Stochastic Optimal Operation of Concentrating Solar Power Plants Based on Conditional Value-at-Risk

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Abstract. This paper presents a stochastic programming approach, using a risk measure defined by conditional value-at-risk, for trading solar energy in a market environment under uncertainty. Uncertainties on electricity price and solar irradiation are considered through a set of scenarios computed by simulation and scenario-reduction. The short-term operation problem of a concentrating solar power plant is formulated as a mixed-integer linear program, which allows modelling the discrete status of the plant. To improve the operational productivity of the plant during the non-insulation periods, energy storage systems are considered. The goal is to obtain the optimal operation planning that maximizes the total expected profits while evaluating trading risks. For risk evaluation, the conditional value-at-risk is used to maximize the expected profits of the least profitable scenarios. A case study is used to illustrate the usefulness and the proficiency of the proposed approach.

Keywords: Concentrating power plant · Conditional value-at-risk · Day-ahead market · Stochastic optimization

1 Introduction

Renewable energy grid integration increased in the E.U. to fulfil the Energy–2020 initiative. The global warming threat is a concern around the world and many policies and agreements are being created to mitigate it [1]. In 2016, the Global Energy Interconnection Development and Cooperation Organization promoted the first council meeting in order to improve the renewable energy efficient usage [2].

In 2016, the Portuguese energy consumption was totally fulfilled by renewable energy sources for almost 4 days. This proves that Portugal has a great potential to be a green energy country although more investments are needed, namely in solar energy [4]. In 2015, the Portuguese total annual energy consumption was fulfilled by 47% from renewable energy sources, but only 1.5% was from solar energy [3].

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Since feed-in tariffs in many countries are coming to an end, the energy trade from renewable energy power plants must occur in electricity markets competing with non-renewable power plants.

Despite the large-scale wind power integration on power systems, other renewable energy technologies are emerging in several countries, such as: photovoltaics (PV) power plants and concentrated solar power (CSP) plants. The non-dispatchable characteristics of a solar energy power plant can be reduced through thermal energy storage (TES) systems. Moreover, TES systems allow the CSP power plants to participate in ancillary service markets [6].

This paper provides an optimization approach that maximizes the expected profits of a CSP producer taking part in the day-ahead electricity market. The main contribution of this paper is: (1) to use a stochastic mixed-integer linear programming (MILP) approach for determining the optimal self-scheduling of a CSP plant having TES systems; (2) to use the conditional value-at-risk so as to mitigate the effect of uncertainty; and (3) to use a scenario reduction algorithm so as to improve the computation time.

2 Relationship to Smart Systems

Smart systems represent a step in the development of a new era for the energy system. Regarding energy efficiency, the smart systems are a new advantage. In the electric power grids of the future, where the internet of things is connecting several measuring devices, are being optimized trough smart systems to increase the energy efficiency [20]. For CSP plants, the smart systems can measure different variables and provide them as inputs for an optimization algorithm. Moreover, the smart systems based on smart meters are vital for solar forecasting which allow to assess forecasts given by external providers. The smart meters allow storing variables in a database, helping power producers to develop the optimal offering strategies to submit in the electricity market [21].

3 State of the Art

The optimal self-scheduling of energy resources is growing in the research community. Different approaches for the short-term scheduling are in research, such as: a novel two-based approach for optimal self-scheduling of CSP plants where the MILP capabilities are combined with the accuracy of the detailed model showing improvements against the simple MILP approach [11], a robust optimization for the maximization of the profit in the day-ahead electricity market for a CSP plant with TES and a backup fossil system and considering bilateral contracts is presented with an acceptable computational time for an industrial application [12], a model-based predictive control approach for optimal generation scheduling of CSP plants is presented unveiling a significant improvement using short-term DNI forecasting and improvements reducing the deviation from the scheduled generation [13]. The location of the CSP plant has been studied due to is direct relation with the DNI [16]. Another research using a deterministic approach presented an optimal offering strategy for CSP plant with TES considering not only day-ahead markets, but also joint energy, reserve and regulations markets [17]. The value of TES is also being subject of high interest among the research community, it was estimated the capacity value of CSP plants with TES in the USA were it was optimized a CSP plant with TES using Solar Advisor Model (SAM) and a mix-integer program (MIP) that unveiled that only the critical hours of the year are necessary to estimate the capacity value of the CSP plant and unveiled that the TES allow extremely high capacities for CSP plant from around 79% to 92% [14], a dense study in TES options for CSP plants is shown in [15]. Coordination of renewable sources like solar and wind are also in the scope of the research community and this subject contributes to increase the renewable energy sources penetration, in [18] it is used robust optimization to integrate CSP plants with TES and wind power which unveiled an uncertainty generation reducing, in [19] a MILP approach is presented to schedule wind and CSP plant with TES revealing to be feasible.

4 Problem Formulation

The self-scheduling problem of a CPS plant having TES system is computed by the maximization of the objective function given by the profit, affected by the risk measure CVaR, subject to technical operation constraints and the risk management constraints.

4.1 Objective Function

The objective function is given by two parts, the first one is the profit which is equal to the revenues from the day-ahead electricity market sales during the time horizon of the schedule, and the second one is the equation resulting from the CVaR risk management application. The objective function is given as follows:

$$F = (1 - \beta)\left(\sum_{\omega=1}^{\Omega}\sum_{t=1}^{T}\left(\pi_{\omega,t}\lambda_{\omega,t}P^{s}_{\omega,t}\right)\right) + \beta\left(\eta - \frac{1}{1-\alpha}\sum_{\omega=1}^{\Omega}\left(\pi_{\omega,t}s_{\omega}\right)\right) \tag{1}$$

In (1), T is the set of hours in the time horizon, Ω is the set of scenarios resulting from the combination of solar resource and electricity market prices, $\pi_{\omega,t}$ is the probability for scenario ω. hour t, $\lambda_{\omega,t}$ is the price of the electricity in the day-ahead market for scenario ω. hour t, $P^{s}_{\omega,t}$ is the power output of the CSP plant having TES for scenario ω. hour t, β the level of risk that the decision maker is willing to take, α. presents the level of confidence and is set to 0.95, η. It's a variable dependent of the first part of the objective function (maximization of the profit) and s_{ω} is a function given by:

$$s_{\omega} = \max\{\eta - f(x, \omega), 0\} \tag{2}$$

In (2), $f(x, \omega)$ represents the first part of the objective function.

4.2 Constraints

The constraints for the scheduling are due to operation, minimum up/down time, electricity market and risk management for the CSP plant having TES system.

Operation Constraints. The operation constraints are given as follows:

$$P^{s}_{\omega,t} = P^{FE}_{\omega,t} + P^{SE}_{\omega,t} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{3}$$

$$P^{FE}_{\omega,t} = \eta_1 Q^{FE}_{\omega,t} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{4}$$

$$P^{SE}_{\omega,t} = \eta_3 Q^{SE}_{\omega,t} \quad \forall\omega \in \Omega, \forall t \in T \tag{5}$$

$$Q^{FE}_{\omega,t} + Q^{FS}_{\omega,t} \le E_{\omega,t} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{6}$$

$$Q^{E}_{min} u_{\omega,t} \le Q^{FE}_{\omega,t} + Q^{SE}_{\omega,t} \le Q^{E}_{max} u_{\omega,t} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{7}$$

$$P^{s}_{min} u_{\omega,t} \le P^{s}_{\omega,t} \le P^{s}_{max} u_{\omega,t} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{8}$$

$$Q^{S}_{\omega,t} = Q^{S}_{\omega,t-1} + \left(\eta_2 Q^{FS}_{\omega,t}\right) - Q^{SE}_{\omega,t} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{9}$$

$$Q^{S}_{min} \le Q^{S}_{\omega,t} \le Q^{S}_{max} \quad \forall\omega \in \Omega,\ \forall t = 0, 1, \ldots, T \tag{10}$$

$$\eta_2\left(Q^{FS}_{\omega,t} - Q^{FS}_{\omega,t-1}\right) \le R^{up} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{11}$$

$$P^{SE}_{\omega,t-1} - P^{SE}_{\omega,t} \le R^{dn} \quad \forall\omega \in \Omega,\ \forall t \in T \tag{12}$$

$$P^{SE}_{\omega,t} \le R\, e_{\omega,t} \qquad \forall\omega \in \Omega,\ \forall t \in T \tag{13}$$

$$Q^{FS}_{\omega,t} \le R\left(1 - e_{\omega,t}\right) \quad \forall\omega \in \Omega,\ \forall t \in T \tag{14}$$

$$P^{FE}_{\omega,t}, P^{SE}_{\omega,t}, P^{FS}_{\omega,t}, P^{s}_{\omega,t}, Q^{FE}_{\omega,t}, Q^{SE}_{\omega,t}, Q^{FS}_{\omega,t}, Q^{S}_{\omega,t} \ge 0 \quad \forall\omega \in \Omega,\ \forall t \in T \tag{15}$$

$$y_{\omega,t} - z_{\omega,t} = u_{\omega,t} - u_{\omega,t-1} \quad \forall\omega \in \Omega, \forall t \in T \tag{16}$$

$$y_{\omega,t} + z_{\omega,t} \le 1 \qquad \forall\omega \in \Omega, \forall t \in T \tag{17}$$

From (3) to (17), $P^{s}_{\omega,t}$ is the electric power produced by the CSP, $P^{FE}_{\omega,t}$ and $P^{SE}_{\omega,t}$ are the power produced by the power block (PB) from the solar field (SF) and from the TES for scenario ω. hour t, η_1 is the SF efficiency, $Q^{FE}_{\omega,t}$ is the thermal power from the SF for scenario ω. hour t, η_3 is the molten-salt tanks efficiency, $Q^{SE}_{\omega,t}$ is the storage power in TES to produce electricity for scenario ω. hour t, $E_{\omega,t}$ is the thermal energy available in the SF for scenario ω. hour t, Q^{E}_{min} and Q^{E}_{max} are the thermal power bounds of the PB for scenario ω. hour t, $u_{\omega,t}$ is a binary variable that represents the CSP plant commitment for scenario ω. hour t, P^{s}_{min} and P^{s}_{max} are the electrical power bounds of the PB, $Q^{FS}_{\omega,t}$ is the stored thermal power from the SF for scenario ω. hour t, $Q^{S}_{\omega,t}$ is the thermal energy stored in TES for scenario ω. hour t, η_2 is the TES efficiency, Q^{S}_{min} and Q^{S}_{max} are the TES thermal energy bounds, R^{up} and R^{dn} are the up and down ramp limitations of the TES, R. a sufficient large constant, $e_{\omega,t}$ is a binary variable that represents if TES is charging our discharging, $y_{\omega,t}$ is a binary variable that represents if the CSP plant started up for scenario ω. hour t, and $z_{\omega,t}$ is a binary variable that represents if the CSP plant shuts down for scenario ω. hour t. In (3), the electric power balance is obtained combining the electric power produced in the SF and the storage. In (4) and (5) are represented the efficiency between power energy and thermal energy for the SF and the TES, respectively. In (6) the bound of the thermal energy from the SF and TES are set. In (7) and (8) are the bounds of the SF and the TES. In (9) is given the thermal energy stored in the TES. In (10) the bounds of the TES are set. In (11) and (12) are represented the ramp-up and ramp-down limitations of the TES. In (13) and (14) guarantee that the SAE is not charging and discharging ate the same time. In (15) is guaranteed the positivity of energy. In (16) and (17) is guaranteed that the CSP plant don't start and shut down at the same time.

Minimum Up/Down Time Constraints. The minimum up/down constraints of the power block are given as follows:

$$\left(x_{\omega,t} - TMF\right)\left(u_{\omega,t-1} - u_{\omega,t}\right) \geq 0 \quad \forall\omega \in \Omega, \forall t \in T \tag{18}$$

$$\left(x_{\omega,t} - TMP\right)\left(u_{\omega,t} - u_{\omega,t-1}\right) \geq 0 \quad \forall\omega \in \Omega, \forall t \in T \tag{19}$$

In the Eqs. (18) and (19), $x_{\omega,t}$ represents the number of hours in which the CSP plant was not working (down time) for scenario ω. hour t, TMF and TMP represents the number of necessary hours of up time and down time, respectively.

Electricity Market Constraints. The electricity market constraints are given as follows:

$$\left(\lambda_{\omega,t} - \lambda_{\omega,t-1}\right)\left(P^{s}_{\omega,t} - P^{s}_{\omega,t-1}\right) \geq 0 \quad \forall\omega \in \Omega, \forall t \in T \tag{20}$$

In (20) the decreased monotony of the electricity market offer curve is guaranteed. By other others if the price of energy in the electricity market don't decrease the amount of energy to bid in the market also can't decrease.

Risk Management Constraints. The risk management constraints are given as follows:

$$\eta - \left(\sum_{t=1}^{T} \lambda_{t.\omega} P^{s}_{\omega,t}\right) \leq s_{\omega} \qquad \forall \omega \in \Omega, \forall t \in T \tag{21}$$

$$s_{\omega} \geq 0 \qquad \forall \omega \in \Omega \tag{22}$$

In (21) and (22) the risk management using CVaR is guaranteed. CVaR it is defined, for a certain level of confidence $\alpha \in \{0, 1\}$, as the average deviation of the worst scenarios.

5 Case Study

The case study intends to show the proficiency of the model developed for the scheduling of CSP plant having TES in the electricity market. The MILP approach has been solved using CPLEX 12.2 solver under GAMS environment [7]. A computer with 8 GB RAM with 2.40 GHz of CPU is used for the simulations of a realistic case study for the CSP plant having TES system carried out with technical data shown in Table 1.

Table 1. CSP having TES system data.

Q^{E}_{min}/Q^{E}_{max} (MWt)	P^{s}_{min}/P^{s}_{max} (MWe)	$Q^{FE}_{min}/Q^{FE}_{max}$ (MWt)	R^{dn} (MWe/h)	R^{up} (MWe/h)
50/125	0/50	0/150	35	80
Q^{S}_{min}/Q^{S}_{max} (MWht)	Q^{S}_{0} (MWht)	R (MWe)	TMF (h)	TMP (h)
45/700	350	150	2	2
K^{on}_{0} (h)	K^{off}_{0} (h)	u_0	y_0	z_0
1	1	0	1	0

The time horizon in the simulations is a day on an hourly basis. The inputs considered within the time horizon are the solar power and the electricity market prices. The solar power profile was obtained using the System Advisor Model [8] and it was converted into available thermal power. The electricity market prices derived from the Iberian electricity market given in [9]. In this case study was used 250 scenarios composed by 25 electricity market prices, as shown in Fig. 1(a), and 10 scenarios for the available thermal power, as shown in Fig. 1(b).

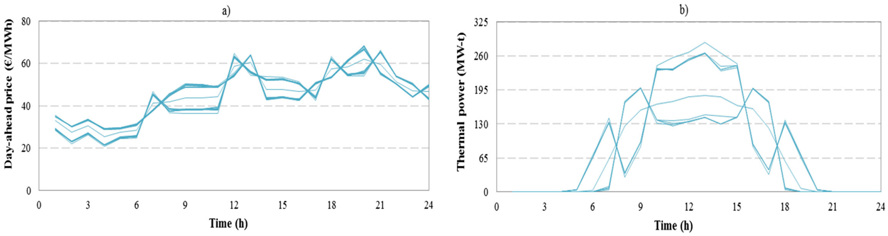

Fig. 1. (a) Electricity market price scenarios, (b) Thermal power scenarios.

The optimizing characteristics for processing the problem presented in the case study in what regards the number of continuous variables, binary variables and constraints are shown in Table 2.

Table 2. Optimization characteristics of the case study.

	Continuous variables	Binary variables	Constraints
Case study	54 002	24 000	162 000

The number of scenarios highly affects the computation burden of the problem to be solved. The application of a scenario reduction algorithm, forward reduction algorithm detailed in [10], was used to assess the implication of the number of scenarios in the expected profit and in the computation time. The scenario reduction algorithm allow to reduce the number of scenarios of the original set maintaining the statistical characteristics. The results are shown in Fig. 3 (Fig. 2).

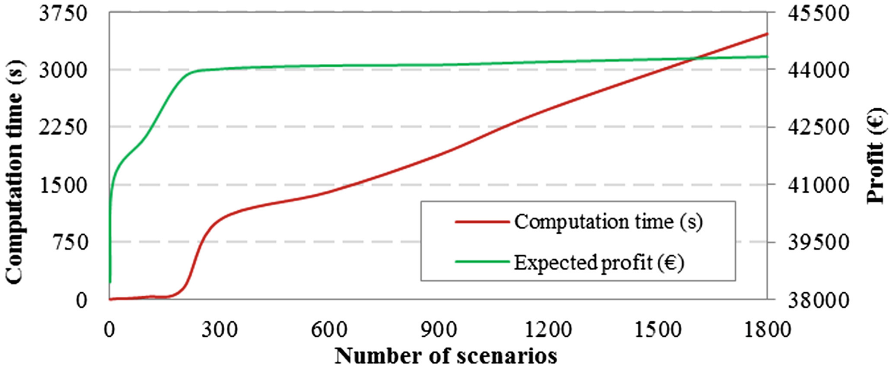

Fig. 2. Expected profit, computation time related with the number of scenarios.

Figure 3 shows that for lower number of scenarios the increase in the computational time it is residual, for moderate to higher number of scenarios the increase in the computational time becomes higher and higher assuming almost a linear evolution. On the other and, the profit tends to stabilize at moderate number of scenarios.

The results of the case study regarding the profit deviation, expected profit and the increase of the expected profit when assuming high levels of risk is shown in Table 3 revealing an increasing of 2.53% when comparing the highest level of risk with the lower level of risk. The portfolio of scenarios is shown in Fig. 4.

In Fig. 4(a) is shown that higher levels of risk lead to a large increase in expected profit, while for lower levels of risk this increase tends to be lower. The differences between the expected profits, depending on the risk levels, are related with the amount of energy that the CSP plant having TES system will produce for selling in the day-ahead electricity market as is shown in Fig. 4(b).

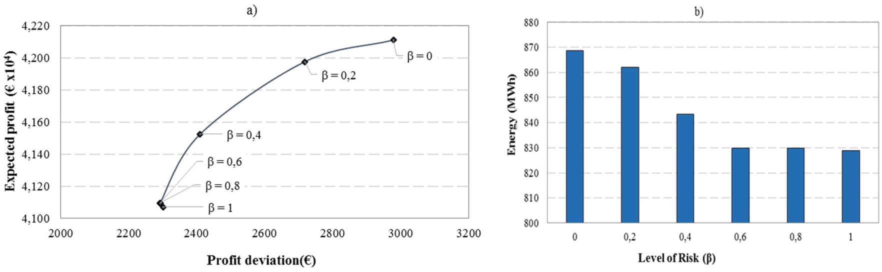

Fig. 3. (a) Portfolio of scenarios, (b) Energy to sell in the electricity market.

Table 3. Profit assessment for different levels of risk.

β	Profit deviation (€)	Expected profit (€)	% Increase
1.0	2 301	41 072	–
0.8	2 293	41 097	0.06
0.6	2 292	41 097	0.06
0.4	2 410	41 525	1.10
0.2	2 718	41 975	2.20
0	2 978	42 110	2.53

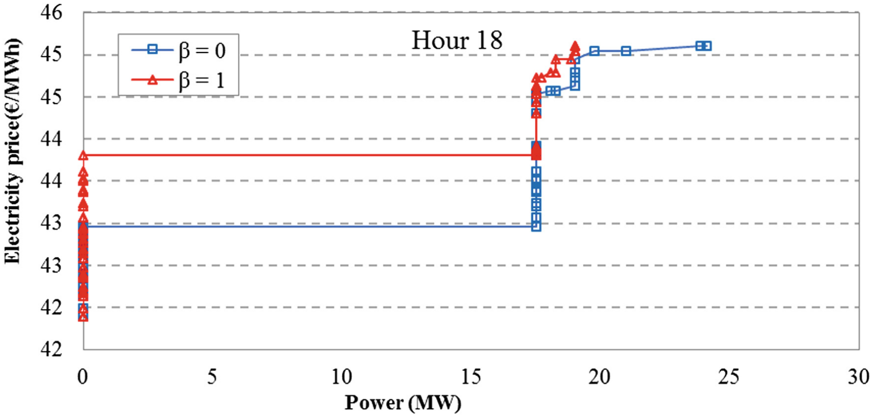

Fig. 4. Offering curves for hour 18.

The offering curves for a conservative power producer (β = 1) and a non-conservative power producer (β = 0) are shown in Fig. 4.

In Fig. 4 is shown that a conservative power producer delivers less power in the day-ahead electricity market to guarantee his revenues, while the non-conservative one delivers more power in the day-ahead electricity market willing to take more risk to increase his revenues.

6 Conclusions

A stochastic MILP approach is proposed to provide optimal decisions for the day-ahead scheduling of CSP plants having TES systems, considering technical operation constraints and risk management constraints. The uncertainty of the solar irradiation and the electricity market prices are considered by scenarios set. A scenario reduction algorithm was applied to reduce the computation burden of the model maintaining the stochastic characteristic of the original set of scenarios. The model includes risk management using the CVaR which allows the decision maker to have a portfolio of expected profits for different risk levels. The case studies are in favor of the approach to support decisions in day-ahead markets. This proposed approach shown to be feasible and accurate for optimal scheduling of the CSP plants with TES.

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References

1. Energy 2020 - a strategy for competitive, sustainable and secure energy (2011). http://europa.eu
2. GEIDCO - Global Energy Interconnection Development and Cooperation Organization (2016). http://www.geidco.org/html/qqnycoen/col2015100724/column_2015100724_1.html
3. REN – Redes Elétricas Nacionais (2016). http://www.ren.pt/
4. APREN – Associação de Energias Renováveis (2016). http://apren.pt/pt/
5. IEA – International Energy Agency (2016). https://www.iea.org/
6. Guannan, H.E., Qixin, C., Chongqing, K., Qing, X.: Optimal offering strategy for concentrating solar power plants in joint energy, reserve and regulation markets. IEEE Trans. Sustain. Energy **7**(3), 1245–1254 (2016)
7. Cplex, Gams, Solver manuals. Gams/Cplex (2014). http://www.gams.com
8. National Renewable Energy Laboratory, USA, Solar Advisor Model User Guide for Version 2.0 (2008). http://www.nrel.gov/docs
9. Market oprator of the electricity market of the Iberian Peninsula, OMEL (2014). http://www.omel.es
10. Conejo, A.J., Carrión, M., Morales, J.M.: Decision Making Under Uncertainty in Electricity Markets. Springer, New York (2000)
11. Vasallo, M.J., Bravo, J.M.: A novel two-model based approach for optimal scheduling in CSP plants. Elsevier, ScienceDirect, Solar Energy **126**, 73–79 (2016). Elsevier, ScienceDirect
12. Pousinho, H.M.I., Contreras, J., Pinson, P., Mendes, V.M.F.: Robust optimization for self-scheduling and bidding strategies of hybrid CSP-fossil power plants
13. Vasallo, M.J., Bravo, J.M.: A MPC approach for optimal generation scheduling in CSP plants. Appl. Energy **165**, 357–370 (2016). ELSEVIER, ScienceDirect
14. Madaeni, S.H., Sioshansi, R., Denholm, P.: Estimating the capacity value of concentrating solar power plants with thermal energy storage: a case study of the southwestern united states. Powersystems, **28**(2) (2013). IEEE

15. Xu, Z., Kariuki, S.K., Chowdhury, S., Chowdhury, S.P.: Investigation of thermal storage options for concentrating solar power plants. In: 2012 47th International Universities Power Engineering Conference (UPEC). IEEE (2012)
16. Llamas, J., Bullejos, D., Barranco, V., Ruiz de adna, M.: World location as associated factor for optimal operation model of parabolic trough concentrating solar thermal power plants. IEEE (2016). 978-1-5090-2320-2
17. He, G., Chen, Q., Kang, C., Xia, Q.: optimal offering strategy for concentrating solar power plants in joint energy, reserve and regulation markets. Sustain. Energy, **7**(3), (2016). IEE
18. Chen, R., Sun, H., Guo, Q., Li, Z., Deng, T., Wu, W., Zhang, B.: Reducing generation uncertainty by integrating CSP with wind power: an adaptative robust optimization-based analysis. Sustain. Energy, **6**(2), (2015)
19. Pousinho, H.M.I., Silva, H., Mendes, V.M.F., Collares-Pereira, M., Pereira, C.: Cabrita: self-scheduling for energy and spining reserve of wind/CSP plants by a MILP approach. Energy **78**, 524–534 (2014). ELSEVIER
20. Ejaz, W., Naeem, M., Shahid, A., Anpalagan, A., Jo, M.: Efficient energy management for the internet of things in smart cities. IEEE Commun. Mag. 84–91 (2017)
21. Vukmirovic, S., Erdeljan, A., Kulic, F., Lukovic, S.: Software architecture for Smart Metering systems with Virtual Power Plant, pp. 448–451. IEEE (2010)