toff_0 (ord(t) = 1) + 1);
toffcounter3(t) = toff_{max} (1 - u(t));
startup1(t) = \sum_i (I_s (i) - \sum (aux (ord(i) - ord(aux)) > 0), \alpha \cdot s(t - (ord(i) - ord(aux)))) + \alpha \cdot s_0 (ord(t) = ord(i)) \cdot \sum (ord(i) < NS)) + y(t);
startup4(t) = y(t) = toff_{max} (uss (t, 'OFF72') - u(t) + 1);
NOTE: Change 'OFF72' to the last value of the set i
startup5(t) .. vstart(t) - vstart(t-1) =e= (us(t)-1) + (vstart(t) - Gstart(t)/Gmax);
startup6(t) .. vstart(t) - vstart(t-1) =e= (us(t)-1) + (vstart(t) - Gstart(t)/Gmax);
startup7(t) .. vstart(t-2) - vstart(t-3) =e= (us(t)-1) + (vstart(t-2) - Gstart(t-2)/Gmax);
startup8(t) .. vstart(t-3) - vstart(t-4) =e= (us(t)-1) + (vstart(t-3) - Gstart(t-3)/Gmax);
startup9(t) .. vstart(t-4) - vstart(t-5) =e= (us(t)-1) + (vstart(t-4) - Gstart(t-4)/Gmax);
startup10(t) .. c(t) =e= c1*us(t) + b1*vstart(t) + b2*Gstart(t);
antifreeze1(t) .. uaf(t) =e= toff(t)/toffmax * 0.999999;
antifreeze2(t) .. uaf(t) =e= toff(t)/toffmax;
antifreeze3(t) .. (Iaf - alpha*sun(t))*uaf(t) =e= Gaf(t);
antifreezecost(t) .. aaf(t) =e= Aaf1*uaf(t) + b1*vaf(t) + b2*Gaf(t);
genlimits1(t) .. (G(t) + S(t)) =e= Pmin*(u(t) - us(t) - us(t-1)) + sum(i, SUmin1(i)*uss(t,i) + SUmin2(i)*uss(t-1,i));
genlimits2(t) .. (G(t) + S(t)) =e= Pmax*(u(t) - us(t) - us(t-1)) + sum(i, SUmax1(i)*uss(t,i) + SUmax2(i)*uss(t-1,i));
boilerlimit1(t) .. Ggen(t) =e= Gminop*vgen(t);
boilerlimit2(t) .. Ggen(t) =e= Gmax*vgen(t);
boilerlimit3(t) .. Gstart(t) =e= Gmin*vstart(t);
boilerlimit4(t) .. Gstart(t) =e= Gmax*vstart(t);
boilerlimit5(t) .. Gaf(t) =e= Gmin*vaf(t);
boilerlimit6(t) .. Gaf(t) =e= Gmax*vaf(t);

commitment1(t) .. u(t) - u(t-1) - u0$(ord(t)=1) =e= us(t) - ustop(t);
commitment2(t) .. vgen(t) + vstart(t) + vaf(t) - vgen(t-1) - vgen0$(ord(t)=1) - vstart(t-1) - vstart0$(ord(t)=1) - vaf(t-1) - vaf0$(ord(t)=1) =e= vs(t) - vstop(t);
commitment3(t) .. vgen(t) + vstart(t) + vaf(t) =e= 1;
commitment4(t) .. us(t) + ustop(t) =e= 1;
commitment5(t) .. vs(t) + vstop(t) =e= 1;
commitment6(t) .. u(t) + uaf(t) =e= 1;
commitment7(t) .. vaf(t) =e= uaf(t);
commitment8(t) .. vstart(t) =e= 1 - u(t) + us(t);
commitment9(t) .. vgen(t) =e= u(t);
model CSPgas /all/;
solve CSPgas using mip maximizing z;
Parameters
  P total generation in power plant i hour t
  Gtot
;
P = sum(t,G.L(t) + S.L(t));
Gtot = sum(t,Gstart.L(t));
## APPENDIX D: Investment study

### FEASIBILITY STUDY OF PELLET BOILER ADAPTATION

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