Constructing Offering Curves for a CSP Producer in Day-ahead Electricity Markets

Ilias Dimoulkas
School of Electrical Engineering
Electric Power and Energy Systems
KTH Royal Institute of Technology
Stockholm, Sweden
Email: iliasd@kth.se

Dina Khastieva
School of Electrical Engineering
Electric Power and Energy Systems
KTH Royal Institute of Technology
Stockholm, Sweden
Email: dinak@kth.se

Mikael Amelin
School of Electrical Engineering
Electric Power and Energy Systems
KTH Royal Institute of Technology
Stockholm, Sweden
Email: amelin@kth.se

Abstract—**In many countries, the installation and operation of concentrated solar power plants has been promoted with high feed-in tariffs and other incentives. However, as this technology is becoming more mature and the installation costs are being reduced, the incentives are minimized or totally abolished. Under these new economic conditions, there is an increased need for operation planning and power trading tools that will help the operators of such systems to make optimal decisions under the various uncertainties they face. This paper provides a model that can be used to derive the offering curves of a CSP producer in the day-ahead (spot) market. The model can also be used for the hourly short-term operation planning of the system. In order to tackle with the uncertainties of electricity prices and solar irradiance, the stochastic programming framework is used and a risk measure is incorporated into the model. A case study is conducted to show the applicability of the model.**

I. Introduction

Concentrated solar power (CSP) is an emerging technology which helps the transition to a cleaner electricity generation, especially in countries with high direct solar irradiance. According to IEA, CSP can provide around 11% of global electricity by 2050 [1]. Similarly to other renewable energy technologies, like wind and photovoltaic power, CSP generation is variable and it highly depends on the meteorological conditions at the production site. This dependency is reduced at some extent when heat storage is used. The high installation costs and the variable generation output is the reason why some countries provide incentives like fixed feed-in tariffs in order to support the CSP production. However, for economical and technological reason, these incentives are being reduced. At some point in the future, CSP production will need to be traded in the electricity markets, something which is already happening in some countries like Spain [2].

Under these conditions, the profitability of CSP production is put at risk. The short-term operation scheduling becomes a complex task where uncertain parameters like the power output and the unknown electricity prices in the market need to be taken into account. In order to reduce the risk of making decisions under uncertainty, new tools and methodologies like stochastic programming, Monte Carlo simulation and robust optimization have been developed and applied to energy system planning [3], [4]. However, the literature on the CSP

systems specifically and their operation and trading in the electricity markets, is not so extended. In [5] for example, a model is proposed to derive the optimal offering curves of a CSP producer to the day-ahead market. The model uses robust optimization to tackle the uncertainty of the thermal production in the solar field and stochastic programming to tackle the uncertainty of the electricity prices in the market. A model for the operation strategy of a CSP plant in the day-ahead electricity market is provided in [6] and dynamic programming is used to solve it. In [7] the short term operation of a fully renewable power system with CSP is studied. A model is proposed which schedules the optimal power generation and deserves allocation using stochastic programming. The effect of using electric heaters to recharge the CSP energy storage is studied in [8]. A deterministic short-term operation scheduling framework is presented in [9] for a CSP system hybridized with a gas boiler. The same is done in [10] where a heat storage also included.

In this paper, a probabilistic model is presented that helps a CSP producer to build the offering curves in the day-ahead electricity market while minimizing the expected imbalance costs in the imbalance settlement. The heat production in the solar field of the CSP plant and the electricity prices in the day-ahead and balancing markets are the stochastic parameters which are incorporated into the model with a set of scenarios according to the stochastic programming framework. The proposed model is formulated as a two-stage problem: in the first stage the offering curves to the day-ahead market are derived while in the second stage, the power generation and imbalance settlement is determined. Furthermore, in order to reduce the probability of high losses, the "conditional value at risk" (CVaR) risk assessment technique is used. A case study is also conducted to test the applicability of the model and show how the use of the heat storage and the size of the solar field affect the results.

The rest of this paper is organized as follows: section II is the main part of the paper where the mathematical formulation of the model is presented in II-D. Before this, a brief description of a CSP system is given in II-A followed by a description of the day-ahead market and the imbalance settlement in the balancing market in II-B. The scenario

generation methods used in this work are also mentioned in II-C. In section III, the results of a case study are presented. Finally, section IV concludes the paper.

II. MODEL DESCRIPTION

A. CSP System Overview

There are four main technologies that are under development for producing heat from solar irradiance. These use solar towers, parabolic troughs, linear Fresnel reflectors or parabolic dishes [10]. The operation of a parabolic trough CSP system is considered here as it is the most mature technology and the majority of the CSP plants that have been installed are based on it. Fig. (1) shows the schematic diagram of a parabolic trough CSP system. Heat is produced in the solar field which consists of parallel rows of parabolic mirrors. These mirrors are focusing the sun beams to a pipe line where a heat transfer fluid (HTF) is running. Usually this is some type of synthetic oil. When HTF reaches the suitable temperature which is around 390°C, it leaves the solar field and through a steam generator, superheated steam is produced. Then the steam is driven to the power block where it expands in the turbine to produce power in the generator. Some CSP systems have the ability to store the excess of heat into a thermal energy storage (TES) unit, which operates with the help of molten salts that move from a cold to a hot tank when TES is charging and vice versa when discharging. Some heat is lost during this process. Furthermore, the temperature in TES should be kept above some certain level to avoid the solidification of the salts.
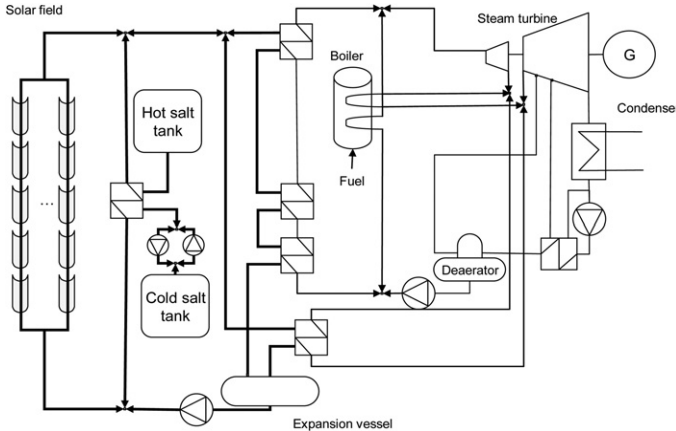

Fig. 1. Schematic diagram of a parabolic trough CSP system [10]

Thermal power production in the solar field is a linear function of the direct solar irradiance and depends on the solar multiple of the field [11]. This is shown in fig. 2. Solar multiple is a measure of the size of the solar field in relation to the size of the power block. It is defined as the ratio between the thermal power production in the solar field at the design point and the thermal power input to the power block at nominal conditions. Solar multiples are chosen to be greater than one in order to let the system operate at nominal conditions for

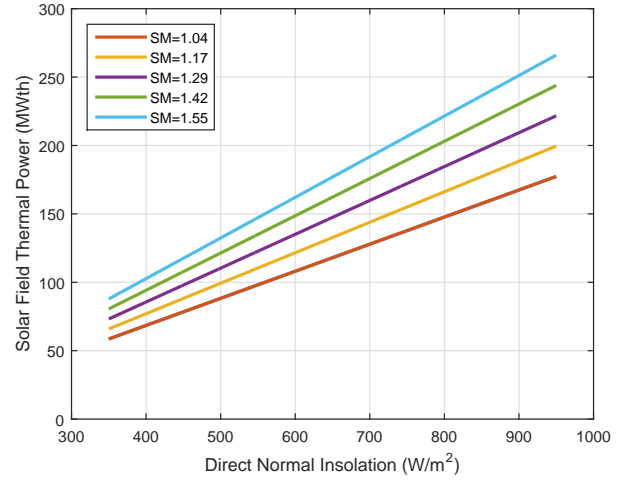more hours during the day, specially in systems without any TES.

Fig. 2. Solar field heat generation as a function of the direct insolation for various solar multiples

When less amount of heat is driven to the power block compared to the amount needed for nominal operation, the plant operates with decreased efficiency. The relation between the efficiency and the thermal power input to the power block is non-linear as can be seen in fig. 3. Furthermore, when heat is coming from the TES, there is an extra decrease around 0.6% in the efficiency of the power block [12].
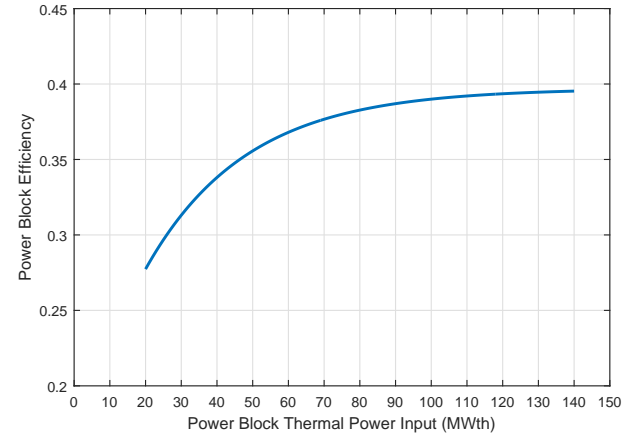

Fig. 3. Relation between the efficiency and the thermal power input to the power block

B. Electricity Markets Operation

Short-term power system operation planning is performed for various time periods and differentiated by proximity to actual operating hour. Two consecutive operation planning steps could be distinguished for short term planning. Both of

them are realized through independent trading floors. The first step is day-ahead planning. Power producers and consumers decide on their offering/bidding curves and submit them to day-ahead market. Once day-ahead market is cleared and day-ahead prices are released, balancing markets take place. These markets are specially designed to adjust the scheduled day-ahead production due to new available information on power system state and updated variable renewable and demand forecasts.

The balancing market acts as a mechanism where TSO's can obtain balancing power offered by dispatchable power producers in order to keep the power system balanced. This is the so called tertiary control. Pricing in the balancing market provides some incentive for power producers to participate. When they have to up-regulate increasing their power output, they will be paid at a price higher to the price in the day-ahead market. On the other hand, when they have to down-regulate, they will have to buy back power at a price lower to the price in the day-ahead market. In the case of CSP systems, as non-dispatchable/intermittent units, they should participate in the imbalance settlement where any deviation from the scheduled production in the day-ahead market is economically settled. When a CSP unit is negative imbalanced, which means that is has produced less than the scheduled production in the day-ahead market, then it should buy this deficit of power at a price greater or equal to the price in the day ahead market. This imposes a cost for the CSP producer. On the other hand, if the CSP unit is positive imbalanced, it will be paid this excess of power at a price lower or equal to the price in the day ahead market. This imposes an opportunity cost for the CSP producer. The conclusion is that imbalances create costs for CSP produces and any scheduled production in the day-ahead market should be done in a way to reduce the imbalances. This is the reason why stochastic programming is used.

C. Stochastic programming and scenario generation

Stochastic programming is a framework for modelling optimization problems that involve uncertainty. Probability distributions of the variable parameters should be known. The common procedure when formulating a stochastic programming problem is to approximate the probability distributions of the uncertain parameters with a set of scenarios and their corresponding probabilities. Then these scenarios are incorporated into the model with a suitable formulation.

In this problem there are three stochastic parameters: the day-ahead market prices, the balancing market prices and the direct solar irradiance. In order to create scenarios for the day-ahead market prices, a procedure based on ARIMA modelling and Monte Carlo simulation is followed [13]. Fig. 4 shows ten daily price scenarios for the Spanish day-ahead market. Real prices for the same day are presented in black. Markov and ARIMA modelling is also used to create the scenarios for the balancing market prices, which define the cost in the imbalance settlement. This method is described in [14]. Regarding the solar source, a simple procedure is followed to create the scenarios for the hourly direct solar irradiance. The procedure

is based on fitting a normal distribution function to the irradiance data for every hour of a day. This is done for each month separately. Then solar irradiance values are simulated from these normal distributions [15]. If any simulated value is negative, the solar irradiance for that hour is considered to be null. Fig. 5 shows ten solar irradiance scenarios for a day in July.
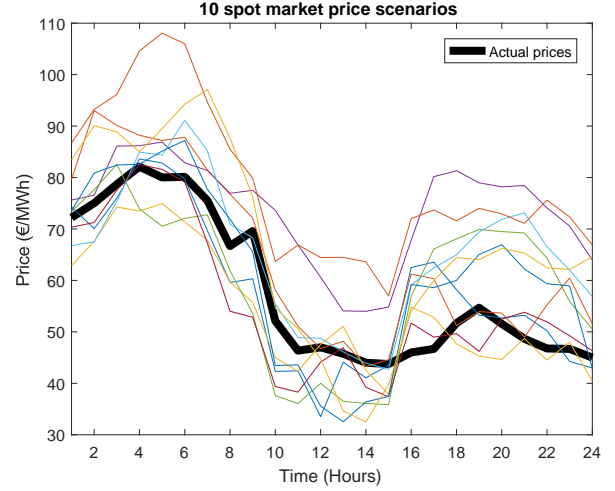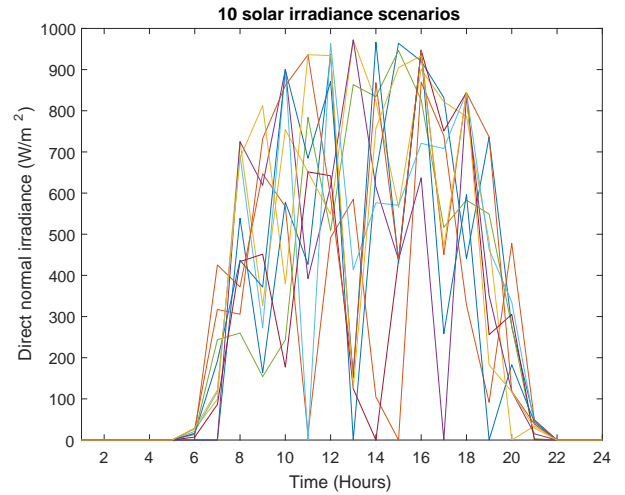

Fig. 4. Scenarios of day-ahead market prices

Fig. 5. Scenarios of direct solar irradiance for a day in July

D. Mathematical Formulation

The mathematical formulation of the model which is given below consists of an objective function (1) and several constraints (2-36) which are grouped into several categories for easier reference. If not defined differently, all constraints are applied for every time period and scenario of the corresponding sets ($\forall t, \forall w$).

1) Objective function:

$$(1-\beta)\cdot\sum_{w=1}^{N_W}\sum_{t=1}^{N_T}\pi_w\left[\lambda_{t,w}^{spot}\cdot P_{t,w}^{spot}+\lambda_{t,w}^{bm+}\cdot\Delta P_{t,w}^{+}\right.$$

$$\left.-\lambda_{t,w}^{bm-}\cdot\Delta P_{t,w}^{-}-c^{start}\cdot Y_{t,w}-c^{off}\cdot(1-U_{t,w})\right.\quad(1)$$

$$\left.-c^{fuel}\cdot F_{t,w}\right]+\beta\cdot\left(B-\frac{1}{1-\alpha}\sum_{w=1}^{N_W}\pi_w\cdot A_w\right)$$

The objective function of the problem stands for the maximization of the system operation expected profit. The scenario revenue consists of the power $P_{t,w}^{spot}$ that is sold to the day-ahead market at price $\lambda_{t,w}^{spot}$ and any possible positive imbalance $\Delta P_{t,w}^{+}$ that is sold at price $\lambda_{t,w}^{bm+}$. Regarding the scenario costs, these include any possible negative imbalance $\Delta P_{t,w}^{-}$ that the operator needs to buy at price $\lambda_{t,w}^{bm-}$, the start up cost c^{start} that occurs every time the plant is beginning its operation, the off-line cost c^{off} applied when the plant is not operating and the cost c^{fuel} per MWh of fuel consumption $F_{t,w}$ in the boiler. The total profit is the weighted average of all scenario profits. The last part of the objective function inside the parentheses consists the risk measure of CVaR multiplied with the risk aversion parameter β which takes values between 0 and 1. Values close to 0 correspond to more risky decisions with higher expected profit but also greater chance for losses. Modelling of CVaR follows the technique presented in [16].

2) Offering curves constraints:

$$P_{t,w}^{spot}\leq P_{t,w'}^{spot}\qquad\forall t,\forall w,w':if\ \lambda_{t,w}^{spot}<\lambda_{t,w'}^{spot}\quad(2)$$

$$P_{t,w}^{spot}=P_{t,w'}^{spot}\qquad\forall t,\forall w,w':if\ \lambda_{t,w}^{spot}=\lambda_{t,w'}^{spot}\quad(3)$$

$$P_{t,w}^{spot}\leqslant p^{max}\quad(4)$$

Constraints (2) and (3) are used to create the offering curves to the day-ahead market according to the method described in [16]. The non-decreasing constraint (2) ensures the ascending order of the power bids and the non-anticipativity constraint (3) ensures common power offers for the same price scenario. The power offers have an upper limit set by the capacity of the power plant p^{max} (4).

3) Heat balance constraints:

$$Q_{t,w}^{BL}=Q_{t,w}^{SN}+\eta^{bl}\cdot Q_{t,w}^{S-}+Q_{t,w}^{F}-Q_{t,w}^{S+}\quad(5)$$

$$Q_{t,w}^{SN}+Q_{t,w}^{U,SN}\leqslant max\{0,a\cdot s_{t,w}+b\}\quad(6)$$

The heat balance constraint (5), ensures that the heat that goes into the power block $Q_{t,w}^{BL}$ is equal to the heat produced in the solar field $Q_{t,w}^{SN}$, in the boiler $Q_{t,w}^{F}$ and the heat which is exchanged with the TES, $Q_{t,w}^{S+}$ when charging and $Q_{t,w}^{S-}$ when discharging. Heat coming from the TES results in a less efficient power generation given by the efficiency

factor η^{bl}. The heat production in the solar field used for power generation $Q_{t,w}^{SN}$ or starting up the plant $Q_{t,w}^{U,SN}$ is upper limited by the maximum heat that can be produced from the direct solar irradiance $s_{t,w}$ (6). As parameter b is negative, heat produced in the solar field is considered only when it is a positive quantity.

4) Fuel boiler constraints:

$$q^{min}\leqslant Q_{t,w}^{F}+Q_{t,w}^{U,F}\leqslant q^{max}\quad(7)$$

$$F_{t,w}=\frac{Q_{t,w}^{F}+Q_{t,w}^{U,F}}{\eta^{f}}\quad(8)$$

$$\sum_{t=1}^{N_T}\left(Q_{t,w}^{F}+Q_{t,w}^{U,F}\right)\leqslant e^{b,max}\quad\forall w\quad(9)$$

Constraint (7) defines the lower and upper limits of heat production in the boiler. $Q_{t,w}^{F}$ stands for the heat used power generation while $Q_{t,w}^{U,F}$ for the heat used for warming up the HTF during the start up process. The fuel consumption is given by (8) where η^{f} is the efficiency of the boiler. Finally, in some countries there is some restriction in the use of the boiler and only a specific amount of heat can produced for a period of time. If such restriction applies, then (9) should be used, where $e^{b,max}$ is the heat limit.

5) Heat storage constraints:

$$V_{t,w}=V_{t-1,w}+\eta^{s+}\cdot Q_{t,w}^{S+}-\frac{Q_{t,w}^{S-}+Q_{t,w}^{U,S-}}{\eta^{s-}}\quad(10)$$

$$v^{min}\leqslant V_{t,w}\leqslant v^{max}\quad(11)$$

$$Q_{t,w}^{S+}\leqslant h^{max}\cdot S_{t,w}^{+}\quad(12)$$

$$Q_{t,w}^{S-}+Q_{t,w}^{U,S-}\leqslant h^{max}\cdot S_{t,w}^{-}\quad(13)$$

$$S_{t,w}^{-}+S_{t,w}^{+}\leqslant 1\quad(14)$$

The heat content in TES at each period is defined by the amount of heat which is transferred to or taken out of the storage. This is given by (10) where $V_{t,w}$ is the heat content, $Q_{t,w}^{S+}$ is the heat that charges the TES and $Q_{t,w}^{S-}$, $Q_{t,w}^{U,S-}$ is the heat used for power generation or the start up process respectively. When charging or discharging is happening there is some loss of heat given by the efficiency factors η^{s+} and η^{s-}. The operation inside the heat content limits v^{min} and v^{max} is given by (11). Furthermore, there is an upper limit of the heat flow h^{max} during charging (12) and discharging of the TES (13). The restriction of simultaneous charging and discharging is given by (14).

6) Generation constraints:

$$Q_{t,w}^{BL} = \sum_{m=1}^{N_M} Q_{m,t,w} \quad \forall m, \forall t, \forall w \tag{15}$$

$$Q_{m,t,w} \leqslant (q_m - q_{m-1}) \cdot M_{m,t,w} \quad \forall m, \forall t, \forall w \tag{16}$$

$$Q_{m,t,w} \geqslant (q_m - q_{m-1}) \cdot M_{m+1,t,w} \quad \forall m, \forall t, \forall w \tag{17}$$

$$P_{t,w} = \sum_{m=1}^{N_M} \eta_m^p \cdot Q_{m,t,w} \tag{18}$$

$$U_{t,w} \cdot p^{min} \leqslant P_{t,w} \leqslant p^{max} \cdot U_{t,w} \tag{19}$$

Constraints (15-18) are used to make piece-wise linear the non linear relation between the heat input and power output of the power block. For this reason the heat input is split into segments defined by points q_m. As heat input increases, constraints (16) and (17) demand the full use of any previous segment with smaller efficiency before moving to the next one. The use of each segment is defined by the binary variable $M_{m,t,w}$. Total heat input $Q_{t,w}^{BL}$ to the power block is equal to the aggregated heat of the segments (15), while power generation $P_{t,w}$ is the aggregated heat of the segments multiplied with their corresponding efficiency factors (18). Power generation is also limited down p^{min} and up p^{max} by (19).

7) Imbalance constraints:

$$\Delta P_{t,w} = P_{t,w} - P_{t,w}^{spot} \tag{20}$$

$$\Delta P_{t,w} = \Delta P_{t,w}^+ - \Delta P_{t,w}^- \tag{21}$$

$$\Delta P_{t,w}^- \leqslant p^{max} \tag{22}$$

$$\Delta P_{t,w}^+ \leqslant P_{t,w} \tag{23}$$

The power generation imbalance $\Delta P_{t,w}$ is defined as the difference between the actual power generation $P_{t,w}$ and the power offered to the day-ahead market $P_{t,w}^{spot}$ (20). A positive $\Delta P_{t,w}^+$ and negative $\Delta P_{t,w}^-$ imbalance is defined in (21). The maximum negative imbalance cannot be greater than the capacity (22) while the maximum positive imbalance cannot be greater than the actual power generation (23).

8) Start up heating constraints:

$$\sum_{\tau=t-t^d}^{t-1} \left(Q_{\tau,w}^{U,SN} + Q_{\tau,w}^{U,S-} + Q_{\tau,w}^{U,F} \right) \geqslant e^{up,min} \cdot Y_{t,w} \tag{24}$$

$$Q_{\tau,w}^{U,SN} + Q_{\tau,w}^{U,S-} + Q_{\tau,w}^{U,F} \leqslant e^{up,min} \cdot (1 - U_{t,w}) \tag{25}$$

HTF needs to reach a specific temperature in order for the plant to be able to start up. This is modelled by demanding the accumulated heat over the previous hours to be over a specific limit $e^{up,min}$ (24). Constraint (25) restricts the start up heat variables to be zero when the plant is operating.

9) Ramp rate constraints:

$$P_{t,w} - P_{t-1,w} \leqslant t^{per} \cdot r^{p,u} \tag{26}$$

$$P_{t-1,w} - P_{t,w} \leqslant t^{per} \cdot r^{p,d} \tag{27}$$

The increase and decrease of power generation should be under the ramp rate limits $r^{p,u}$ and $r^{p,d}$. These limits are satisfied by (26) and (27) respectively.

10) Unit commitment constraints:

$$Y_{t,w} \leqslant U_{t,w}, \; Y_{t,w} \leqslant 1 - U_{t-1,w}, \; Y_{t,w} \geqslant U_{t,w} - U_{t-1,w} \tag{28}$$

$$Z_{t,w} \leqslant U_{t-1,w}, \; Z_{t,w} \leqslant 1 - U_{t,w}, \; Y_{t,w} \geqslant U_{t-1,w} - U_{t,w} \tag{29}$$

$$M_{1,t,w} \leqslant U_{t,w} \tag{30}$$

The set of constraints (28) and (29) assign the correct values to the binary variables that define the operating $U_{t,w}$, start up $Y_{t,w}$ and shut down $Z_{t,w}$ status of the units. The way these constraints are implemented allows the start up and shut down variables to be defined as positive variables. Constraint (30) restricts the binary variables $M_{t,w}$ to be zero when the plant is not operating, shutting down in that way the power generation.

11) Unit minimum up and down time constraints:

$$\sum_{t=1}^{l} (1 - U_{t,w}) = 0 \quad \forall w \tag{31}$$

$$\sum_{\tau=t}^{t+t^u-1} (U_{\tau,w} - Y_{t,w}) \geqslant 0 \tag{32}$$

$$\sum_{t=1}^{f} U_{t,w} = 0 \quad \forall w \tag{33}$$

$$\sum_{\tau=t}^{t+t^d-1} (1 - U_{\tau,w} - Z_{t,w}) \geqslant 0 \tag{34}$$

Constraints (31) and (32) restrict the plant to operate if the time that has passed since its starting up is less than the minimum up time. Similar limitations are applied for the minimum down time (33-34). In (31) , $l = min \left\{ N_T, \left(t^u - t^{u,0} \right) \cdot u^0 \right\}$ are the hours in the beginning of the planning horizon that the unit is restricted to operate due to initial conditions. Similarly, $f = min \left\{ N_T, \left(t^u - t^{d,0} \right) \cdot \left(1 - u^0 \right) \right\}$ are the hours that the unit is restricted to be off-line in (33). Here, N_T is the cardinality of T, u^0 the initial operating status of the plant, and $t^{u,0}/t^{d,0}$ the hours the plant was on-line/off-line before the planning period.

12) CVaR constraint:

$$\sum_{t=1}^{N_T} \left[\lambda_{t,w}^{spot} \cdot P_{t,w}^{spot} + \lambda_{t,w}^{bm+} \cdot \Delta P_{t,w}^+ - \lambda_{t,w}^{bm-} \cdot \Delta P_{t,w}^- \right.$$

$$\left. -c^{start} \cdot Y_{t,w} - c^{off} \cdot (1 - U_{t,w}) - c^{fuel} \cdot F_{t,w} \right] \geqslant B - A_w \tag{35}$$

$$A_w \geqslant 0 \quad \forall w \tag{36}$$

Finally, constraints (35) and (36) are used in conjunction with the term in the objective function to calculate CVaR [16].

III. CASE STUDY

In this case study a CSP plant of 50MW nominal power output is considered which is located in Spain and is trading in the Spanish day-ahead market. Technical parameters of the system are given in table I. The boiler of the system is not allowed to be used for power generation. Instead, it can be used for the start up process when it is needed.

TABLE I
MAIN TECHNICAL PARAMETERS OF THE CASE STUDY CSP SYSTEM

Parameter	Value
Power generation limits, [MW$_{el}$]	50 / 0
Ramp up / down rates [MW$_{el}$/min]	5 / 5
Minimum up / down times [h]	2 / 2
Boiler heat generation limits, [MW$_{th}$]	50 / 0
Boiler efficiency	0.9
Fuel cost [€/MWh$_{th}$]	55
TES upper / lower limit [MWh$_{th}$]	600 / 40
TES discharging /charging efficiency	0.9 / 0.8

Two reference days are used to test the model, one in January and one in July. The variation of solar irradiance during these two months in Spain is shown in fig. 6.
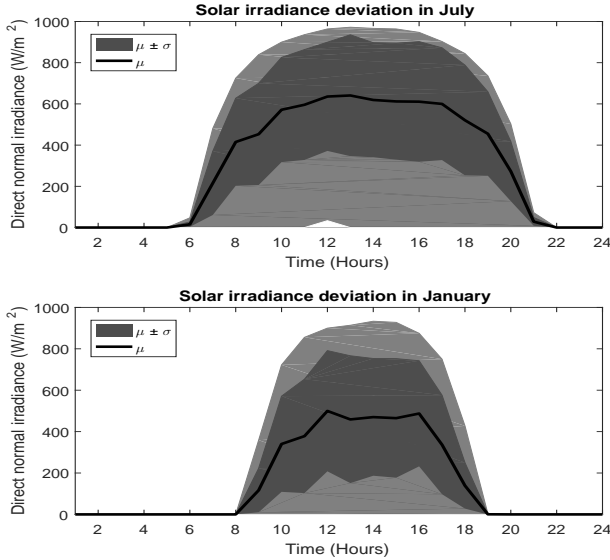

Fig. 6. Hourly solar irradiance deviation during July (up) and January (down) in Spain

Three different sizes of the solar field are assumed in order to test how this parameter affects the expected profit of the CSP producer. The solar multiple of the solar fields and the corresponding thermal power function coefficients are given in table II [11]. The expected profit in relation to the solar multiple is shown in fig. 7. It can be seen that the use of TES increases the expected profit. The impact of TES use on the profit increases with the increase of the solar field size. Furthermore, the impact is stronger for the operation in July.

The higher expected profit in January compared to July is due to the much higher prices in the market that period.

TABLE II
THERMAL POWER FUNCTION COEFFICIENTS FOR DIFFERENT SOLAR MULTIPLES

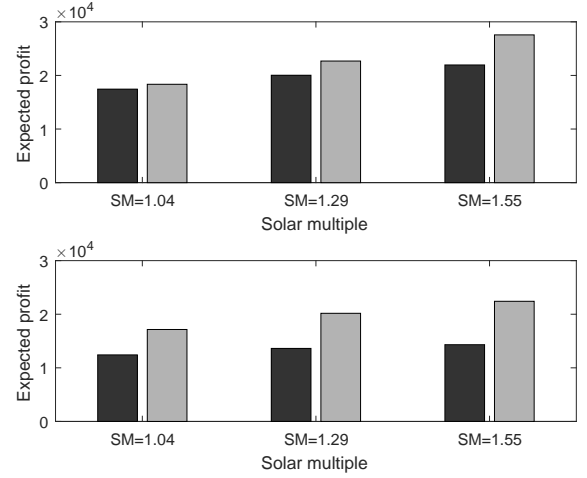| Solar multiple	Thermal power function coefficients a / b
1.04	0.198 / -10.737
1.29	0.248 / -13.422
1.55	0.297 / -16.106

Fig. 7. Expected profit for different values of solar multiple in January (up) and July (down) of a CSP system without TES (dark grey) and with TES (light grey)

The solution of the problem provides the volumes of power that should be sold for each scenario of the day-ahead market prices. By joining these price-volume points we get the offering curves of the CSP producer to the day-market. In fig. 8 the offering curves for hours 12:00 and 18:00 are given for the two reference days. Bids are done at lower prices in July as a result of the low price scenarios as it was referred previously. Furthermore, when the CSP system operates without TES, the offering curves are just straight lines. This is an expected result as there is no possibility to shift the production at later hours. Whole production should be offered at any price. On the other hand, the existence of TES allows the producer to schedule the production at the hours with higher prices. This results in offering curves with different volumes for different prices.

Finally, the model is run for three different values of the risk-aversion parameter β. Fig. 9 presents the expected profit in relationβ. The increase of β results in a more risk averse solution where the scenarios with the lowest profit are penalized. On the other hand, the expected profit is reduced.
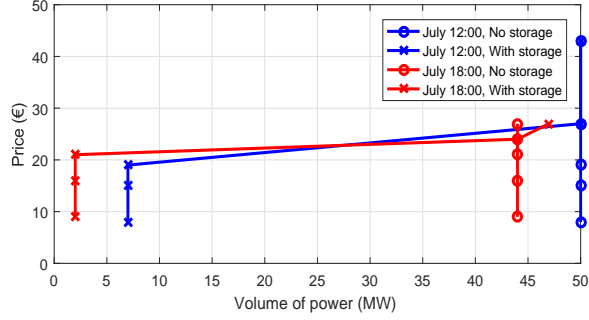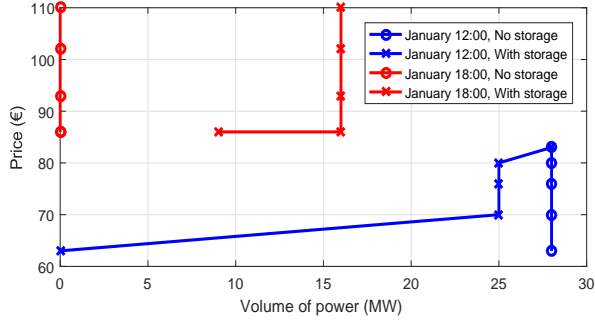
Fig. 8. Day-ahead offers for hours 12:00 and 18:00 of a CSP system with and without TES, in January (up) and in July (down)
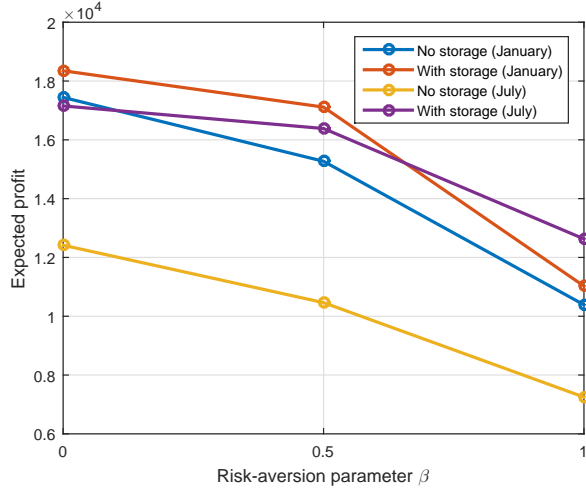

Fig. 9. Expected profit as a function of the CVaR risk-aversion parameter β, ($\beta = 0, 0.5, 1$)

IV. CONCLUSIONS

This paper presents a probabilistic optimization model for a CSP electricity producer with the aim to design the offering curves for the day-ahead electricity market. The model takes into account various stochastic parameters such as CSP production, day-ahead market prices and imbalance costs. The proposed model is a two-stage model, where first stage decision variables are the offering curves to the day-ahead market

while second stage variables includes real time operation and imbalance settlement. In addition the CVaR risk assessment technique is used to reduce the probability of high losses. The model was applied on case study of a CSP electricity producer with 50 MW nominal power output which is located in Spain. Results also show the effect of the solar field size on the expected profits. A model that it also includes trading in the intraday electricity markets could be an extension of this work.

APPENDIX A
NOMENCLATURE

Indices and Numbers:

t	Index of time periods, running from 1 to N_T
w	Index of scenarios, running from 1 to N_W
m	Index of segments, running from 1 to N_M

Parameters:

π_w	Probability of occurrence of scenario w
$s_{t,w}$	Direct solar irradiance in period t and scenario w, [W/m^2]
$\lambda_{t,w}^{spot}$	Day-ahead market price in period t and scenario w, [€/MWh$_{el}$]
$\lambda_{t,w}^{bm+}$	Balancing market upward price in period t and scenario w, [€/MWh$_{el}$]
$\lambda_{t,w}^{bm-}$	Balancing market downward price in period t and scenario w, [€/MWh$_{el}$]
c^{start}	Start-up cost, [€/h]
c^{off}	Off-line cost, [€/h]
c^{fuel}	Fuel cost, [€/MWh$_{th}$]
α	Per unit confidence level
β	Risk-aversion parameter
a, b	Thermal power function coefficients
η^{bl}	Efficiency factor for use of TES heat
η_m^p	Segment efficiency
η^f	Boiler efficiency
η^{s+}	TES charging efficiency
η^{s-}	TES discharging efficiency
q_m	Power block thermal input segment point
p^{max}	Power production upper limit, [MW$_{el}$]
p^{min}	Power production lower limit, [MW$_{el}$]
q^{max}	Boiler heat production upper limit, [MW$_{th}$]
q^{min}	Boiler heat production lower limit, [MW$_{th}$]
$e^{b,max}$	Maximum thermal energy allowed to be produced in the boiler, [MWh$_{th}$]
$e^{up,min}$	Minimum thermal energy needed for the start up , [MWh$_{th}$]
v^{min}	Heat storage lower limit, [MWh$_{th}$]
v^{max}	Heat storage capacity, [MWh$_{th}$]
h^{max}	Maximum flow to and from storage, [MW$_{th}$/h]
t^u	Minimum up time, [h]
t^d	Minimum down time, [h]
$r^{p,u}$	Upward ramp rate [MW$_{el}$/min]
$r^{p,d}$	Downward ramp rate [MW$_{el}$/min]
t^{per}	Length of a period, [min]

Variables:

$P_{t,w}^{spot}$ Power offer to day-ahead market in period t and scenario w, [MW$_{el}$]

$\Delta P_{t,w}$ Power imbalance in period t and scenario w, [MW$_{el}$]

$\Delta P_{t,w}^{+}$ Positive deviation in period t and scenario w, [MW$_{el}$]

$\Delta P_{t,w}^{-}$ Negative deviation in period t and scenario w, [MW$_{el}$]

$P_{t,w}$ Power generation in period t and scenario w, [MW$_{el}$]

$F_{t,w}$ Boiler fuel consumption in period t and scenario w, [MW]

$Q_{t,w}^{BL}$ Heat input to power block in period t and scenario w, [MW$_{th}$]

$Q_{t,w}^{SN}$ Heat production in solar field in period t and scenario w, [MW$_{th}$]

$Q_{t,w}^{S+}$ Heat charging storage in period t and scenario w, [MW$_{th}$]

$Q_{t,w}^{S-}$ Heat discharging from storage in period t and scenario w, [MW$_{th}$]

$Q_{t,w}^{F}$ Heat production in boiler in period t and scenario w, [MW$_{th}$]

$Q_{t,w}^{U,SN}$ Heat production in solar field for starting up in period t and scenario w, [MW$_{th}$]

$Q_{t,w}^{U,S-}$ Heat discharging from storage for starting up in period t and scenario w, [MW$_{th}$]

$Q_{t,w}^{U,F}$ Heat production in boiler for starting up in period t and scenario w, [MW$_{th}$]

$Q_{m,t,w}$ Heat production of segment m in period t and scenario w, [MW$_{th}$]

$V_{t,w}$ Heat storage content in period t and scenario w, [MWh$_{th}$]

$U_{t,w}$ Binary variable: 1 if plant is operating in period t and scenario w, else 0

$Y_{t,w}$ Binary variable: 1 if plant is starting up in period t and scenario w, else 0

$Z_{t,w}$ Binary variable: 1 if plant is shutting down in period t and scenario w, else 0

$S_{t,w}^{+}$ Binary variable: 1 if heat storage is charging in period t and scenario w, else 0

$S_{t,w}^{-}$ Binary variable: 1 if heat storage is discharging in period t and scenario w, else 0

$M_{m,t,w}$ Binary variable: 1 if heat segment m is used in period t and scenario w, else 0

B Auxiliary variable used to compute CVaR, [€]

A_w Auxiliary variable used to compute CVaR in scenario w, [€)]

All variables are positive apart from $U_{t,w}$, $S_{t,w}^{+}$, $S_{t,w}^{-}$ and $M_{m,t,w}$ which are binary and B which is free variable.

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