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Abstract. This paper presents a coordination approach to maximize the total profit of wind power systems coordinated with concentrated solar power systems, having molten-salt thermal energy storage. Both systems are effectively handled by mixed-integer linear programming in the approach, allowing enhancement on the operational during non-insolation periods. Transmission grid constraints and technical operating constraints on both systems are modeled to enable a true management support for the integration of renewable energy sources in day-ahead electricity markets. A representative case study based on real systems is considered to demonstrate the effectiveness of the proposed approach.

Keywords: Concentrated solar power; wind power; mixed-integer linear programming; transmission constraints.

1 Introduction

Renewable energy grid integration increased in the E.U. to fulfill the Energy – 2020 initiative. Energy efficiency improvement, renewable technologies and lower emissions are priorities to ensure environmental sustainability [1]. Wind power systems and concentrated solar power (CSP) systems are engaged in the meeting of demand increase in the Southern Mediterranean, profiting from favorable renewable energy sources. But, the non-controllable variability and limited predictability of the energy source of these systems [2] conveys real-time uncertainty posing capacity planning challenges related to the tuning of ancillary services needed to ensure system stability and reliability [3]. Also, real-time uncertainty on renewable energy availability can increase costs if an unfitting prediction occurs. Hence, a coordination approach seems to be an adequate required option in order to reduce the uncertainty in power output. The wind-CSP systems coordination is a reliable option, enabling to accommodate energy integration into the power grid and day-ahead electricity markets [4], as well as to increment the dispatchability attribute on the accommodation. The non-dispatchable characteristic of CSP systems is lessened with thermal energy storage (TES) systems, enabling plant base load support. TES not only allows offsetting generation deficit during non-insolation periods, reducing real-time net generation variability, but also allows shifting of generation towards appropriate periods [5]. TES has proved to be a reliable option [6], allowing control on the energy, improving the capacity value and profits. Moreover, TES further increments the dispatchability and can reduce the running of conventional thermal power plants in short-term ancillary services [7], reducing the need for spinning, implying a noted reduction in reserve costs. Also, TES allows reducing high marginal cost units when an unpredicted drop in renewable energy input occurs. Therefore, the line of research of coordination approach for wind-CSP having TES systems is regarded as an important promising one offering new technical challenges to the researchers and this paper presents a contribution on this regard.

The paper presents a mixed-integer linear programming (MILP) model for solving the generation scheduling problem of wind-CSP having TES systems. The aim is to achieve the optimal generation schedule that maximizes the profit of a power producer taking part in a day-ahead electricity market. The optimization approach considers not only transmission line constraints, but also technical operating constraints on wind power systems and on CSP systems to enable a true management support for the integration of renewable energy sources in day-ahead electricity markets.

2 Relationship to Cloud-based Solutions

Cloud-based solutions can help the processing of approaches for helping trading in a day-ahead electricity market in order to take greater advantages of bids, requiring methodological approaches demanding computational effort not currently available to all power producers. Among these approaches the ones for the solution of the problems concerned with scheduling: energy management, unit commitment and energy offers are particular vital for upholding power producers. The approaches to solve these problems have been limited by the available computational resources, i.e., details concerning some reality are disregard in view of the excessive use of processing requirements. These limitations are evident for large systems and lead to solutions not addressed in convenient agreement with the reality, because the computational resources do not allow the usage of data or modeling for delivering more real adequate solutions.

Cloud-based solutions are able to contribute for upholding a power producer exploiting wind-CSP systems by setting out an adequate availability of computational resources needed to address scheduling problems in due time. Although of the uncertainty on the wind and solar power, i.e., intermittency and variability, cloud-based engineering systems will deal with problems having a better approach to the full reality in due time with gains in terms of profit. Cloud-based solutions will help on the smoothing of the electricity price due to the fact of having bids of wind power with higher level of energy and with more certainty in what regards the satisfaction on delivering the electric energy accepted at the closing of the market. Also, environmental benefit is expected with mitigation of the deviation from the assumed compromises by a better finding of offers able of fulfillment, less spinning reserved is needed, less thermal units are needed and less fossil fuel is used. Eventually, cloud-based solutions will allow approaches in order that when a power producer exploiting a wind-CSP systems at site has renewable energy available is all captured to be converted into electric energy injected without concerns on dynamic stability into the power grid in due time.

3 State of the Art

The literature on optimal scheduling is still rapidly growing. Coordination strategies and optimization approaches for short-term scheduling have been are in research, for instances: a envisaged wind-thermal coordination via simulated annealing unveiled an improvement of smoothing the active power fluctuations [8], and one via MILP unveiled a reduction of the uncertainty in wind power output [9]; a envisaged coordination of wind power with compressed air energy storage unveiled an improvement due to the synergies between wind power and compressed air energy storage [10]; a envisaged wind and hydro power coordination, specially pumped-storage hydro power systems [11,12], unveiled an improvement on minimization of curtailment, energy imbalance and dispatchability. Furthermore, electrical vehicles connection to the power grid are expected to be used as controllable loads and a convenient operation with suitable market design may help in the accommodation more wind power [13].

Coordination strategies have unveiled progress in reducing of the uncertainty of wind power output by the use of different dispatchable resources or loads, even though resources may not be installed in the same region of wind power systems deployment. But, when the surrounding of the load centres has attractive conditions of wind speed and solar irradiation, wind-CSP is an option design to be considered. This option enables a better accommodation of energy integration into the power grid and day-head electricity markets [14], as well as to increase the dispatchability attribute on the accommodation. The scheduling proposed in this paper is based on a MILP approach, which has been a successful approach for solving scheduling problems in general. So, also is expected to be one to help support decisions in a day-head electricity market.

4 Problem Formulation

The scheduling is computed by the maximization of the objective function given by the profit subject to transmission and systems constraints.

4.1 Objective Function

The profit is equal to the revenues from day-ahead electricity market sales and wind production incentive rate minus the CSP variable costs during the time horizon of the schedule. The objective function to be maximized is given as follows:

$$F = \sum_{k\in K}\left[\pi_k^{da}\,(p_k^s - p_k^b) + \sum_{i\in I}\xi\, p_{i,k}^{Wind} - \sum_{c\in C}\beta_c\, p_{c,k}^{CSP}\right] \quad \textbf{(1)}$$

In (1), K is the set of hours in the time horizon, π_k^{da} is the forecasted day-ahead market price in hour *k*, p_k^s is the power sold to day-ahead electricity market in hour *k*, p_k^b is the power purchased from day-ahead electricity market in hour *k*, I is the set of wind turbines, ξ is the wind production incentive rate, $p_{i,k}^{Wind}$ is the power output of the wind turbine *i*, C is the set of CSP systems, β_c is the variable cost of the CSP system *c* and $p_{c,k}^{CSP}$ is the power output of the CSP system *c* in hour k.

4.2 Constraints

The constraints for the scheduling are due to the transmission grid, operation of wind systems, operation or minimum up/down time of CSP systems.

Transmission grid

The transmission grid constraints are given as follows:

$$(1-\psi)^{-1} p_k^s - (1-\psi) p_k^b = \sum_{i \in I} p_{i,k}^{Wind} + \sum_{c \in C} p_{c,k}^{CSP} \quad \forall k \tag{2}$$

$$-\chi \le (1-\psi)^{-1} p_k^s - (1-\psi) p_k^b \le \chi \quad \forall k \tag{3}$$

$$0 \le \sum_{i \in I} p_{i,k}^{Wind} + \sum_{c \in C} p_{c,k}^{CSP} \le \chi \quad \forall k \tag{4}$$

$$0 \le p_k^s \le \chi y_k \quad \forall k \tag{5}$$

$$0 \le p_k^b \le \chi (1 - y_k) \quad \forall k \tag{6}$$

In (2) to (6), ψ is the transmission loss, χ is the transmission capacity, and y_k is a 0/1 variable. In (2), the electric power balance is enforced between the day-ahead electricity market trading with wind power systems and CSP systems. In (3) and (4), the electric power bounds are set for the transmission line. In (5) and (6), the energy flow in the line is set infeasible for simultaneously trading by selling and purchasing.

Operation of wind systems

The operational constraints of wind power system are given as follows:

$$0 \le p_{i,k}^{Wind} \le W_{i,k} \quad \forall i,k \tag{7}$$

$$0 \le p_{i,k}^{Wind} \le \overline{P}_i^{Wind} \quad \forall i,k \tag{8}$$

where $W_{i,k}$ is the scheduled of wind turbine *i* in hour *k*, and $\overline{P}_i^{Wind}$ is the wind turbine *i* power bound. In (7), the operating limits for the scheduled wind power of each wind turbine *i* are set. In (8), the maximum power capacity of each wind turbine *i* is set.

Operation of CSP systems

The operational constraints of CSP systems are given as follows:

$$p_{c,k}^{CSP} = p_{c,k}^{FE} + p_{c,k}^{SE} - X_c \quad \forall c,k \tag{9}$$

$$p_{c,k}^{FE} = \eta_1 q_{c,k}^{FE} \quad \forall c,k \tag{10}$$

$$p_{c,k}^{SE} = \eta_3 q_{c,k}^{SE} \quad \forall c,k \tag{11}$$

$$\underline{Q}_c^{PB} u_{c,k} \le q_{c,k}^{FE} + q_{c,k}^{SE} \le \overline{Q}_c^{PB} u_{c,k} \quad \forall c,k \tag{12}$$

$$q_{c,k}^{FE} + q_{c,k}^{FS} \le S_{c,k} \quad \forall c,k \tag{13}$$

$$q_{c,k}^{S} = q_{c,k-1}^{S} + \eta_2 q_{c,k}^{FS} - q_{c,k}^{SE} \quad \forall c,k \tag{14}$$

$$\underline{Q}_c^{S} \le q_{c,k}^{S} \le \overline{Q}_c^{S} \quad \forall c,k \tag{15}$$

$$\underline{Q}_c^{FE} \le q_{c,k}^{FE} \le \overline{Q}_c^{FE} \quad \forall c,k \tag{16}$$

$$0 \le p_{c,k}^{CSP} \le \overline{P}_c^{CSP} \quad \forall c,k \tag{17}$$

$$p_{c,k}^{SE} - p_{c,k+1}^{SE} \le RD_c^T \quad \forall\, c, k = 0,...,K-1 \qquad \textbf{(18)}$$

$$\eta_2 (q_{c,k+1}^{FS} - q_{c,k}^{FS}) \le RU_c^T \quad \forall\, c, k = 0,...,K-1 \qquad \textbf{(19)}$$

$$0 \le p_{c,k}^{SE} \le M\, z_{c,k} \quad \forall\, c, k \qquad \textbf{(20)}$$

$$0 \le p_{c,k}^{FS} \le M\,(1 - z_{c,k}) \quad \forall\, c, k \qquad \textbf{(21)}$$

$$p_{c,k}^{FE},\, p_{c,k}^{SE},\, q_{c,k}^{FE},\, q_{c,k}^{SE} \ge 0 \quad \forall\, c, k \qquad \textbf{(22)}$$

In (9) to (21), $p_{c,k}^{FE}$ and $p_{c,k}^{SE}$ are the power produced by the solar field (SF) *c* and the TES *c* in hour *k*, X_c is the parasitic power of the CSP plant *c*, η_1 is the SF efficiency, $q_{c,k}^{FE}$ is the thermal power from the SF *c* in hour *k*, η_3 is the molten-salt tanks efficiency, $q_{c,k}^{SE}$ is the storage power in TES *c* to produce electricity in hour *k*, $\underline{Q}_c^{PB}$ and $\overline{Q}_c^{PB}$ are the thermal power bounds of the power block of CSP plant *c*, $u_{c,k}$ is the CSP plant *c* commitment in hour *k*, $q_{c,k}^{FS}$ is the thermal power from the SF *c* stored in hour *k*, $S_{c,k}$ is the thermal power produced by the SF *c* in hour *k*, $q_{c,k}^{S}$ is the thermal energy stored in TES *c* at the end of hour *k*, η_2 is the TES efficiency, $\underline{Q}_c^{S}$ and $\overline{Q}_c^{S}$ are the TES *c* thermal energy bounds, $\underline{Q}_c^{FE}$ and $\overline{Q}_c^{FE}$ are the thermal power bounds from the SF *c*, $\overline{P}_c^{CSP}$ is the CSP plant *c* power bound, RD_c^T and RU_c^T are the ramp-up and ramp-down limits for charging and discharging the stored energy of TES *c*, M is a sufficiently large constant $M \ge \overline{P}_c^{CSP}$, and $z_{c,k}$ is the 0/1 variable equal to 1 if TES *c* discharges power in hour *k*. In (9), the electric power balance is enforce between the power output of CSP system with the electric power produced from the SF, the storage and the parasitic power needed for maintaining the molten-salt fluid in operation conditions. This parasitic power occurs even if a CSP system is not operating, eventually implying that if the producer has not enough energy available, a small quantity of energy is soak up from the grid, incurring on an associated cost. The parasitic power is assumed constant. In (10) and (11), the electric power from the SF and TES is considered dependent on the efficiencies associated with the thermal power of the SF and the storage power, respectively. In (12), the bounds for the sum of the power from the SF and TES are set. In (13) and (14), the balance of the thermal power in the SF and the energy stored in the TES is set, respectively. In (15), the bounds for the thermal power storage in the TES are set in order to avoid the solidification of salts and the maximum storage capacity to be exceeded. In (16), the bounds for the thermal power from the SF are set. In (17), the bounds for the power output of the CSP systems are set. In (18) and (19), the charge and the discharge ramp rates of the TES are set, respectively. In (20) and (21), power restrictions are set to prevent simultaneous discharging and charging of the TES in the same hour, imposed by the 0/1 variable, z_k.

Minimum up/down time of CSP systems

The minimum up/down time constraints of CSP systems are given as follows:

$$\sum_{r=k-UT_c^{SF+T}+1,\, r\geq 1\in k} (u_{c,r} - u_{c,r-1}) \leq u_{c,k} \quad \forall\, c, k = L^{SF+T} + 1, \ldots, K \tag{23}$$

$$\sum_{r=k-DT_c^{SF+T}+1,\, r\geq 1\in k} (u_{c,r-1} - u_{c,r}) \leq 1 - u_{c,k} \quad \forall\, c, k = F^{SF+T} + 1, \ldots, K \tag{24}$$

In (23) and (24), the minimum up/down times for the CSP system c are set based on [18], where $L_c^{SF+T} = \min[K, UT_c^{SF+T}]$ and $F_c^{SF+T} = \min[K, DT_c^{SF+T}]$.

5 Case Study

The case study is intended to show the advantages of the coordination between wind power systems and CSP systems having TES. These advantages are coming from the synergies between both systems and the adequate optimal mix of synergies is in favor of the proposed approach. The MILP for the approach has been solved using CPLEX 12.1 solver under GAMS environment [15]. A computer with 8 GB RAM with 2.30 GHz of CPU is used for the simulations of realistic case studies based on a Iberian wind-CSP system with 40 wind turbines, $i = 1, \ldots, 40$, and 2 CSP plants, $c = 1, 2$ and carried out with technical data shown in Table 1.

Table 1. Wind-CSP system data.

$\underline{P}_i^{Wind}$ / $\overline{P}_i^{Wind}$ (MW)	$\underline{P}_c^{CSP}$ / $\overline{P}_c^{CSP}$ (MWe)	$\underline{Q}_c^{S}$ / $\overline{Q}_c^{S}$ (MWht)	$\underline{Q}_c^{FE}$ / $\overline{Q}_c^{FE}$ (MWt)
0 / 2	0 / 50	45 / 700	0 / 150
$\underline{Q}_c^{PB}$ / $\overline{Q}_c^{PB}$ (MWt)	$q_{c,0}^{S}$ (MWht)	RU_c^T / RD_c^T (MWe/h)	UT_c^{SF+T} / DT_c^{SF+T} (h)
50 / 125	120	35 / 80	2 / 2

All wind power systems have the same data as well as CSP systems, respectively. The installed wind power capacity is 80 MW and for CSP is 100 MW_e. The systems share a transmission line connecting to the power grid. This line has 3 % of losses and exported power is assumed to be between 50 MW and 130 MW. The module efficiencies for the CSP systems are respectively: 1) $\eta_1 = 0.40$; 2) $\eta_2 = 0.35$; 3) $\eta_3 = 0.80$. The parasitic power is 3.5 MW_e and the wind production incentive rate is assumed to be of 35 €/MWh.

The time horizon in the simulations is a day on an hourly basis, corresponding to a participation in a day-ahead electricity market. Within the time horizon are considered as input data not only the solar and the wind power profiles, but also the day-ahead market prices profile. The solar irradiation profile derived from the System Advisor Model [16] was converted into available thermal power. The wind power profile is derived from the ANN forecaster designed in [17]. The wind power and thermal power output profiles respectively are assumed to be the same for each wind turbine and CSP systems as is shown in Fig. 1.

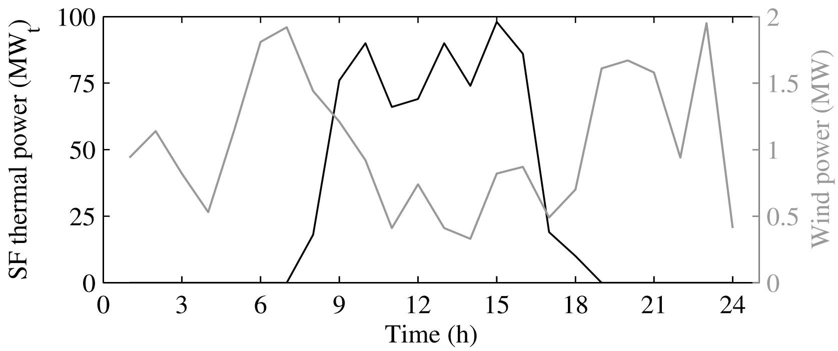

Fig 1. SF thermal and wind power profiles.

The scheduling problem for the wind-CSP coordination has a day-ahead time horizon, due to this short horizon, the energy market prices can be assumed as deterministic input data given by forecast average prices. The prices of the Iberian electricity market given in [18] are used in the case study and shown in Fig. 2.

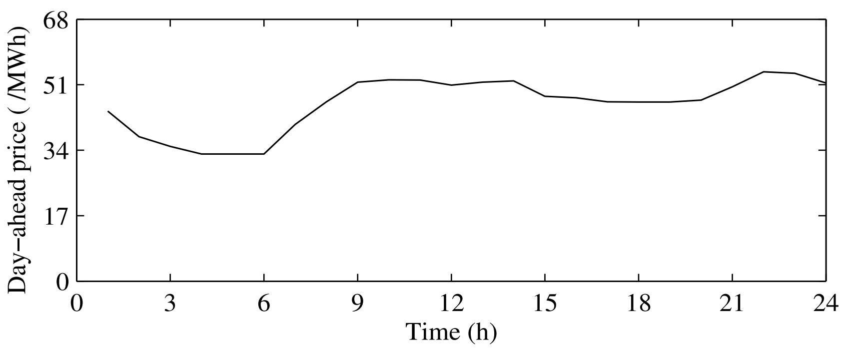

Fig 2. Day-ahead energy market prices.

A summary of the optimizing characteristics for processing the problem presented in the case study in what regards the number of constraints, continuous variables, binary variables and computation times is shown in Table 2.

Table 2. Optimizing characteristics of the case study.

#	Constraints	Continuous variables	Binary variables	CPU time (s)
Case study	1,436	864	120	8

The number of installed wind turbines and CSP systems having TES are 20 and 2, respectively. The total installed capacities of wind power systems and CSP systems having TES are 80 MW and 100 MW_e, respectively. The energy and profit for the transmission line capacity of $\chi = 60$ MW and $\chi = 130$ MW associated with the enforced system are shown in Table 3.

Table 3. Energy and profit in function of transmission capacity.

#	Transmission capacity (MW)	Energy stored (MWh)	Energy sold (MWh)	Profit (€)
Case study	60	6,405	1,259	83,527
	130	6,269	1,544	95,673

Table 3 allows a comparison between the profits, revealing a reduction of about 15% for $\chi = 60$ MW. Table 3 shows that an increase in the transmission line capacity of the line allows to make a better use of the energy stored, allowing an augmented profit.

The optimal schedule for the wind-CSP coordination in what regards the assessing of the impact of transmission line constraints with $\chi = 60$ MW and with $\chi = 130$ MW are respectively shown in Fig. 3 (a) and (b).

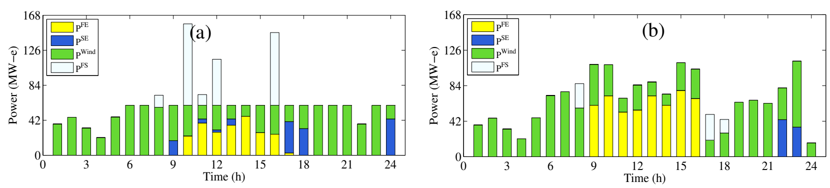

Fig 3. Coordination for transmission capacities: (a) $\chi = 60$ MW; (b) $\chi = 130$ MW.

Fig. 3 (a) shows for the high price hours a significant CSP production in comparison with low price hours. The benefit of TES shifting the production is revealed and the excess energy eventually overloading transmission from hours 8, 10 to 12 and 16 is able to be stored for a convenient discharge at hours 11 to 13, 17, 18 and 24. Additionally, the synergies between wind energy and solar energy allows for the possibility of enhancing the scheduling due to the negative correlation. Thus, an efficient energy schedule is obtained, illustrating the proficiency of the optimization approach for accommodating this deployment with different changing patterns of renewable energy in a power grid. The thermal energy storage shows the significance of the line capacity regarding the storage in the TES. For instance, the increase in the line capacity raises the level of the storage in the low prices hours with solar thermal power in order to be conveniently used during the other hours. If the capacity factor is incremented by downsizing the transmission capacity, then curtailment is to be expected and consequent decrease of the energy produced. The thermal energy storages in function of the transmission capacity and of the time are shown in Fig. 4.

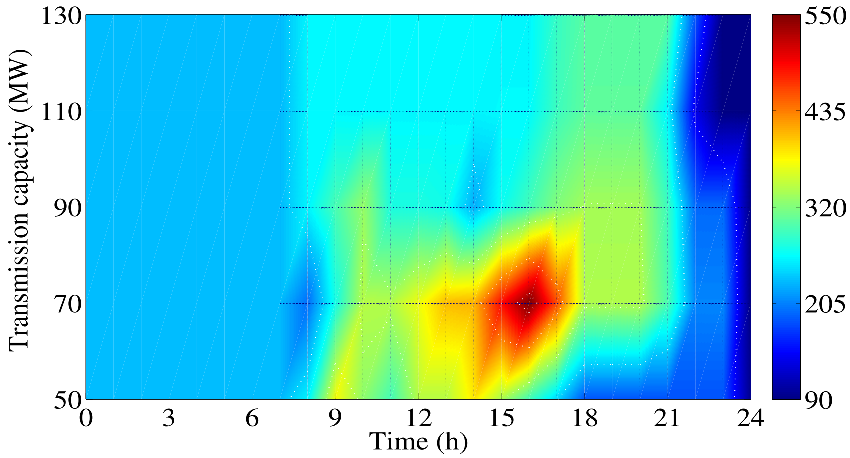

Fig 4. Thermal energy storages in function of transmission capacity and over the time horizon.

6 Conclusions

An approach based on MILP is proposed for the coordination problem of wind-CSP having TES systems and for supporting decisions of participating in day-ahead markets, taking into account transmission line constraints and prevailing technical operating ones for the wind power, CSP and TES. The approach reduces uncertainty and improves the integration of more energy into a grid due to the convenient optimal mix of synergies. The TES is effectively handled to improve the operational productivity. The case studies are in favour of the approach to support decisions in day-ahead markets.

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