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Abstract

The increase of electric power demand and the wish to protect the environment are leading to a change in the energy sources. Conventional energy plants are losing strength against the renewable energy plants and, in particular, solar energy plants have a huge potential to provide clean energy supply for the increasing world's energy demand. Among the existing solar technologies, Concentrating Solar Power (CSP) is one of the most promising technologies. One of the major advantages of CSP plants is the technically feasible and cost-effective integration of Thermal Energy Storage (TES) systems.

To increase the plant dispatchability, it is possible to create different operational strategies defining how such TES system is used. In this work, different strategies with different overall goals have been simulated over a complete year and the results are presented and compared here to demonstrate the capabilities of the operational strategies towards an increased dispatchability and plant economic effectiveness. The analysis shows that different strategies may lead to significant differences in the plant annual production, expected economic incomes, number of power block stops, mean efficiency, etc. Specifically, it has been found that the economic incomes of a plant can be increased (+1.3%) even with a decreased total energy production (-1.5%) if the production is scheduled to follow a demand/price curve. Also, dramatic reduction in the number of turbine stops (-67%) can be achieved if the plant is operated towards this objective. The strategies presented in this study have not been optimized towards any specific objective, but only created to show the potential of well designed operational strategies in CSP plants. Therefore, many other strategies as well as optimized versions of the strategies explained below are possible and will be analyzed in future works.

Keywords: Concentrating solar power (CSP); Thermal Energy Storage; energy management and dispatchability; operational strategies; CSP plant modeling and simulation.

1. Introduction

The current situation of the energy system, consisting primarily of fossil fuels generation, will be unsustainable in the long term because of the environmental, economic and security of supply [1]. In this framework, the use of the renewables resources emerges and gains strength. The major problem of this type of energy is the uncertainty and non-dispatchable nature of such generation, which may cause problems to the electric grid; e.g.: the integration of the fluctuating generation of wind and solar photovoltaic technologies. However, the storage can partially sort out the problems caused by this variability and uncertainty of the renewable energies by means of the improvement of the dispacthability and uncertainty related to the renewable resource [2][3].

Among all renewable resources, solar energy is the largest energy source. The solar energy reaching the earth is 10000 times greater than the total energy consumption. Therefore, this resource is expected to be the most widely used among all renewable resources in the future [4].

Given the above, although the Concentrated Solar Power (CSP) technology is still more expensive than other renewable technologies, it is making its own way among these renewable technologies due to the availability of cost effective thermal energy storage. Consequently, CSP installed capacity has increased nearly 10-fold since 2014, up to 3,425 GW in 2013 [5], being US and Spain the countries with the largest CSP installed capacity. Among the four major CSP technologies, parabolic trough is the most proven and commonly used, but solar tower is recently gaining relevance since seems to be the most promising one. In fact, around the 90% of the global installed capacity is parabolic trough (3GW) and over 1 GW is under construction [6], while tower technology is rapidly increasing its share, with189 MW in operation but more than 500 MW in commissioning, construction and promotion. Anyway, the research of the different CSP technologies is leading to a continuous reduction of the LCOE which is getting close to a competitive price of the energy. According to the CSP roadmap published by the IEA [7], CSP will be competitive to conventional technologies by 2030 and moreover, it could provide an 11.3% of the global energetic demand also by 2050 [8].

The main current targets of CSP are to achieve a competitive sale price of the energy and to adapt the production to demand or price curves. Both goals are strongly benefitted by TES, since it permits to operate the CSP plant in different ways, making it possible create distinct operational strategies to increase the plant dispatchability and to provide steady capacity to the grid as conventional generation plants do. However, although the operation strategies study seems to be a very promising field, only few studies aimed to improve the dispachtability and the revenues of a CSP plant from operation strategies can be found in the literature.

The pioneering work about the operation of CSP is due to Sioshansi and Denholm [9], who analyzed the value of CSP plants and TES in different regions in US. The authors developed a mixed integer program (MIP), this model takes the main characteristics of a CSP plant (location, weather conditions …) and mixes them with the market data in order to optimize the plant´s operation and maximize the profits. The previous model uses SAM´s energetic model [10]; a software platform based in the time-series program TRNSYS which simulates the dynamic of a CSP plant. The weather data and solar field characteristics are inputs for SAM, used to calculate the amount of thermal energy collected per hour by the solar field, which, in turn, is the input read by the MIP-model. [11] used the previous model to determine the best configuration out of 100 possible, in terms of solar multiple (MS) and storage capacity.

Guedez, Spelling, Fransson and Laumert [12] analyzed the integration of TES in CSP plants to shift the power production from times where is low demand to periods where electricity prices are higher. The authors present different optimum plant configurations using a thermo-economic optimization approach to compare the benefits obtained, with an instant-dispatch strategy respect to a peak price strategy. They conclude for the location regarded and considering a larger MS and smaller size storage that the peaking approach will generate better profits, highlighting the importance of a reliable forecasting.

In the present work, the focus is not on the CSP plant configuration but on the control of the energy streams in the plant through the operation strategies, in order to improve the plant operation, once it is designed or constructed. For this, it is considered that there are three main objectives for the operation strategies: achieving large energy yields, achieving good adjustments of the production to demand or price curves, and reducing maintenance costs. Therefore, the paper aims to develop, implement and analyze the behavior of different operation strategies for already designed power plants. In the following, a very flexible strategy allowing for the creation of different specific strategies aiming at different objectives as well as the simulation of three of these specific strategies and the different results in the plant operation over a one year period are explained.

2. A Flexible Operation Strategy:

The possibilities for the operation of a CSP power plant regarding the management of the energy streams from the solar field, to and from the storage system and from a possible fuel burner are infinite, since the decision may depend not only on the available solar energy or on the state of charge of the storage, but also and most importantly, on the specific date and time (day or night, instantaneous electricity demand or selling price, grid requirements or limitations, etc.). In this sense, if operational strategies are to be analyzed, the first required step is to create a finite set of options to be studied. For this, different strategies can be created independently or, more often, a single strategy offering certain degree of flexibility through a set of defining parameters can be used. The later approach can be found in models and previous studies found in the literature [13] and is also the approach used in the current work.

To limit the infinite options, a single but extremely flexible operational strategy defined by a limited set of user chosen parameters has been created. This strategy allows the implementation of a wide range of specific strategies regarding the use of the storage and burner depending on the date, time and status of the plant. Basically, supporting on the definition of a set of parameters it is possible to control the state of charge of the TES and the electric production of the power block. This flexible operational strategy can be modified in order to obtain different strategies oriented to reach different goals. The parameters of this flexible strategy will have different values for each hour of the year, providing enough flexibility to operate the plant in a different way depending on the hour and date and, therefore, allowing for considering demand or price curves. The way this flexible strategy works is explained in the following paragraphs through the description of its defining parameters.

There are three parameters related to the TES charging strategy and the operation of the power block:

- Power block minimum power from solar field supply (pbMinPowerFromSF, see Figure 1**):**
  1. **Use:** Defining a minimum load under which the power block must be operating when the solar field is delivering thermal power.
  2. **Behavior:** The first goal in the plant operation whenever the solar field is producing thermal energy will be to keep the power block running at a specific minimum load defined by this parameter. This means that all the power supplied by the solar field will be used to run the power block up to this minimum load. Only when the power block is already operating at this minimum load, the excess of power produced by the solar field can be used for other means, for instance charging the storage system. If the solar field is not providing enough power to reach this minimum load, the power block will be run at the maximum possible load with the available power from the solar field.
- Storage minimum level from solar field (tesMinLevelFromSF, see Figure 1):
  1. **Use:** Defining a minimum state of charge to be reached in the storage system before running the power block at nominal load.
  2. **Behavior:** Once the power block is operating at the minimum power defined through the "pbMinPowerFromSF" parameter, the excess of power produced by the solar field is used to charge the storage up to the minimum level defined by this parameter. Again, only when this minimum storage state of charge is reached the excess of thermal power produced by the solar field will be used to run the power block at higher loads, up to its nominal power..
- Power block nominal power from solar field (pbNominalPowerFromSF, see Figure 1):
  1. **Use:** Defining the nominal/desired load of the power block, once the storage has reached its minimum desired level.
  2. **Behavior:** When the storage system has reached the minimum level defined with the tesMinLevelFromSF parameter (and therefore the power block is already running at the minimum desired load defined by pbMinPowerFromSF) the power supplied by the solar field will be used to run the power block at its nominal load. Note that in this case, nominal does not necessarily mean full load or rated power of the power block, but whatever desired power defined by the user/operator for each specific hour of the year. The value of this parameter might vary from "pbMinPowerFromSF" and the maximum power allowed for the power block (could be over the rated power of the power block).

If the solar field provides more power than the needed for running the power block at its nominal power, the excess will be used to charge the storage system up to its maximum capacity. If the storage is full and an excess of power keeps coming from the solar field, it is considered that the power block will be overloaded up to its maximum allowable level. Finally, only when the storage is completely full and the power block is running at its maximum allowable load, the solar field will be defocused and the excess of power dumped.

On the other side, when the thermal power provided by the solar field is not enough to operate the power block at certain aimed load, the storage will be discharged to reach such desired load. A second set of parameters is used to control the discharging strategy of the storage system:

- Storage minimum level to discharge (tesMinLevelDischarge, see Figure 1):
  1. **Use:** Defining a minimum storage state of charge value over which it will be discharged at nominal power block load and below which it will be discharged at a minimum power block load.
  2. **Behavior:** It allows operating the power block in two different ways when it receives the energy from the storage. As long as in the case the state of charge is larger than tesMinLevelDischarge, the power block will work at pbNominalPowerFromTES, and when the state of charge is lower it will operate at pbMinimumPowerFromTES.

- Power block nominal power from storage supply (pbNominalPowerFromTES, see Figure 1):
  1. **Use:** Defining the power block desired load to be reached when discharging the TES while the storage level is higher than “minLevelTESdischarge”.
  2. **Behavior:** If there is not enough power from the solar field, the storage system will be discharged to provide the power required to keep the power block running at the nominal load defined by this parameter. The nominal power block load when working from the TES should not necessarily be the same than the nominal load when operating from the solar field and, of course, neither be its rated power. This nominal power of the power block will be kept until the storage is discharged below the minimum level defined by the previous parameter and then the power block load will be reduced (or turned off). .
- Power block minimum power from storage supply (pbMinimumPowerFromTES, see Figure 1):
  1. **Use:** Defining the load at which the power block will be operated from the storage when the state of charge is lower than “tesMinLevelDischarge”.
  2. **Behavior:** When the storage is being discharged to keep the power block running at the nominal load defined in the previous parameter and its state of charge falls below the minimum level defined by the parameter tesMinLevelDischarge, the power block is no longer run at its nominal load but at a minimum load defined by this parameter.

Finally, during those moments in which the energy coming from the solar field and from the storage is less than the necessary to operate the power block at certain desired load, it is possible to use a burner to provide the power for the power block to work at such load. The following parameter is the one used to control the burner use:

- Power block set point power from burner supply (pbSetPointPowerFromBU):
  1. **Use:** Defining which load to operate the power block at when part of the thermal power comes from the burner (may also be coming from the solar field and/or storage).
  2. **Behavior:** The burner is used to complete the energy coming from the solar field and/or the storage, so that the power block can operate at certain aimed load defined by this parameter. This is, for each hour, when the energy coming from the solar field and the storage is not enough to operate the power block at this load, the burner will be used to provide the required thermal power. If the power of the burner is not enough to reach the aimed load of the power block, its maximum power will be used.

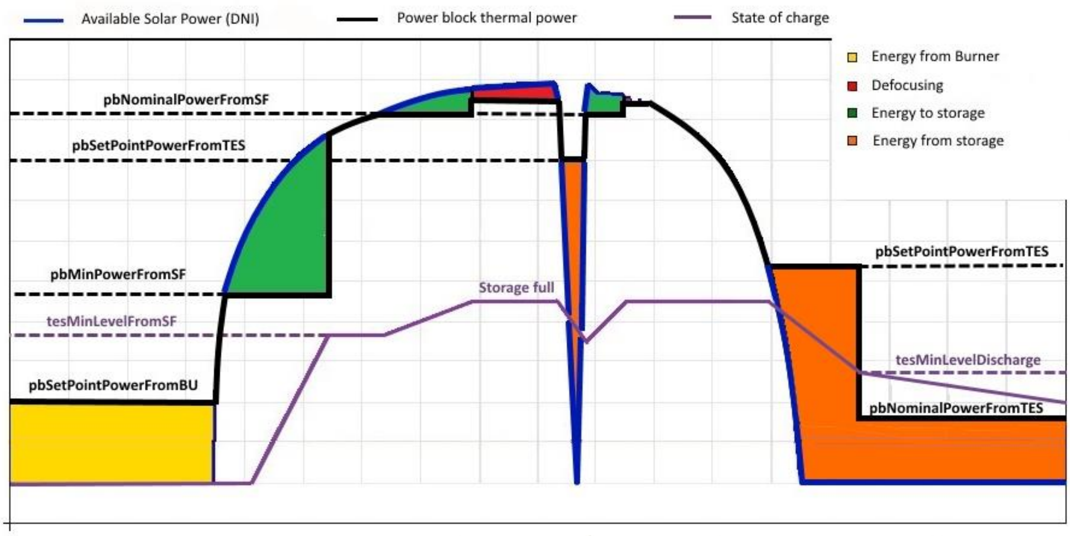

Figure 1. Conceptual behavior of the power block power (black, solid), storage state of charge (purple, solid) and available solar power (blue, solid) for a reference day according to the flexible operational strategy.

3. Comparison of 3 specific Operation Strategies

In the present work, three different strategies for the TES charge and discharge have been implemented in a CSP plant dynamic simulation model and then simulated and compared. These strategies are a reference solar driven strategy, a so called peak production strategy trying to meet a demand/price curve and a strategy aiming to reduce turbine stops. The three specific strategies have been developed from the flexible operation strategy explained in the previous section by setting specific values to each of the parameters. In the text below, a brief description of the CSP plant and simulation models as well as details of the different strategies are explained.

3.1 CSP plant and simulation model:

The CSP plant used for the simulation is a state-of-the-art commercial parabolic trough plant with 8.5 hours indirect two-tank molten salts TES. No hybridization is used in order to clearly focus the analysis on the use of the storage system. Strategies based on the fuel usage have been previously analyzed in [14] and mixed strategies are left for future work. A location in southern Spain (Seville) has been selected for the present analysis, with a reference annual Direct Normal Irradiation of 1950 kWh/m2.

The thermodynamic model of the CSP plant is an object-oriented, differential algebraic equation based model, which is able to describe the physical behavior of the plant and therefore accurately represents its transient response adapting to the extremely changing solar resource. The model is based on both physical or empirical approaches depending on the each component. This model and its validation has been described with further detail in [14] and there is no need to repeat this description here. However, the CSP plant simulated in this work is different to the one presented in [14] due to the use of the storage system. In this case, the selected TES model is a fitted quasi-steady active indirect molten salts storage, adjusted to correctly fulfill the work explained in [15], [16]. Also, although the solar field operation strategy is similar, the developed operation strategies will be used for the storage charging and discharging strategies.

3.2 Solar Driven Operational Strategy:

This strategy is the reference operation for any CSP plant, showing the typical behavior of all renewable energy plants, since its aimed to produce the maximum possible electric power whenever there is enough resource available. This strategy represents the straightforward TES operation strategy, charging the storage with the excess of solar power once the power block is operating at full load and discharging the storage whenever the solar power is not enough to drive the power block at full load, until completely depleting it. This type of operation is close to maximizing the efficiency and the energy yield of the CSP plant.

The solar driven operational strategy can be developed from the flexible operation strategy, setting appropriate values for each parameter. It should be noticed that for this strategy the power block desired operation (full load) is independent of the hour of the year, so it works in the same way all the time. Therefore, the definition of the parameters is equal for each hour of the year. The parameters are defined according to the objective of the solar driven strategy:

- **“pbMinPowerFromSF”:** The main goal is maximize the energy yield and efficiency, so the power block is required to operate at maximum load whenever it´s possible.
- **“tesMinLevelFromSF”:** Since the power block will be operating at full load from the beginning, a minimum level for the storage makes no sense, so it is set to zero.
- **“pbNominalPowerFromSF”:** Since there isn´t any minimum level for the storage, pbNominalPowerFromSF is equal to pbMinPowerFromSF, i.e. again full load (note that this parameter won’t have any influence in the plant operation, since the power block will already be running at full load).
- **“pbNominalPowerFromTES”**: As stated before, if there isn´t enough power from the solar field, the storage is used to run the power block aiming to reach the full load. Therefore, the value of this parameter is full load.

- **"tesMinLevelDischarge":** The storage will be used to feed the power block at full load until completely depleting it, therefore there is no a minimum level to be kept in the storage.
- **"pbMinimumPowerFromTES":** Since there isn´t any minimum level for the storage while it is being discharged, pbNominalPowerFromTES is equal to pbNominalPowerFromTES, i.e. full load.

In the following table the specific values used for each parameter for this simple strategy are shown:

Table 1. Value of the parameters for the Solar Driven Operational Strategy

	Value
pbMinPowerFromSF	1
tesMinLevelFromSF	0
pbNominalPowerFromSF	1
pbNominalPowerFromTES	1
tesMinLevelDischarge	0
pbMinimumPowerFromTES	1
pbNominalPowerFrombu	0

The following figure shows the typical behavior of a CSP Plant working under the Solar Driven Operation Strategy for a sample set of days:

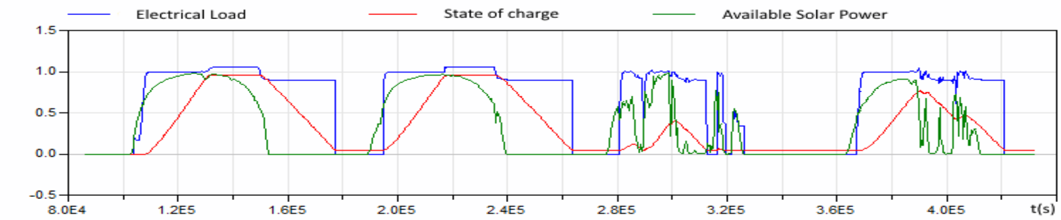

Figure 2. Power block thermal load (blue, solid), State of charge of the storage (green, solid) and Available Solar Power (kW) (red, solid) for a reference set of 6 representative days under the Solar Driven Operational Strategy conditions. (Falta de modificar la imagen con Paint).

As figure 1 shown, the power block starts operation when the solar field provides enough power. Once the power block reaches full load, the excess of energy from the solar field is used to charge the storage. When the storage is full and an excess of power keeps coming from the solar field, the power block is overloaded up to its maximum allowable load. Once the power block is overloaded to its maximum, if the energy excess is still larger, defocusing is used in the solar field to dump the solar power excess. When the dni begins to drop, the storage provides the required energy to keep working the power block at full load until the storage is empty.

3.3 Peak Production Operational Strategy:

The main goal of this strategy is to adapt the electric energy production to a demand or price curve, therefore increasing economic profits. This peak production operational strategy aims to follow, to a reasonable extent, a defined demand or energy selling price curve, by preferentially charging the storage system during valley and off-peak hours and preferentially discharging it during peak (demand or price) hours.

Peak production operational strategy can be developed from the flexible operation strategy, setting the value of the main operation parameters. For this, each of the hours in the year has been classified into peak, off-peak and valley hours and different value of each parameter has been used for each hour type. Since the selected location is Spain, this hourly classification has been obtained from Red Electrica Española, REE [18]. The strategy is defined in different way during winter and summer periods, since REE also defines a different hourly classification for these periods. .

For winter, the parameters are defined as follows:

- **"pbMinPowerFromSF"**: The wish is to produce the maximum energy when the energy price is higher to maximize the profits, therefore during the peak hours the set point load for the power block is the maximum allowable load (overloading). During off-peak and low hours the power block does not work and the priority is to charge the TES up to the TesMinLevelFromSF.
- **"tesMinLevelFromSF"**: For peak hours the priority is to produce, therefore there isn't any minimum level to be kept in the storage. During off-peak hours, the target is to charge the storage up to the half capacity (4 hours), to ensure the supply to the power block during the next peak period (also 4 hours). For low hours, the storage will be charged up to full capacity prior to run the power block.
- **"pbNominalPowerFromSF":** For peak hours, the power block will already be working up to full load. During off-peak hours, once the storage reaches the "TesMinLevelFromSF**"** the goal is to operate the power block at full load. For low hours, when the storage is completely charged the objective is to operate the power block at full load (actually, since the storage will be full, the power block will be overloaded prior to defocusing).
- **"pbNominalPowerFromTES":** During peak hours the power block will be operated at the maximum allowable load always there is available energy in the storage. For off-peak hours while the state of charge is higher than tesMinLevelDischarge (Off-Peak), the target is to produce energy with the best efficiency so the power block will also work at full load. For low hours, the storage will not be discharged.
- **"tesMinLevelDischarge":** During peak hours, the storage will be completely depleted, so there is no minimum level for the storage discharging. However, for off-peak hours the target is to ensure that the storage could provide enough energy to the power block during peak hours. Therefore the minimum level during the discharge is half capacity. For low hours, the storage is not being discharged, keeping it at maximum capacity.
- **"pbMinimumPowerFromTES":** Again, the power block will be running at full load during peak periods. For off-peak periods once the state of charge is lower than tesMinLevelDischarge (half capacity), the power block will be turned off the same as during low hours.

In the following table, the different parameters´ values defined for every hour type for the peak production strategy during winter are shown:

Table 2. Value of the parameters for the Peak Production Operation Strategy during winter

	Peak	Off-Peak	Low
pbMinPowerFromSF	1.05	0	0
tesMinLevelFromSF	0	0.6	1
pbNominalPowerFromSF	1.05	1	1
pbNominalPowerFromTES	1.05	1	1
tesMinLevelDischarge	0	0.6	1
pbMinimumPowerFromTES	1.05	0	0
pbNominalPowerFrombu	0	0	0

The behavior of Peak Production strategy during winter can be seen in the following figure for a sample set of days:

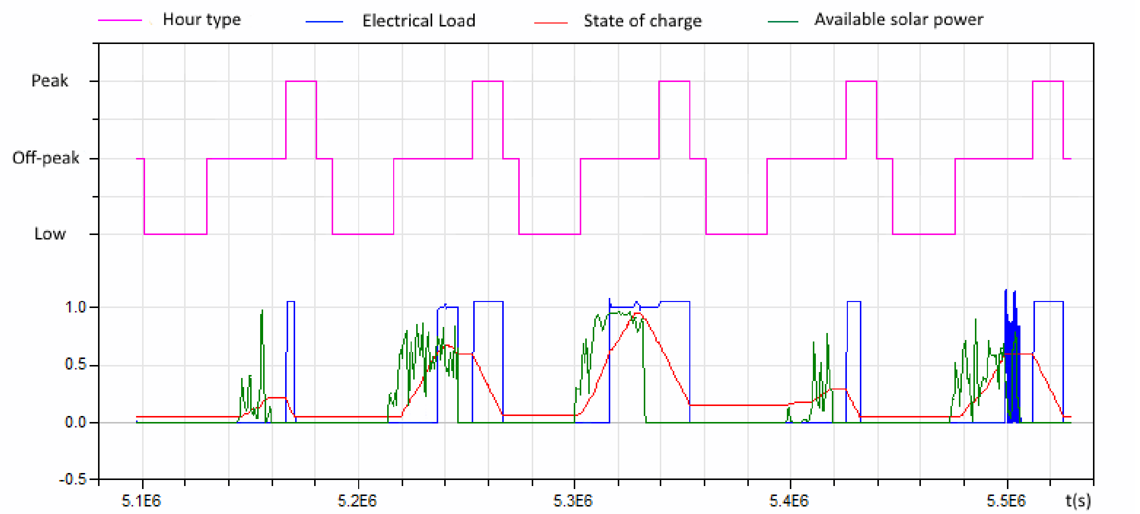

Figure 3. Power block thermal load (blue, solid), State of charge of the storage (green, solid) Available Solar Power (kW) (red, solid) and hourType (magenta,solid) for a reference set of 6 representative summer days under the Peak. Production Operational Strategy.

As an example, in Figure 3 it can be seen how the solar field starts producing thermal power during a valley hour, and therefore this power is used to charge the storage system keeping the power block offline. After a while, an off-peak period is reached and the power block will be kept offline until a specific minimum state of charge is reached in the storage. Once this level is reached, the power block is operated at full load. When the dni drops in the afternoon, the power block keeps working at full load if the level of the storage is higher than the minimum level set for the off-peak hours, but if the level is lower the power block stops. Once peak hours are reached, the power block is run at its maximum allowable load until the next off-peak period or until the storage is empty.

For summer, the distribution of the peak, off-peak and valley hours defined by REE resulted in a strategy completely similar to the solar driven strategy, with the only exception that the power block is overloaded to its maximum allowed power during the peak hours.

3.4 Reduce Stops Operational Strategy:

The main goal of this strategy is to reduce the power block stops and, consequently, to maximize the power block online hours. This can be achieved by always ensuring certain level of energy stored in the TES while solar power is available and by discharging the storage system at reduced power block loads (therefore during longer time) while no solar power is available.

As in the previous cases, the reduce stops operational strategy can be developed from the flexible operation strategy by setting the value of the operation parameters. It should be noted that for this strategy the power block operation is independent of the type of hour, so it works in the same way all time. Therefore, the definition of the parameters is equal for each hour of the year. The parameters are defined according to the objective of the reduce stops strategy:

- **"pbMinPowerFromSF"**: As long as there is available solar power to run the power block, the goal is to charge the storage and avoid future stops. Therefore, the power block will operate at its minimum load and the excess of energy will be used to charge the storage.
- **"tesMinLevelFromSF"**: As already explained above, the main objective is to keep always the storage as charged as possible, this is, a minimum level of full capacity once the minimum power is reached in the power block. Only after completely charging the TES the power block will be operated at larger

loads, thus ensuring that there will be the maximum available energy when the solar radiation is not enough to keep the turbine online.

- **"pbNominalPowerFromSF":** Considering that TES will be completely charged, if there is an energy excess, it will be used to run the power block up to its maximum allowable load prior to defocusing the power excess..
- **"pbNominalPowerFromTES"**: To keep the power block running from the storage for the maximum time, the nominal power block load to discharge the storage is set to the minimum load.
- **"tesMinLevelDischarge":** In this strategy, the storage should be completely depleted at the nominal, which is the minimum load of the power block. Therefore, the minimum level is set to zero.
- **"pbMinimumPowerFromTES":** Since the minimum level is zero and the nominal power block load is the minimum load, this parameter has no effect (although it is ser also to the minimum load).

In the following table the specific values used for each parameter for this strategy are shown:

Table 3. Value of the parameters for the Reduce Stops Operational Strategy

	Value
pbMinPowerFromSF	0.2
tesMinLevelFromSF	1
pbNominalPowerFromSF	1
pbNominalPowerFromTES	0.2
tesMinLevelDischarge	0
pbMinimumPowerFromTES	0.2
pbNominalPowerFrombu	0

The behavior of stops reduction strategy can be seen in the following figure for a sample set of days:

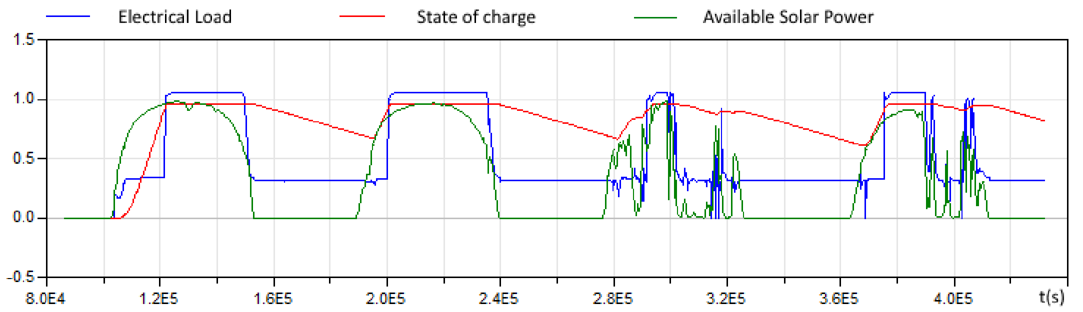

Figure 4. Power block electric load (blue, solid), State of charge of the storage (green, solid), Available Solar Power (kW) (red, solid) and hourType (magenta, solid) for a reference set of 6 summer representative days under the Reduce Stops Operational Strategy.

As figure 4 shows, at the beginning of the simulation the storage is empty so the power block does not work until enough thermal power is available from the solar field. When this happens, the power block starts to operate at minimum load, and the energy excess from the solar field is used to charge the storage. When the storage is full, the power block is overloaded working at maximum load until there is not enough power to operate from the solar field. At this moment, the power block works at minimal load from the storage, which in this case is its minimum load. Note that for these sunny days the strategy is not optimized at all for the 8.5h storage system of the simulated plant. It can be seen that only about 30-40% of the storage capacity is used even during cloudy days. It is quite obvious that it makes more sense to increase the nominal load of the power block when operating from the storage to better use the 8.5h storage. Therefore, for the annual simulations presented later the nominal load of the power block working from the storage has been set to half load, which is not an optimized strategy but results in a more reasonable usage of the storage system.

3.5 Qualitative comparison of the three strategies

The three strategies described above have been simulated for a reduced set of days to show their different behavior. The results are presented in Figure 6, where the gross electricity production and the state of charge of the TES systems obtained by the three different strategies are shown.

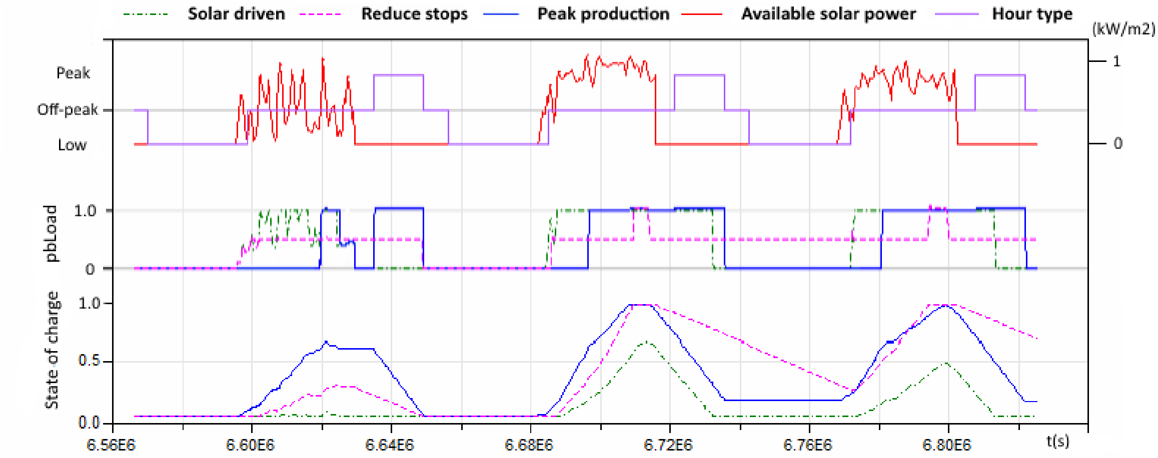

Figure 5. Power block Thermal Load and State of charge (Storage) of a Parabolic Trough plant with 8.5 hours storage system operating under three different operational strategies: solar driven (green, dash-dotted), peak production (blue, solid) and reduce stops (magenta, dashed) for a reference set of 6 representative days. DNI (red, solid) and demand/price reference curve (magenta,solid) are show as reference.

As figure 5 shows, for the solar driven and reduce stops strategies the power block starts to work before than for the peak production strategy because at the beginning of the day it is off-peak hour and the energy from the solar field is used to charge the storage. For solar driven the power block works at full load, but for reduce stops it works at half load. For peak production strategy, once the storage reaches the minimum level for the charge, the power starts to work at full load. Also, the reduce stops strategy once the storage is completely charged increases the power block load up to the maximum allowable.

4. – Results and discussion:

The three operation strategies developed for this study have been used to simulate a CSP plant with the same configuration and metheorogical data for a complete year every five minutes. Among the large quantity of output variables provided by the simulation model, only the most representative are used to study the influence that the operation strategy has on plant performance. Table 4 shows the results obtained by the different operation strategies for the simulations.

Table 4. Most representative results for the different developed strategies

	Solar driven	Peak production	Reduce stops
Gross energy production	223,541 MWh	220025 MWh	194542 MWh
HTF thermal energy	642,608 MWh_t	640433 MWh_t	620068 MWh_t
Power block gross efficiency	34.76%	34.36%	31.37%
Full Load equivalent hours	4471 h	4401 h	3891 h
Capacity Factor	51.03%	50.24%	44.42%
P. block operation hours	4679 h	4418 h	7350 h
Power block stops	487	726	161
Energy to storage	2.25×10^5 MWh_t	2.906×10^5 MWh_t	2.1673×10^5 MWh_t
Dumped energy	1.069×10^5 MWh	1.275×10^5 MWh	2.87×10^5 MWh
Incomes	100%	101.3%	85.47%

As Table 1 demonstrates, different operation strategies lead to different CSP plant operation. The results obtained for the straightforward solar driven strategy are used as a reference for the comparison of the results obtained with the other strategies. Since the plant has been simulation in Spain, the incomes have been compared using a different Time Of Delivery factor (TOD) for peak, off-peak and valley hour calculated for the Spanish market according to [18]. Table 4 presents the normalized value for the incomes, so it is no need to suppose a specific energy price but only it's variation according to the different TODs.

The solar driven strategy turns in the highest electric energy production as is expected, due to the very efficient usage of the power block, most times running at full load and of the storage, since it is discharged whenever is possible. Therefore, this strategy leads to the best power block efficiency among all strategies and the lowest dumped energy. This perfectly meets the main objective of the strategy: to maximize the energy yield and the energy conversion efficiency.

The peak production strategy is an intermediate strategy in terms of electric energy, producing a 1.57% less than the solar driven strategy. Although usually the power block works at maximum or full load, the power block efficiency is 1% lower. Due to the power block is fed from the storage during the winter peak hours. In this strategy the power block stops are increased in a 50 %, given that during the winter the power block stops at off-peak hours and the storage is discharged during the peak hours.

One conclusion obtained from the analysis of these results is that if a fixed energy selling is established for the CSP plant production the solar driven can be the best strategy because it is the strategy that reaches the highest energy production. However, if the energy selling price is adjusted to the energy demand curve as in this study, the "peak production" leads to major annual revenues despite of total electric production is lower.

The "reduce stops" strategy presents the lowest electric output, because the power block usually operates at medium load and the gross efficiency is decreased in 10 %-points respect to the solar driven strategy. Another reason that causes a 12% decrease in energy production is that the "reduce stops" strategy is not optimized and during the night the storage is not discharged, so the power block is overloaded earlier during the day and the solar field is defocused. Therefore, the dumped energy is increased in more than 100% respect the other strategies.

On the other hand, the main advantage of the "reduce stops" strategy is that cyclic operation stress is reduced in the power block components, thus reducing their degradation and maintenance. The power block stops are reduced from more than 450 in a year for "solar driven" and "peak production" strategies to 161 in the "stops reduction" strategy. Therefore, for this strategy the number of operating hours is 57%-points bigger than in "solar driven" strategy.

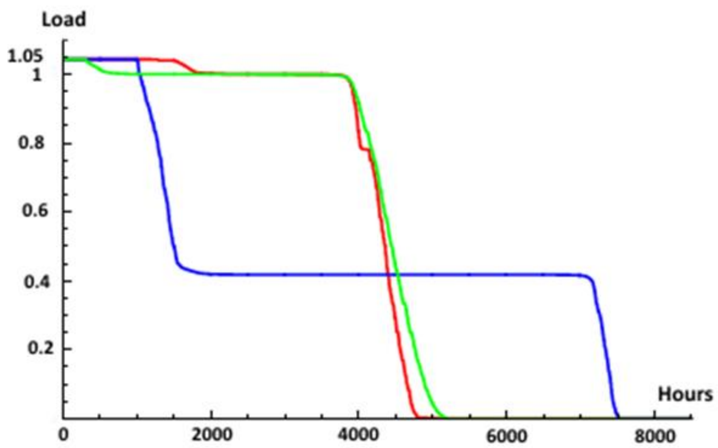

Figure 6. Power block loads sorted from highest to lowest for each hour in the year corresponding to the three operational strategies. "Solar Driven" (green, solid), "Peak Production" (red, solid) and "Reduce Stops" (blue, solid)

As shown the figure 6, each of the developed strategies has different effect both power block load and in power block operation hours. Similar conclusions can be deduced from this figure, showing how the "reduce stops" strategy leads to the highest number of operating hours while the "solar driven" leads to the best efficiency, given that it usually works at full load. The "peak production" leads to overload the power block more times than the other as expected, because the wish is to overload always the power block during the peak hours.

5. Conclusions and future work

This works shows that special attention should be paid to the design of different operation strategies. The simulation results show up that the strategies can have an important influence in the long term performance of the plant. The use of the storage allows controlling some aspects of the behavior of the plant and shifts its production, what as results show, can increase plant incomes if energy production is fitted to demand/price curves. In this paper, three storage operation strategies have been implemented and simulated. Each of them could be select, depending on the choice of the plant operator to favor operation with maximized the energy yield, and with achieved a great adjustment of the production to the demand curve or with reduced maintenance cost.

The comparison of the strategies through the annual results leads to conclude that the solar driven strategy makes produce the highest quantity of energy working the power block with the best efficiency. On the other hand, for peak production strategy has been found that the economic incomes increase (+1.3%) even the energy production decrease (-1.5%). The reduce stops strategy leads to an important reduction in the number of turbine stops (-67 %) and to increase the power block operation hours (+57%).

Planned future work includes the optimization of the strategies explained above to fit more accurately the results to the proposed objectives and the study of mixed strategies introducing a burner into the CSP plant. Furthermore, the study of the operation strategies with forecasting is proposed, given that it will permit the operator to decide which strategy use to run the CSP plant according to the solar radiation that will come into the solar field the next day.

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