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Optimization of thermal energy storage integration strategies for peak power production by concentrating solar power plants

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Abstract

The integration of thermal energy storage systems in concentrating solar thermal power plants allows power production to be shifted from times where there is low demand to periods where electricity prices are higher. Although increasing the total investment, thermal energy storage can therefore enhance profitability of the solar power plant. The present study presents optimum power plant configurations for a given location considering different price-based grid integration strategies. Such optimum plant configurations were determined using a thermo-economic optimization approach to compare the profitability of generating electricity assuming an instant-dispatch strategy with respect to a selective operating strategy where electricity is produced only during peak price hours of the day. For each of these price-operating strategies, optimum plant configurations were found by varying two solar-related design parameters, namely the solar multiple and the storage size, whilst simultaneously evaluating the economic performance of each design. Results show that for the case of smaller storage units and solar field size a peaking approach will yield more revenues at the end of the project, thus highlighting the importance of the availability of reliable predictable demand and meteorological data for the plant operators. Moreover, results confirm that for the location considered, the best plant configurations encompass large storage units and solar field sizes, for which the gain of a peaking operation strategy becomes negligible since the plants start behaving similar to a baseload power generation station. Finally, it is performed a sensitivity analysis with respect to the available price data and the influence of renewable electricity incentives, particularly the investment tax credit treasury cash grant, showing the positive impact that such measurements could have in augmenting the economic viability of concentrating solar power and thus serve as a driving force for technology deployment.

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1. Introduction

The role of thermal energy storage (TES) in extending the operation of concentrating solar power plants (CSPPs) is well-known, and to date, over 40% of all commercial CSPPs have integrated TES systems [1]. The increase in power plant capacity factor resulting from the integration of TES has been shown by numerous studies [2][3][4] to reduce the cost of electricity, and thereby increase the economic viability of the power plant, despite the addition costs for the TES units. Furthermore, the integration of TES also increases the flexibility of the CSPP, allowing the production of electricity to be decoupled from the instantaneous solar energy input. This opens up a large number of possibilities, including the ability to shift production to times of high electricity prices, in order to maximize the profit from sale of electricity. As high electricity prices are correlated with times of peak electricity demand, a CSPP operating in this manner effectively fills the role of peaking power plant.

Relatively little research has been performed into the potential role of CSPPs for peak power production. Currently, the most promising technology for this role would appear to be the molten-salt solar tower, where high operating temperatures and a direct TES system result in lower storage costs. In this paper, the design of such a power plant will be analyzed to identify economically optimum power plant configuration when targeting peak power production.

Nomenclature

α	Capital return factor
λ_{el}	Annual Revenues from Electricity Production
C	Costs
CSP	Concentrating Solar Power
CSPP	Concentrating Solar Power Plants
E_{net}	Electricity Produced
f_{avail}	Availability factor
i	Real interest rate
IRR	Internal Rate of Return
ITC	Investment Tax Credit
k_{ins}	Insurance rate
LCOE	Levelized Electricity Costs
n	Lifetime of the Power Plant in years
OM	Operating Mode
SF	Solar Field
SM	Solar Multiple
TES	Thermal Energy Storage

2. Study case and market oriented operating strategies

Depending upon the market role of the CSPP, the TES system can be designed in different ways. If continuous power production is desired, for example to provide baseload power to the electricity, a large TES unit can be combined with an electrical power output smaller than the nominal thermal power from the SF. In this way, all the daytime heat input from the Sun can be collected and stored. With a turbine size smaller than the nominal solar heat input during peak hours, the storage allows the collected energy to be spread over the whole 24 hours of the day, for continuous power production. Another option is to store heat and shift load to peak demand hours, so that instead of attempting to produce electricity continuously, TES allows to shift power production to times when it is needed more and thus sell it for higher prices. An example would be to store energy in the morning and use it to extend power production into the evening and night when production from other sources such as photovoltaic decreases. Furthermore, in markets where the prices are known to be higher in the evenings or with a pronounced peak demand time, TES allows shifting production to such hours so as to assure achieving maximum revenues.

In order to find optimum plant configurations for such different market roles, price-based grid integration strategies are followed in this work. Optimum plant configurations were determined using a thermo-economic optimization approach. For a typical CSP plant layout [5] with a nominal capacity of $100MW_e$, peaking and instant-dispatch operation strategies were designed. For the case of the instant-dispatch strategy, the plant is set to operate whenever there is input energy available from the SF, so that the integration of storage serves to guarantee a continuous production once the solar resource is no longer available in a day. On the other hand, the peaking operating strategy was achieved through an algorithm designed to calculate the number of hours that the CSP plant should operate per day as a function of the solar field size, the storage size, and lastly the hourly average irradiance and price values for the considered location, which is described in §2.1. After defining the number of hours that the plant should operate per day, another optimization routine selects which of these hours should be covered by the energy in the storage with the objective of maximizing revenues. Lastly, it is worth mentioning that regardless the operating strategy, large plant configurations (e.g. exceeding the 12 hours of storage and SM of 3) will likely have a continuous operation thus behaving similar to baseload power plants upon good resource availability.

2.1. Location of study

For the location of the study, a promising site for the deployment of solar electricity was chosen. The study is limited to the region of Seville in Spain; key information about this location is displayed in Table 1. The choice of Spain as the location is also based on the fact that renewable energy technologies represent a significant fraction of the total electricity generation in this country [6][7]. Furthermore, Spain is the only country to have successfully demonstrated the molten salt central tower technology with two-tank molten salt storage [5], upon which this work is based. All the required meteorological data was obtained from the Meteonorm dataset [8], whereas the hourly 'average final price for Spain demand' for the year 2012 is displayed in Fig. 1 as available from [9]. As can be seen, the mean and maximum prices in 2012 were approximately 80 USD/MWh and 182 USD/MWh respectively.

Table 1. General information on the location of study

Location	Coordinates	DNI
Seville, Spain	37°34'N, 2°39'E	2100 kWh/m^2/yr

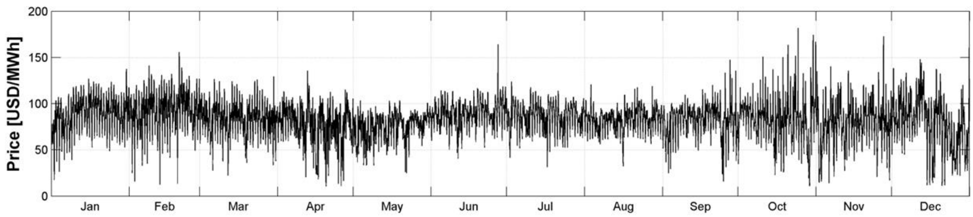

Fig. 1 Hourly average final electricity price for Spain in 2012 [9]

3. Power plant thermodynamic design and modeling

The thermodynamic design of the CSPP is based on a quasi-steady state model of the whole system, which has been elaborated using DYESOPT, an in-house tool, described in a previous work [10]. The modeling approach adopted in this study is shown in Fig. 2, which schematizes the flow of information and calculations in the DYESOPT tool. Firstly, the CSPPs are designed in MATLAB based on a number of decision variables, giving the nominal steady-state performance of the plant. The nominal point data is then used to size the components in the TRNSYS studio [8] which, coupled with meteorological and demand data plus a specified operation strategy, allows prediction of the annual performance of the power plants. A time-step of 10 minutes was used in the study; the same as the resolution of the meteorological data. The results from the simulation are then combined with cost functions to provide the final thermoeconomic analysis of the power plant. As mentioned before, the decision variables in this particular study are the solar multiple (SM) and the storage capacity of the power plant, which were varied between

1 and 3 and from 1 to 15 hours respectively. A single objective function was targeted, which was maximizing the economic viability of the power plant for each operating strategy, measured in terms of the levelized cost of electricity (LCOE) and the internal rate of return (IRR). These economic performance indicators are described in §4.

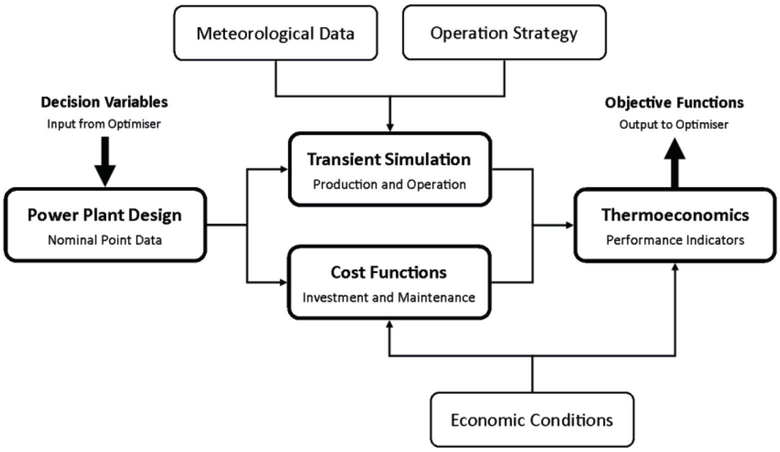

Fig. 2 In-house tool DYESOPT modelling approach

3.1. Power plant modeling

As stated before, the size of the SF and TES are determined based on the two input variables, i.e. the SM and the storage capacity. Within TRNSYS, the solar collector field was modeled using STEC Types 394 and 395 for the heliostat field and central receiver respectively [14]. TRNSYS Type 394 uses an externally supplied efficiency matrix which maps the solar position to a value of overall heliostat field efficiency. This matrix is determined using an in-house model, described in a previous work [10]. The TESS TRNSYS Library Type 39 variable volume tank was used to model both the hot and cold tanks of the two-tank direct TES system [8]. In order to calculate the thermal properties of the HTF, an additional subroutine in MATLAB was developed with data obtained from NREL [15]. A flowsheet of the HTF cycle (the SF and TES), including the auxiliary gas burner, is shown in Fig. 3(a), where the central receiver is denoted R, the hot and cold tanks HT and CT respectively.

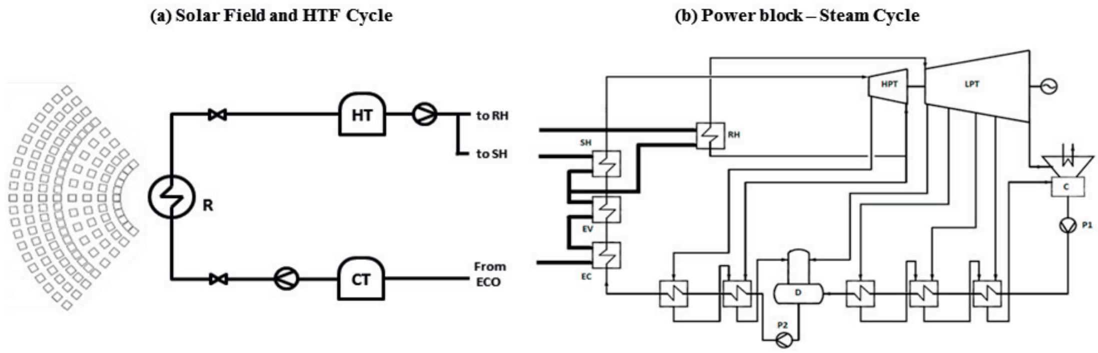

Fig. 3 Power plant layout for HTF and Steam cycles

On the other side, the power cycle in a typical molten-salt CSPP is a reheat Rankine steam-cycle, with mass flow extractions for feed water preheating, with a thermal efficiency of 44.5% [5], similar to that achieved by contemporary European central tower CSPPs. In this study, the power cycle has been designed for a nominal capacity equal to 100 MW_e. A flowsheet of the modeled power cycle is shown in Fig. 3(b), where thin lines represent water-steam and thick lines represent the molten salts used as HTF. The turbine units are denoted HPT and LPT for the high-pressure and low-pressure units respectively; similarly, the heat exchangers in the steam generation chain are denoted SH, RH, EV and EC for the superheater, reheater, evaporator and economizer respectively. The condenser and pumps are denoted C and P whereas the deaerator is denoted D. The transient model calculates the steam mass flow input to the turbine based on the conditions of the hot molten salts at the inlet to the steam-generator heat exchanger train, using components from the TRNSYS STEC library, as described in a previous work [11]. All of these components have been validated in previous studies for the transient modeling of Rankine cycles for CSPPs [12]. Off-design performance of the power block takes into account variations in efficiency and mass flows a function of the turbine inlet conditions using the Stodola ellipse law [13]. Full details and equations governing each of the component models are presented in [14]. The main input parameters involved in the design of the power block are summarized in Table 2.

Table 2 Design parameters for CSPP power block

Design Parameter	Value	Unit
Superheater Steam Temperature	560.00	[°C]
Live Steam Pressure	85.00	[bar]
Reheat Steam Pressure	21.00	[bar]
Number of preheating extractions	5 + Deaerator	
Cooling System Condenser Type	Dry Cooling	
Pressure at turbine exhaust	0.07	[bar]

3.2. Power plant operating modes

The overall performance of the CSPP is strongly influenced by its operating mode. For this study four simple operating modes, OMs, have been defined. These are shown in Fig. 4, where the black solid lines represent the path followed by the HTF, and briefly described in Table 3.

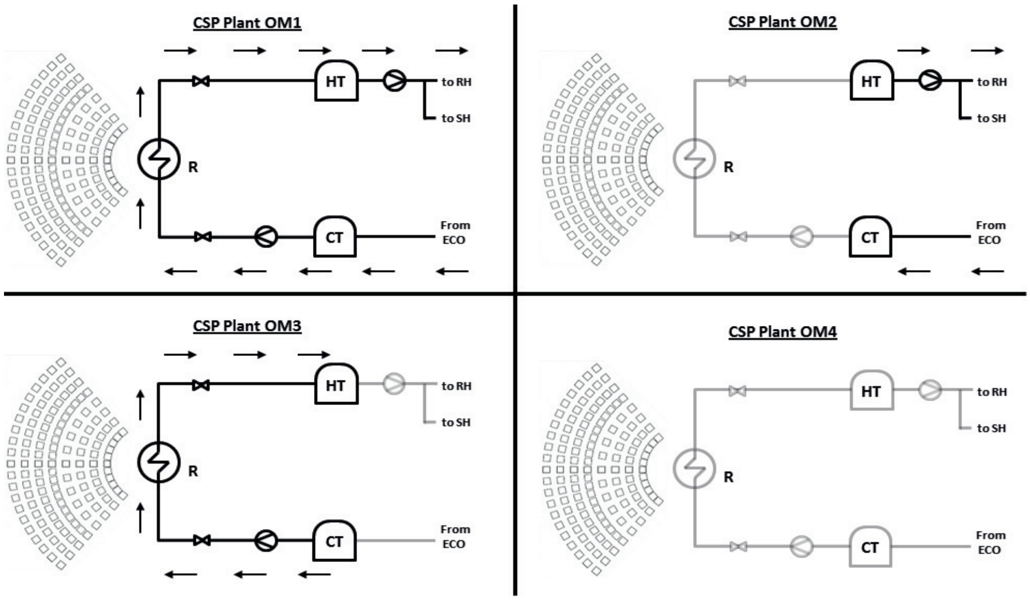

Fig. 4 Operating Modes of CSPPs

Table 3 Operating modes of CSPPs

Operating Mode	Description
OM1	The TES hot tank is charged by heat from the SF. It is discharged at a flow rate that meets nominal power output whenever the plant should go online (e.g. peaking hours or excess energy from SF).
OM2	There is no heat input from the SF but there is enough energy stored in the TES hot tank to allow the power plant work at its nameplate capacity during specified peaking hours.
OM3	The plant is offline and the prices remain low so that the TES hot tank is being charged with heat input from the SF.
OM4	The plant is offline as there is not enough energy from the SF nor stored in the TES hot tank.

4. Performance indicators for thermoeconomic analysis

In order to measure the economic performance of the CSPPs, two performance indicators were considered in this study, namely the levelized cost of electricity (LCOE) and the internal rate of return (IRR). LCOE was calculated using Eq. 1, as a function of the total investment cost C_{inv} of the system, the annual maintenance cost $C_{O\&M}$ and the total electricity produced throughout the year E_{net} multiplied by an availability factor f_{avail} obtained following similar analysis as that shown in [11] which is based on the equivalent operating hours method.

$$LCOE = \frac{\alpha \cdot C_{inv} + C_{O\&M}}{E_{net} \cdot f_{avail}} \quad (1)$$

The CSPP investment cost, C_{inv}, was calculated using a detailed cost model [16], which takes into account the costs related to all the power plant equipment, as well as indirect project costs. The capital return factor α was calculated using Eq. 2, where i stands for the real interest rate, n for the power plant lifetime and k_{ins} for the insurance rate, with values taken from [17]. Similarly, the annual cost for operation and maintenance of the system $C_{O\&M}$ was estimated using information also found in [16]. On the other hand the IRR is calculated by use of Eq. 3 as the discount rate that makes the net present value (NPV) of all cash flows equal to zero at the end of the lifetime of the CSPP. In addition to the fore mentioned parameters used to calculate the LCOE, Eq. 3 is also a function of the years of plant construction n_{con}, the years of plant operation n_{op}, the annual revenue from electricity sells λ_{el}, the years of plant decommissioning n_{dec} and the decommissioning costs C_{dec}, with values extracted from [18].

$$\alpha = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} + k_{ins} \quad (2)$$

$$NPV = -\sum_{t=0}^{n_{con}-1} \frac{C_{inv}}{n_{con}(1+IRR)^t} + \sum_{t=n_{con}}^{n_{con}+n_{op}-1} \frac{\lambda_{el} E_{net} f_{avail} - C_{O\&M}}{(1+IRR)^t} - \sum_{t=n_{con}+n_{op}}^{n_{con}+n_{op}+n_{dec}-1} \frac{C_{dec}}{n_{dec}(1+IRR)^t} = 0 \quad (3)$$

5. Results from thermoeconomic analysis

5.1. Economic performance of CSPPs for the different operating strategies

The economic performance of the CSPP configurations for both an instant-dispatch and a peaking operating strategy are illustrated in Fig. 5 and Fig. 6 respectively; where the markers represent the optimum TES size for each SM, being the blue one the most optimal configuration. It can be seen that, regardless the operating strategy, as the SM is increased, the optimum TES size found was larger since it allows storing the excess energy produced, thus justifying the higher SF costs, which typically represent up to half of the total investment in these plants [1].

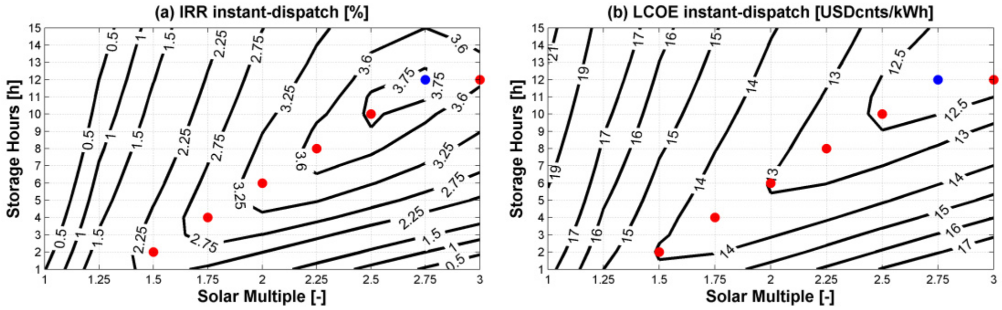

Fig. 5 Performance of CSPPs for instant-dispatch operating strategy

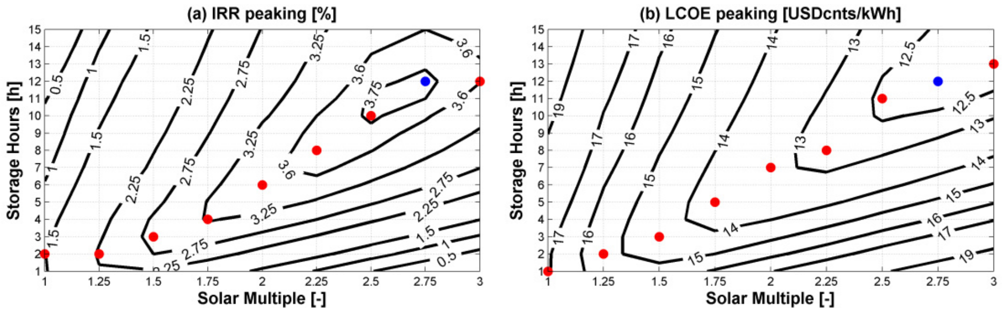

Fig. 6 Performance of CSPPs for peaking operating strategy

It is shown that despite the strategy adopted, a large plant configuration accounting for 12 hours of TES and a SM of 2.75 will yield the minimum electricity costs and the maximum IRR, thus implying that such configuration is the optimal one for the specific location considered. Nonetheless, when comparing Fig. 5(a) and Fig. 6(a) it is possible to see that adopting a peaking operating strategy is more beneficial for the smaller CSP plant designs (i.e. with less than 7 hours of storage capacity and smaller SF sizes). For instance, a configuration with 2 hours of TES and a SM of 1.25 will yield an IRR of 2.25% for the case of a peaking strategy, whereas for an instant-dispatch strategy the IRR will be 1.5%. Such results were expected as the algorithm developed aims to ensure the generation of electricity at times of higher prices, which is more noticeable for the smaller storage designs. In this concern, the results for plant configurations having large TES capabilities and a large SF size did not varied from one operating strategy to another (for any of the performance indicators considered). Indeed, as stated in §2, such large plant configurations start behaving as a baseload power plant, similar to the operating strategy followed by the Gemasolar power plant with 15 hours of storage and continuous operation throughout the whole year [5]. Furthermore, Fig. 5 shows that for SM values smaller than 1.5 no optimum TES size was found, as the addition of storage will only lead to lower IRR and higher LCOE. This was not the case for the peaking operating strategy (Fig. 6), where even plants with SM of 1 will perform better if two hours of storage are considered from the design. Therefore, it is possible to say that the choice of integrating storage in CSPPs might not be always justified and should be linked to the operating strategy.

Concerning the LCOE figures, it is clear that electricity costs remain similar regardless the operating strategy adopted. This is mainly due to the fact that the LCOE indicator does not accounts for the annual revenues but instead it is a function of the costs and electricity production, which overall remains similar regardless the operating strategy. The small difference found between Fig. 5(b) and Fig. 6(b) is mainly due to the availability factor f_{avail}, shown in Eq. 1. In general, a plant with a peaking operating strategy will have higher annual equivalent operating hours than a plant with continuous operation since the number of plant start-ups is increased. Moreover, as possible to see from Fig. 5 and Fig. 6, the remained optimum LCOE values show that the technology is not competitive by itself when compared against conventional power generation systems [19]. Such statement is reinforced by the fact that the optimum IRR yielded remained below 4% which is considerably lower than the real interest rate of 7%, assumed for the LCOE calculations [17]. This implies that the construction of a CSPP under current cost estimates and economic assumptions is not viable for the chosen location of study, thus calling for the need of considering economic incentives or analyzing the sensitivity of the results with respect to the electricity price data used.

5.2. Sensitivity analysis to ITC incentives and electricity prices

Results prove that economic incentives are needed in order to make CSPPs competitive in a liberalized market. Feed-in-tariffs (FITs) is an incentive policy that has been widely implemented worldwide to drive the growth of new technologies. However, previous studies have determined that for the case of CSP although a FITs policy guarantees reasonable IRR for investors, it does not help subsidize the high up-front costs and in addition it needs to be periodically adjusted in order to really drive technology growth [20]. A measure that directly attacks the problem of having high investment costs is giving subsidies or cash grants. Indeed, as most of the solar-related projects are based on tax-driven structures, two suitable incentives namely the production tax credit and the investment tax credit have been adopted by the US government as policies for CSP deployment [21]. The ITC is an incentive that reduces federal income taxes for eligible renewable energy projects based on capital investment and earned once the equipment is placed into service. Furthermore, a cash grant incentive is an option for ITC-eligible projects in order to get the total value of the ITC as a direct grant instead of the credit [22]. Such cash grant can be up to 30% of the capital expenditure for the case of CSP, thus meaning that the investment costs are considerably decreased and the profitability of the project is enhanced.

Fig. 7 shows the variation of the IRR for a CSP project as a function of the percentage increase in electricity prices and the accessibility to the 30% ITC cash grant. For such sensitivity analysis two optimal configurations were chosen: firstly a plant with SM of 2.75 and 12 hours of storage (as proven to be the best for the location) and also a power plant with a SM of 1.5 and 3 hours storage with a peaking strategy. The selection of the latter configuration was based on the fact that its upfront investment cost represents only two thirds of the investment required for the larger configuration, which in turn means a 33% reduction in the potential economic risk incurred by investors.

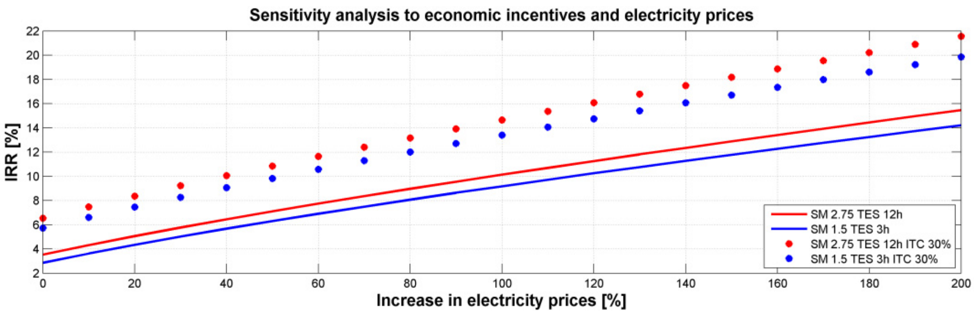

Fig. 7 Influence of electricity prices and 30% ITC cash grant incentives on the performance of optimum CSPPs

It can be seen that the overall profitability, measured in terms of the IRR, is strongly influenced by the hourly electricity price data. In particular, considering an increase of 100% in the electricity prices will yield IRR values of approximately 10% without the need of any incentive, which could be economically attractive enough for investors. Indeed, according to statistics from the European Commission [23] the average electricity price for industry in Spain in the year 2012 was approximately 150USD per MWh, which represents a 90% increase with respect to the annual mean price from the data used in this work (80USD per MWh [9]). Additionally, if there is the possibility for incentives then the profitability of the plants is largely increased. It is shown that even for the prices considered in the study (0% increase) ITC grants could lead to IRR values of approximately 7%, whereas for the case of the 100% increase in prices, a 30% ITC grant will yield an IRR close to 15% for the case of the most optimal plant configuration. Lastly, when comparing both configurations chosen, it can be seen that the trends remain similar for both as the IRR increases with respect of the increase in prices. Moreover, it is shown that for a same reference price data, the large CSPP slightly outdoes the smaller plant. In such concern, if the final percentage profitability is similar and the investment is considerably lower, smaller CSP plants with suitable peaking operating strategy could become a more attractive investment, at least whilst the technology remains in its earlier steps of development.

6. Conclusions

A thermoeconomic optimization analysis for the design of CSPP configurations for both instant-dispatch and peaking operating strategies has been presented in this work. Results ratify that for a given location the process of dimensioning the TES system goes together with the oversizing of the SF, and that optimal configurations yielding more revenues can be found depending on the operating strategy adopted. It is shown that adopting a peaking operating strategy is more critical and beneficial for the smaller CSP plant designs (smaller SF size), where storage plays an important role by allowing shifting production to peak demand hours, which could occur during absence of solar radiation depending on the season. This is not the case for large plant configurations, which due to the extensive SFs and storage capabilities are able to perform continuously throughout the day, like baseload power plants. Indeed, the most profitable plant configuration found for the location analyzed will account for 12 hours of storage and a SM of 2.75, for which the benefits from a peaking operating strategy become negligible.

Furthermore, results show that the construction of CSP plants in the given location does not represent an economically viable project unless incentives are provisioned. In this regard, the profitability of the CSPPs was measured in terms of the IRR, which remained below 4% for the most optimal configuration. Similarly, the LCOE values for all the considered designs remained higher than LCOE figures from other renewable and conventional energy sources. However, it is shown that the provision of incentives such as the 30% ITC cash grants would positively impact the profitability of the designs, leading to IRR values of approximately 7%. Moreover, upon the provision of incentives, it is shown that smaller CSP plants with a selective peaking operating strategy could represent an attractive investment as these have lower upfront costs and also are almost as profitable (percentage-wise) as the optimum large configurations found.

Finally, and despite of the values encountered, it is demonstrated that the results were strongly influenced by the hourly electricity price data used as reference, for which average values differ considerably from other available resources. As such, it can be highlighted that a more reliable prediction on the economic performance of the plants depends upon the certainty of available information. However, although sensitive to the cost models and economic assumptions, a thermoeconomic approach such as the one followed in this work serves as a first assessment for the designing and dimensioning of a CSPP, for which subsequent detailed analyses at component level as well as with respect to the economic aspects must be performed.

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