Short-Term Trading for a Concentrating Solar Power Producer in Electricity Markets

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***Abstract*—Concentrating solar power (CSP) plants with thermal energy storage (TES) are emerging renewable technologies with the advantage that TES decreases the uncertainty in the generation of CSP plants. This study introduces a stochastic mixed integer linear programming model, where the objective function is the maximization of the expected profit that can be obtained by selling the energy generated by the CSP plant in the day-ahead electricity market. The proposed model considers three main blocks of constraints, namely, renewable generator constraints, TES constraints, and electricity market constraints. The last category of constraints considers the penalties incurred due to positive or negative imbalances in the balancing market. A case study using data from the Spanish electricity market is introduced, described and analyzed in terms of trading of the CSP plant generation. The conclusions highlight the influence of TES capacity on the energy trading profile, the expected profits and the volatility (risk) in the trading decisions.**

***Keywords*—ARIMA models, concentrating solar power producer, day-ahead electricity market, renewable energy, thermal energy storage.**

I. Introduction

The Kyoto Protocol encouraged the exploitation of renewable energy sources (RES) in order to reduce the contribution of the electricity sector to CO_2 emissions and to ease the adverse effects of climate change [1]. Nowadays a number of technologies that can exploit different RES are available. Clearly, the deregulation of electricity markets in combination with roadmaps that promote the integration of significant amounts of RES in the generation mix have led to discussions regarding the economic viability of RES technologies in a market environment without relying on subsidies.

It is widely known that wind and photovoltaic energy technologies are leading the proliferation of the RES share in electricity production, while they are considered sufficiently mature in order to be able to economically withstand competition in electricity markets. Nevertheless, the major drawback of the leading RES-based generation technologies is that their power output depends largely on external factors such as weather conditions and the time of day. As a result, their power output is, up to a certain extent, uncertain, volatile and intermittent. This in turn might complicate the short-term trading of their energy and render their integration challenging from the power system operation perspective. Much research has focused on addressing the aforementioned issues. Apart from efforts to improve the accuracy of forecasting methods and introduce market sessions closer to real-time, one of the most salient solutions is to couple RES-based generation technologies with a storage system in order to reduce the uncertainty in their output or to temporarily shift their generation.

Motivated by the operational flexibility offered by energy storage-based solutions to the aforementioned problems, this paper will focus on an emerging RES technology, namely concentrating solar power (CSP) plants with thermal energy storage (TES). The TES system has the potential to reduce the uncertainty pertaining to the generation of CSP plants and therefore allows for a more efficient trading of the generated energy in electricity markets.

As a relatively new technology, CSP is in a development phase and the total installed capacity of CSP plants in 2016 was less than 5000 MW worldwide. For the same reason, only a limited number of studies have proposed strategies for the participation of CSP in electricity markets. More specifically, among the different tools that can be used to evaluate renewable energy projects, the System Advisor Model (SAM) can be used to evaluate technologies such as photovoltaic power plants, battery storage systems, parabolic CSP, power tower CSP, biomass, etc. [2]. In [3] the capabilities and costs of CSP plants were modeled by formulating a mixed-integer problem based on SAM [2], where the profits of CSP plants with TES in energy markets were evaluated. Also, a solar parabolic model was created in [4]. This model aimed to maximize the profits from selling the energy generated in the spot market. A robust optimization formulation was presented in [5], evaluating a parabolic CSP participating in the Spanish electricity market. Another study investigated the flexibility of CSP with TES and the provision of ancillary services in the reserve and regulation markets [6].

Aiming to enrich the relevant literature, this study proposes a stochastic mixed-integer linear programming model with the objective of maximizing the expected profit of selling the energy generated by a power tower CSP in the day-ahead electricity market. The proposed model includes constraints such as renewable generation constraints, TES constraints

978-1-5386-5326-5/18/$31.00 © 2018 IEEE

TABLE I
NOMENCLATURE

Indices and Sets	
$\mathcal{S}$	Set of scenario indices.
$\mathcal{T}$	Set of period indices.
s	Index related to scenarios.
t	Index related to periods.
Parameters	
$cost^{CSP}$	Marginal cost of the CSP [€/MWh].
$g_{s,t}^{CSP}$	Generation of the CSP in scenario s and period t [MWh].
$g_{s,t}^{SUN}$	Energy comes from the sun in scenario s and period t [MWh].
$hour^{STG}$	Hours that the TES can provide electricity [hour].
O^{MAX}	Upper limit of the offer [MWh].
$\lambda_{s,t}$	Day-ahead electricity price in scenario s and period t [€/MWh].
$\lambda_{s,t}^{\Delta-}$	Downward imbalance price in scenario s and period t [€/MWh].
$\lambda_{s,t}^{\Delta+}$	Upward imbalance price in scenario s and period t [€/MWh].
ρ_s	Probability of scenario s.
τ	Energy conversion efficiency of the TES.
φ	Percentage of TES self-discharge.
Decision variables	
$charge_t^{CSP}$	Energy transferred from the CSP plant to the TES in period t [MWh].
$cost_{s,t}$	Cost in scenario s and period t [€].
$generation_t^{CSP}$	Generation of the CSP that comes from the TES in period t [MWh].
$income_{s,t}$	Income in scenario s and period t [€].
$j_{s,t}$	0/1 variable that is equal to 0 if the imbalance in scenario s and period t, is negative; 1 otherwise.
j_t	0/1 variable that is equal to 0 if the imbalance in period t, is negative, considering the presence of TES; 1 otherwise.
$losses_t$	TES self-discharge in period t [MWh].
$offer_t$	Energy offer in the day-ahead electricity market associated with the CSP plant without TES in period t [MWh].
$offer_t^{STG}$	Energy offer in the day-ahead electricity market associated to the CSP plant with TES in period t [MWh].
PF^T	Total expected profit of the CSP plant without TES [€].
$PF^{T^{STG}}$	Total expected profit of the CSP plant with TES [€].
$profit_{s,t}$	Expected profit of the CSP plant with/without TES in each scenario s and period t [€].
SOE_t	State-of-energy of the TES in period t [MWh].
$\Delta_{s,t}$	Imbalance between the generation and the energy offer of the CSP plant without TES in scenario s and period t [MWh].
Δ_t^{STG}	Imbalance between the generation and the energy offer of CSP plant with TES in period t [MWh].
$\Delta_{s,t}^-$	Negative imbalance between the generation and the energy offer of CSP plant without TES in scenario s and period t [MWh].
Δ_t^{-STG}	Negative imbalance between the generation and the energy offer of CSP plant with TES in period t [MWh].
$\Delta_{s,t}^+$	Positive imbalance between the generation and the energy offer of CSP plant without TES in scenario s and period t [MWh].
Δ_t^{+STG}	Positive imbalance between the generation and the energy offer of CSP plant with TES in period t [MWh].

and electricity market constraints, also including penalties for positive and negative imbalances in the balancing market. One objective of this paper is to analyze the effects of uncertainty on the trading profile of a CSP plant. In the proposed framework, the uncertainty is related to market prices and concentrated solar generation. To evaluate how the uncertainty of the CSP plant can be managed, the coupling with three TES systems will be analyzed, namely cases with 0, 8 and 16 hours of continuous discharge in order to provide electricity continuously.

The contribution of this paper is threefold:

- The development of a stochastic mixed-integer linear model to trade the CSP plant generation in the day-ahead electricity market.
- The analysis of the optimal short-term trading profile for a CSP producer, depending on the TES system characteristics.
- The introduction of optimal control over the stored energy in the TES system, whose energy is then known in the short-term, to reduce the uncertainty of the CSP generation.

The remainder of this paper is structured as follows: in Section II the problem definition is provided, while in Section III the developed optimization models are presented. Then, in Section IV a case study is presented and the obtained results are discussed. Finally, conclusions are drawn in Section V. For ease of reference, the indices, sets, parameters and decision variables used throughout the paper are alphabetically listed in Table I.

II. DESCRIPTION OF THE PROBLEM

As a new technology, CSP generation is in a continuous process of development, where an optimal offering strategy can help increase the expected operational profits of a CSP plant. In this paper, such an optimal offering strategy is devised by relying on the use of stochastic mixed-integer linear programming. The optimization model receives the day-ahead and imbalance electricity market prices, the CSP plant production and marginal cost, as well as the TES system parameters as inputs. The electricity market prices and the CSP plant production are unknown at the time the decision making takes place and, as a result, a set of scenarios is generated in order to model their uncertainty.

As there are several CSP plants in Spain, the Spanish electricity market is investigated in this paper. In the Spanish imbalance market both positive and negative imbalances are penalized. The negative imbalance is a cost for the generator with a price equal to or higher than the day-ahead market price, while the positive imbalance is a reduced income (opportunity cost) with a price equal to or lower than the day-ahead market price.

The CSP production is unknown and all the energy inputs considered in the proposed model represent flows of energy in MWh. Figures 1 and 2 show the two main configurations of the CSP plant under study, with and without TES. These figures portray the flow of the uncertain energy that comes from the Sun, $g_{s,t}^{SUN}$, the energy coming from the mirrors to the TES, $charge_t^{CSP}$ and the energy that is provided by the steam turbines, $g_{s,t}^{SUN} = g_{s,t}^{CSP}$ and $generation_t^{CSP}$, without and with TES system, respectively. The energy transferred to the TES system is controlled by the position of the mirrors. The marginal cost is considered to be a known parameter.

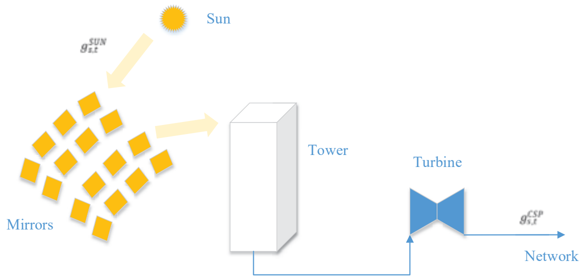

Fig. 1. Illustration of the CSP plant without TES.

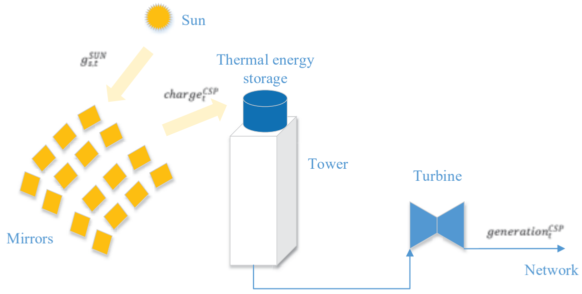

Fig. 2. Illustration of the CSP plant with TES.

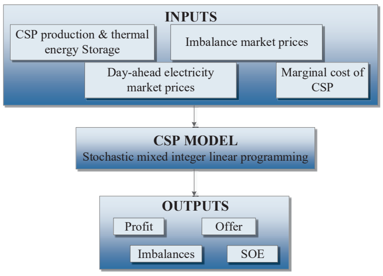

Fig. 3. Inputs and outputs of the optimization model.

As result of the simulation, the most important decision variables are the expected profit as the objective function of the proposed model, the energy offer to be traded in the electricity market and the possible imbalances that the CSP could face over the 24 hours of the trading horizon. The main inputs and outputs of the proposed mathematical model are shown in Fig. 3.

III. Mathematical Formulation

In this section two optimization models based on two-stage stochastic programming to determine the optimal offering strategy of the CSP producer are developed. The first considers a CSP plant without a TES system, while the second considers the combination of the CSP plant with a TES system.

Decision variables without a scenario index belong to the first-stage decision variable set and represent *here-and-now* decisions. On the contrary, variables indexed by scenario belong to the second-stage set of decision variables that stand for *wait-and-see* decisions. The first-stage variables are of immediate interest, while the second-stage variables implement recourse decisions to a particular realization of the random variables. It is to be noted that the models are cast using a node-variable formulation and as a result, non-anticipativity constraints do not need to be explicitly enforced.

A. Mathematical formulation of a CSP producer without TES

The absence of TES entails that the generation comes directly from the CSP plant, which in turn depends on irradiance. Irradiance is converted to thermal energy and subsequently electrical energy. For this reason, the expected profit is maximized (1) by selling the energy at the moment it is available. More specifically, profit is maximized by optimally deciding on $\Phi = \{offer_t\}$. For this configuration of the CSP plant, only one decision per period is made, the energy offer in the day-ahead electricity market, $offer_t$.

$$\underset{\Phi}{\text{Maximize}} \;\; PF^T. \tag{1}$$

The constraints of this optimization problem are:

1) Expected profit constraints: The expected profit of the CSP plant owner in (2) is the expected income minus the expected cost in each scenario s and period t as expressed by (3).

The income and cost in each scenario s and period t are given by constraints (4) and (5), respectively. The income, $income_{s,t}$, in each scenario s and period t, is defined by the price, $\lambda_{s,t}$, of the day-ahead electricity market multiplied by the offer, $offer_t$, and the upward imbalance price, $\lambda^{\Delta^+}_{s,t}$, multiplied by the upward imbalance volume, $\Delta^+_{s,t}$. The cost is defined by the energy generated, $g^{SUN}_{s,t} = g^{CSP}_{s,t}$, multiplied by the marginal cost, $cost^{CSP}$, and the downward imbalance price, $\lambda^{\Delta^-}_{s,t}$, multiplied by the downward imbalance volume, $\Delta^-_{s,t}$.

$$PF^T = \sum_{s \in \mathcal{S}} \rho_s \sum_{t \in \mathcal{T}} profit_{s,t}; \tag{2}$$

$$profit_{s,t} = income_{s,t} - cost_{s,t}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \tag{3}$$

$$income_{s,t} = \lambda_{s,t} \cdot offer_t + \lambda^{\Delta^+}_{s,t} \cdot \Delta^+_{s,t}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \tag{4}$$

$$cost_{s,t} = g^{CSP}_{s,t} \cdot cost^{CSP} + \lambda^{\Delta^-}_{s,t} \cdot \Delta^-_{s,t}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \tag{5}$$

2) Market constraints: The energy offer is constrained by the maximum generation of the CSP plant, O^{MAX}, as indicated by (6). Similarly, both the positive and negative imbalance volumes are bounded by O^{MAX} through the disjunctive constraints (7) and (8) respectively. Note than when the imbalance is positive $\Delta^+_{s,t} \geq 0$, and as a result $j_{s,t} = 1$. The opposite holds when the imbalance is negative. The imbalance volume $\Delta_{s,t}$ in each scenario s and period t is calculated as the actual generation minus the energy offer in the electricity market by the linking constraint (9), while (10) is used in order to evaluate whether the imbalance is positive or negative.

$$offer_t \leq O^{MAX}; \forall t \in \mathcal{T}; \quad (6)$$
$$\Delta^+_{s,t} \leq O^{MAX} \cdot j_{s,t}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \quad (7)$$
$$\Delta^-_{s,t} \leq O^{MAX} \cdot (1 - j_{s,t}); \forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \quad (8)$$
$$\Delta_{s,t} = g^{CSP}_{s,t} - offer_t; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \quad (9)$$
$$\Delta_{s,t} = \Delta^+_{s,t} - \Delta^-_{s,t}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \quad (10)$$

Finally, (11) enforces the non-negativity of the decision variables.

$$cost_{s,t} \geq 0; \Delta_{s,t} \geq 0; \Delta^+_{s,t} \geq 0; \Delta^-_{s,t} \geq 0;$$
$$income_{s,t} \geq 0; offer_t \geq 0; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \quad (11)$$

B. Mathematical formulation of a CSP producer with TES

As an extension to the previous model, a model that considers the coupling of the CSP plant with a TES system is considered in this section.

Similarly to the previous model, the objective function (12) is the maximization of the expected profit. However, in this case a larger number of decision variables are of practical importance. More specifically, the optimal values of $\Theta = \{charge^{CSP}_t$, Δ^{STG}_t, Δ^{+STG}_t, Δ^{-STG}_t, $generation^{CSP}_t$, $losses_t$, $offer^{STG}_t$, $SOE_t\}$ must be decided.

$$\underset{\Theta}{\text{Maximize}} \ PF^{T^{STG}}. \quad (12)$$

The constraints of this optimization problem are:

1) Expected profit constraints: The constraints associated with the definition of the expected profit are (13)-(16). The main difference with the model that did not consider the TES system is that the decision on $generation^{CSP}_t$, is decided following the market constraint (20) and the TES constraints (22) and (24).

$$PF^{T^{STG}} = \sum_{s \in \mathcal{S}} \rho_s \sum_{t \in \mathcal{T}} profit_{s,t}; \quad (13)$$
$$profit_{s,t} = income_{s,t} - cost_{s,t}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \quad (14)$$
$$income_{s,t} = \lambda_{s,t} \cdot offer^{STG}_t + \lambda^{\Delta^+}_{s,t} \cdot \Delta^{+STG}_t;$$
$$\forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \quad (15)$$
$$cost_{s,t} = generation^{CSP}_t \cdot cost^{CSP} + \lambda^{\Delta^-}_{s,t} \cdot \Delta^{-STG}_t;$$
$$\forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \quad (16)$$

2) Market constraints: The main difference of (17)-(21) with respect to the model without TES is that the variables involved in this block are actual decisions because the TES allows the CSP plant owner to control them. The imbalance, Δ^{STG}_t, in period t is the generation, $generation^{CSP}_t$, minus the energy offer, $offer^{STG}_t$, in period t. This coupling of the CSP plant with a TES system that controls the CSP generation introduced in the TES allows easing the uncertain primary generation of the CSP plant. The elimination of the uncertain imbalance volume lets the CSP plant owner to reduce imbalance costs.

$$offer^{STG}_t \leq O^{MAX}; \forall t \in \mathcal{T}; \quad (17)$$
$$\Delta^{+STG}_t \leq O^{MAX} \cdot j_t; \forall t \in \mathcal{T}; \quad (18)$$
$$\Delta^{-STG}_t \leq O^{MAX} \cdot (1 - j_t); \forall t \in \mathcal{T}; \quad (19)$$
$$\Delta^{STG}_t = generation^{CSP}_t - offer^{STG}_t; \forall t \in \mathcal{T}; \quad (20)$$
$$\Delta^{STG}_t = \Delta^{+STG}_t - \Delta^{-STG}_t; \forall t \in \mathcal{T}. \quad (21)$$

3) Energy storage constraints: The constraints related to the operation of the TES system are (22)-(27).

Constraint (22) updates the state-of-energy, SOE_t. The state-of-energy in interval t is the state-of-energy of the previous interval plus the energy that is provided to the TES system, $charge^{CSP}_t$, bounded by $g^{SUN}_{s,t}$, as indicated by (23), minus the energy, $generation^{CSP}_t/\tau$, that is discharged, but also the loss of energy due to self-discharge that is considered through $losses_t$.

The upper limit of the generation considering also the primary source of energy (the CSP), $generation^{CSP}_t$ is the maximum possible offer (24), while the upper limit for the SOE_t is the number of hours multiplied by the maximum offer that can provide this CSP plant configuration (25). Self-discharge is taken into account by (26).

$$SOE_t = SOE_{t-1} + charge^{CSP}_t - (generation^{CSP}_t/\tau)$$
$$- losses_t; \forall t \in \mathcal{T}; \quad (22)$$
$$charge^{CSP}_t \leq g^{SUN}_{s,t}; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}; \quad (23)$$
$$generation^{CSP}_t \leq O^{MAX}; \forall t \in \mathcal{T}; \quad (24)$$
$$SOE_t \leq hour^{STG} \cdot O^{MAX}; \forall t \in \mathcal{T}; \quad (25)$$
$$losses_t = SOE_t \cdot \varphi; \forall t \in \mathcal{T}. \quad (26)$$

Finally, (27) enforces the non-negativity of decision variables.

$$charge^{CSP}_t \geq 0; cost_{s,t} \geq 0; \Delta^{STG}_t \geq 0; \Delta^{+STG}_t \geq 0;$$
$$\Delta^{-STG}_t \geq 0; generation^{CSP}_t \geq 0; income_{s,t} \geq 0;$$
$$offer^{STG}_t \geq 0; \forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \quad (27)$$

IV. Case Study and Results

A. Case study

In this section three test cases are presented:

- a CSP plant without a TES system,
- a combined CSP-TES plant and a TES system with 8 h of continuous discharge,
- a combined CSP-TES plant and a TES system with 16 h of continuous discharge.

The CSP capacity (O^{MAX}) is 50 MWh in all the test cases. The evaluation of the CSP plant configurations in terms of short-term energy trading is done over a 24-hour long trading horizon. It is considered that the CSP producer participates in the Spanish day-ahead electricity market [7] and the Spanish imbalance market penalizes the excess or deficit of energy [7].

Given that a number of inputs are uncertain, a set of scenarios is constructed in order to model uncertainty of the

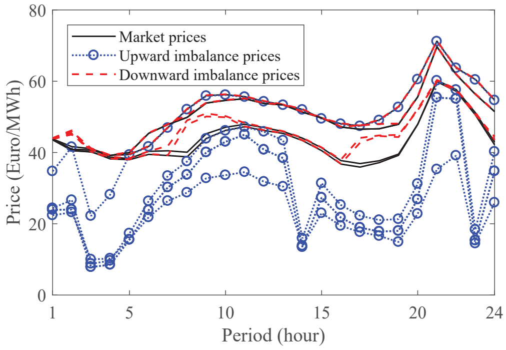

Fig. 4. Day-ahead market price scenarios, upward imbalance market price scenarios and downward imbalance market price scenarios.

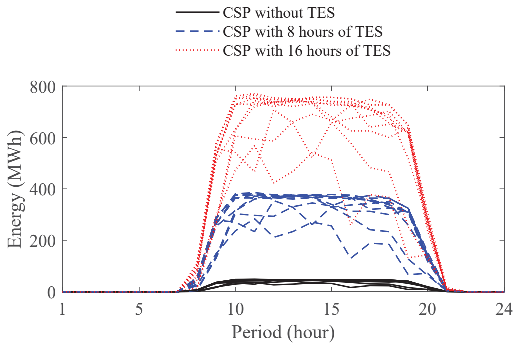

Fig. 5. Energy for the CSP without TES, with a TES of 8 hours and with a TES of 16 hours.

associated random variable. More specifically, 4 scenarios are generated for day-ahead market prices (and their associated imbalance prices), as well as 10 scenarios for the generation profile of the CSP plant. The price and generation scenarios are combined in a scenario tree resulting in 40 scenarios that are considered equiprobable (2.5%). The four scenarios of prices for day-ahead and imbalance market prices are shown in Fig. 4. The price scenarios stem from different ARIMA models [8] and where constructed using ECOTOOL [9].

A parameter that introduces uncertainty is the energy comes from the sun as $g_{s,t}^{SUN}$. The generic scenarios $g_{s,t}^{SUN}$ created in order to analyze the three cases are depicted in Fig. 5.

The marginal cost of the CSP plant is defined in [10]. The marginal cost values considered in the three cases analyzed in this paper are €2.43/MWh, €2.92/MWh, and €3.25/MWh for the cases without TES, with a TES system of 8 hours and 16 hours of discharge, respectively.

Other parameters are also defined; the conversion efficiency of the TES system is 98.5 % as shown in [4], while the self-discharge of the TES system is equal to 2 %. The SOE_t is 50 % when the 1st hour starts and at the end of hour 24. The minimum SOE is 10 % of the maximum limit of the TES defined in (25).

B. Results and Discussion

In this section the main results of the simulations that were run in order to analyze the case study are presented and discussed.

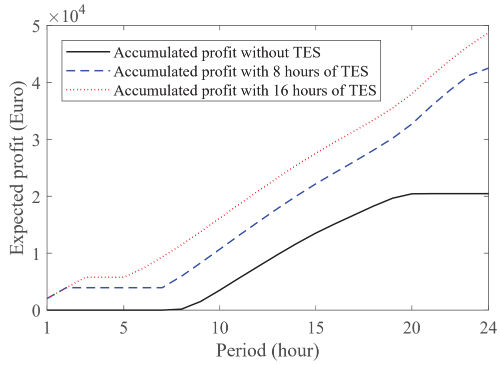

Fig. 6. Accumulated profits without TES, with a TES of 8 hours and with a TES of 16 hours.

First, the accumulated expected profit is depicted in Fig. 6 for the three cases. It can be noticed that the accumulated profit is the same in the 4th and 5th trading periods because the associated market prices are at their minimum values. Hence, a constant accumulated expected profit means that the expected profit is equal to zero for these two periods. In addition to that, it can be observed that the CSP producer without a TES system only produces energy when concentrated generation is available, while the CSP with a TES system reduces the generation when lower prices occur. In this regard, the expected profit of a CSP with a TES system of 16 hours is, therefore, zero in the two lowest price periods, i.e., the 4th and 5th trading periods, while, for the case of a CSP with a TES of 8 hours, it is equal to zero in the 3rd, 4th, 5th, 6th, 7th trading periods.

Evidently, the expected profit behavior depends on the offer made in the day-ahead market. Both models have the offer as part of the decisions to be taken in the sets $\Phi = \{offer_t\}$ and $\Theta = \{charge_t^{CSP}, \Delta_t^{STG}, \Delta_t^{+STG}, \Delta_t^{-STG}, generation_t^{CSP}, losses_t, offer_t^{STG}, SOE_t\}$. Hence, the offer follows the same behavior as the expected profit, as shown in Fig. 7. It should be noted that when the accumulated expected profit is constant, the associated energy offer is zero. Finally, it is worth mentioning that, as it can be observed from Fig. 6, the slope of the growth of the expected profit for a CSP producer without a TES system is not as steep as the slope for a CSP producer that uses TES.

The concentrated generation starts in the 8th and finishes in the 21st trading period. It may be observed from Fig. 8 that the energy that is used to charge the TES system takes non-negative values during the same time span, indicating that only the energy that is being produced by the CSP plant is used in order to charge the TES system. However, $charge_t^{CSP}$ with a TES of 16 hours is equal to zero in the hours $t = \{15, 16, 17\}$ as a consequence of the volatility of the scenarios for the concentrated generation at those prices. When the decision variable, $charge_t^{CSP}$, is equal to zero, SOE_t is equal to or lower than SOE_{t-1} because the CSP producer can also provide energy to the electricity market. For the last period, $SOE_{t=24}$ is equal to 50 % of the total TES system capacity as it was established by the operational constraints.

Imbalances can happen when the CSP producer does not

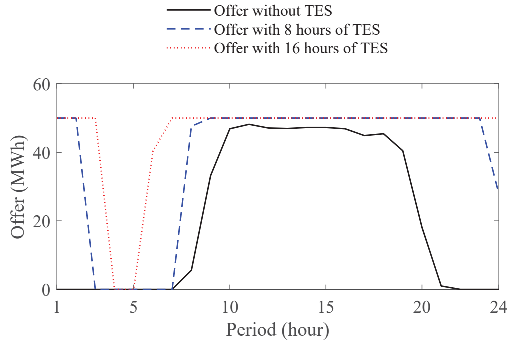

Fig. 7. Offer without TES, with a TES system of 8 hours and with a TES system of 16 hours.

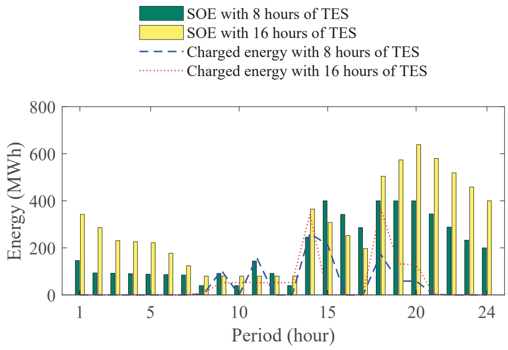

Fig. 8. SOE and charged energy with a TES system of 8 hours and with a TES system of 16 hours.

TABLE II
TOTAL EXPECTED PROFIT, STANDARD DEVIATION OF THE EXPECTED PROFIT, TOTAL ENERGY OFFERED AND β

Case study	PF^T (€)	$\bar{\sigma}(PF^T)$ (€)	$\sum_t offer_t$ (MWh)	β (€/MWh)
Without TES	20,457	184.4	519	39.4
8 h of TES	42,503	157.7	925	45.9
16 h of TES	48,722	175.4	1,090	44.6

have TES and there is an energy deficit with respect to the offer that was submitted to the day-ahead market. When the CSP producer does not have a TES system, imbalances over the 24 hours are either positive or negative. However, a CSP producer with TES should not have imbalances due to a known short-term production profile.

The results that have been presented so far do not provide a decisive answer as to which configuration of the CSP plant is the best. For this reason, the ratio of the total expected profits divided by the total energy offered in the trading horizon (β) is introduced as a performance metric. This metric can provide more information for the three CSP plant configurations that were considered, while the relevant information is collected in Table II.

The highest expected profit and total volume of offered energy emerges for a CSP with a TES system of 16 hours because the CSP producer can offer more energy in the day-ahead market. However, the standard deviation of the expected profits is between the lowest and the highest value of the associated column. The lowest expected profit is related to the operation of the CSP plant without a TES system, while the standard deviation takes on its highest value. Finally, the CSP plant with a TES of 8 hours returns profits between the lowest and the highest total expected profits of Table II. However, this configuration presents the lowest risk (standard deviation) and the highest β ratio. In other words, the CSP producer with a TES of 8 hours has the highest β ratio, which means that every MWh offered is more profitable and has a lower volatility, i.e., risk.

V. CONCLUSIONS

In this paper, a stochastic mixed-integer linear programming model was presented with the purpose of modeling the trading behavior of several configurations of a CSP producer in the day-ahead market. Based on the results obtained, the main conclusions of this paper can be summarized as follows:

- The energy offers and therefore the expected profit for all the CSP producer configurations depend on the prices and the available generation. The lower the prices and generation are, the lower the energy offers and the expected profit.
- A TES with a larger capacity attains the highest expected profit, but this does not necessarily lead to a higher value per MWh offered in the day-ahead electricity market.
- The control of the concentrated generation as an input to the TES system partially mitigates the volatility of the expected profit.

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