Optimal energy management strategy for CSP-CPV integrated power plants with energy storage

Giorgio Cau[a], Daniele Cocco[b], Mario Petrollese[c]

[a] Dept. of Mechanical Chemical and Materials Eng,. Univ. of Cagliari, Italy, gcau@unica.it
[b] Dept. of Mechanical Chemical and Materials Eng,. Univ. of Cagliari, Italy, daniele.cocco@unica.itc
[b] Dept. of Mechanical Chemical and Materials Eng,. Univ. of Cagliari, Italy, petrollese@unica.it

Abstract:

This work focuses on the study of the most suitable energy management strategies for solar power plants based on the integration of a concentrating solar power (CSP) plant with thermal energy storage and a concentrating photovoltaic (CPV) power plant with electrochemical storage. Due to the presence of the energy storage system, these integrated CSP-CPV plants are able to produce electricity with scheduled profiles as well as to provide ancillary services at distribution level. The algorithm for the optimal plant management uses weather forecast data to schedule the optimum generation profile by maximizing the power production of the integrated plant, while different constraints due to equipment limits are satisfied. A comparative analysis is carried out by means of the implementation of a deterministic or a stochastic approach to take into account the uncertainties in weather forecast. A time horizon of 48 h is imposed in the optimization problem with an updating of the input data and results each 24 h. The integrated CSP-CPV power plant here analyzed refers to the solar pilot facility that is currently under construction in the industrial district of Ottana (Sardinia, Italy). The facility consists of a CSP plant based on linear Fresnel collectors using thermal oil as heat transfer fluid, a two-tank thermal energy storage system (capacity of about 15 MWh), a 600 kWe ORC power plant, a 400 kWe CPV power plant and an electrochemical storage system with a capacity of 430 kWh. The results of the study demonstrate that the use of a stochastic approach instead of a deterministic one allows to generate more robust solutions. In particular, with the proposed stochastic approach unexpected phenomena and the variation in the foreseen conditions only marginally affect the scheduling planning, which results in an improvement of about 3-5% in the yearly power production.

Keywords:

CSP; CPV; Thermal energy storage; Energy storage system; EMS.

1. Introduction

Owing to the implementation of suitable environmental policies and economic subsidies, renewable energy sources (RES) have grown considerably in the last decade and a further increase is foreseen for the future. However, the massive implementation of RES technologies into the exiting energy production and distribution systems requires the overcoming of some important drawbacks. The main issue is related to the variable and intermittent nature of many renewable sources. In particular, wind and solar power plants cannot produce power steadily since wind speed and solar radiation change during the day and the year. In large electricity networks, these fluctuations can be balanced by conventional power plants and up to now, critical situations have occurred only in local power grids with a high RES penetration. For the future, the introduction of suitable energy storage systems (EES) and the reinforcement of the balancing service at distribution level will be required to keep high standards for reliability and power quality of the electrical supply [1].

A promising option to mitigate the effects of the variability and intermittency of the renewable source is represented by the integration of the energy conversion systems based on different RES technologies and different energy storage systems. In particular, in the field of solar power plants, the integration of different concentrating technologies (thermal and photovoltaic) and energy storage systems (electrochemical and thermal storage) can be a very interesting option to enhance their dispatch features. Obviously, the effective optimization of these highly integrated energy systems is essential in order to give the ability to produce electricity with scheduled profiles and to reduce energy losses. To achieve this objective, the control system of the integrated power plant must be provided by advanced optimization tools and techniques. Among them, the adoption of an energy management strategy (EMS) provided by a tool for the optimal scheduling procedure is a fundamental task.

In literature, the optimal scheduling of the CSP plants is often modelled as a mixed-integer linear programming (MILP) problem. MILP is a well know optimization method and standard software can be found commercially. An optimisation approach to maximise profits of CSP with TES in Spain [2] is proposed taking into account market prices. The capacity value of CSP with and without TES addressed to the U.S. by using a deterministic MILP approach for optimal operation shows the benefits lead by the TES [3]. Despite most short-term approaches have been based on deterministic models, stochastic modelling via a set of scenarios has been recently introduced. A mathematical model for the generation of optimal offering curves in the pool for the maximization of the expected profit of the CSP plant is proposed in [4]. This model takes into account the uncertainty in the availability of the solar resource and the uncertainty of the market prices. A robust MILP approach is also presented in [5] to enable a hybrid CSP–fossil fuel power producer to participate as a price-taker in a day-ahead market, considering bilateral contracts, financial penalties, backup system costs and emission allowance levels.

This work focuses on the study of the most suitable energy management strategies for solar power plants based on the integration of a concentrating solar power (CSP) plant with thermal energy storage (TES) and a concentrating photovoltaic (CPV) power plant with electrochemical storage. In particular, the integrated CSP-CPV power plant here analyzed refers to the solar pilot facility which is currently under construction in the industrial district of Ottana (Sardinia, Italy). The Ottana solar facility is supported by the Regional Government of Sardinia (Italy), in the framework of the POR FESR 2007-2013 Program and its design has been developed with the scientific support of Sardegna Ricerche and the University of Cagliari with the aim to produce electricity with scheduled profiles according to weather forecast [6].

In this paper, the expected yearly performance of the Ottana pilot facility are presented and different EMSs based on weather forecast data are compared. In particular, the algorithm of the EMS finds the solution that ensures the accomplishment of the scheduled power generation profile, maximizes the power production of the integrated plant and satisfies different constraints due to equipment limits. A comparative analysis between a deterministic and a stochastic approach for the determination of the optimal scheduling of the CSP-CPV power plant is carried out and the expected annual performance are evaluated.

2. CSP-CPV power plant configuration

As shown by Fig. 1, the Ottana solar pilot plant includes two different power generation sections integrated with two different energy storage sections.

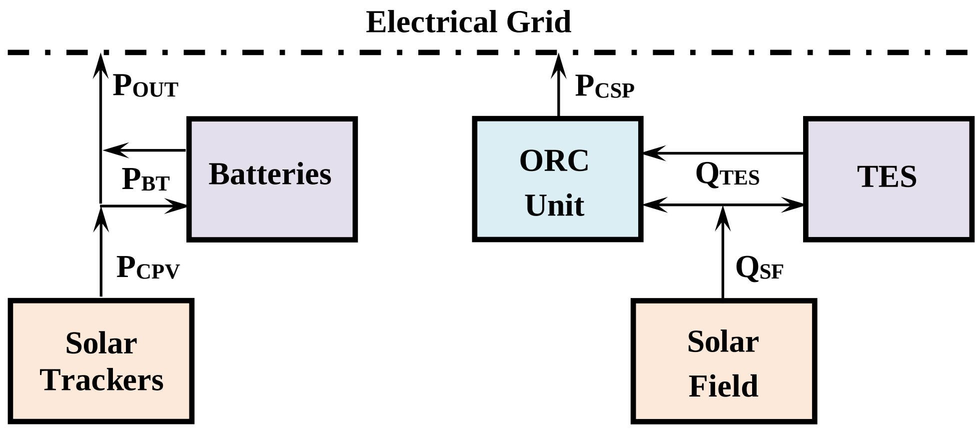

Fig. 1. Simplified scheme of the CSP-CPV integrated solar plant.

In particular, the facility consists of a 600 kWe CSP plant based on linear Fresnel collectors using thermal oil as heat transfer fluid, a two-tank TES system (capacity of about 15 MWh), a ORC (Organic Rankine Cycle) power plant, a 400 kWe CPV power plant and an electrochemical storage system with a capacity of 430 kWh.

2.1. Concentrating solar power plant

Figure 2 shows a simplified diagram of the CSP plant considered in this paper. The CSP plant includes three main sections: the solar field, the power block and the thermal energy storage section.

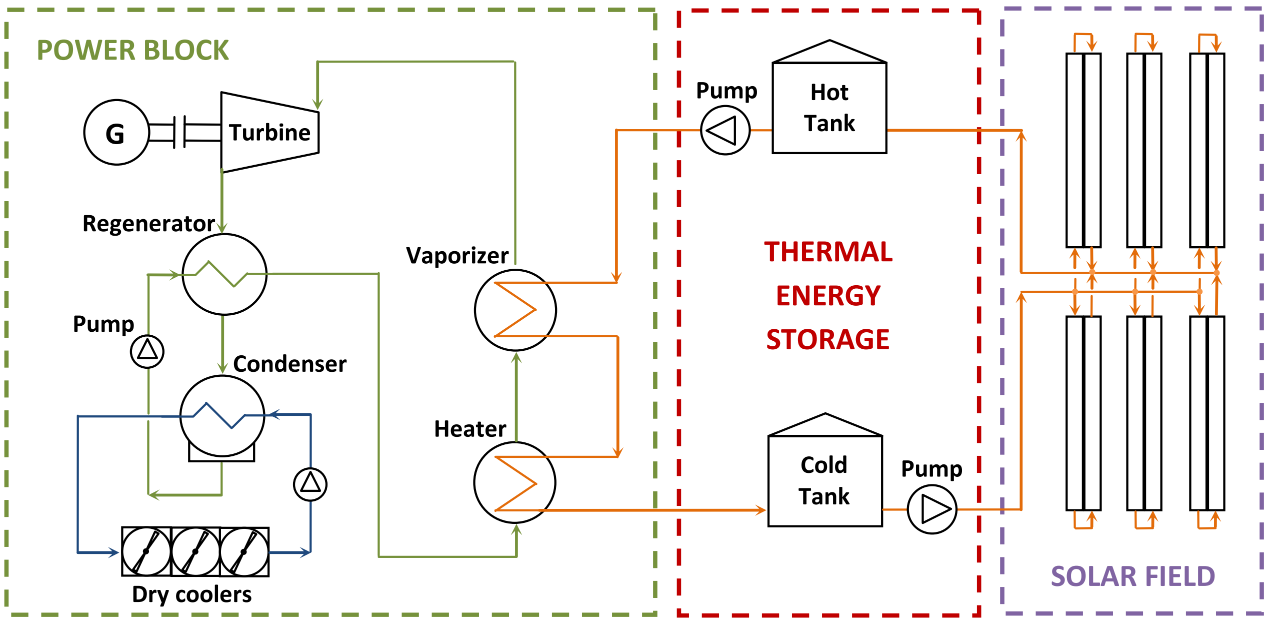

Fig. 2. Simplified scheme of the CSP plant.

The solar field is based on several lines of linear Fresnel collectors connected in parallel to achieve the required oil mass flow and temperature and therefore the required thermal power output. Each collector line includes several collector modules, which in turn are connected in series, and each collector module is composed of several rows of flat mirrors whose slope continuously changes to follow the sun position. The mirrors concentrate solar radiation onto an evacuated receiver tube installed several meters above the mirror plane where the thermal oil is heated.

The power block is based on an ORC unit, where thermal energy is converted to electrical energy by using an organic fluid that follows a regenerated Rankine cycle. As shown in Fig. 2, the thermal energy produced by the solar field is used in the ORC unit to heat and to vaporize the organic fluid. The organic vapour expands in the turbine, and subsequently it is cooled in the regenerator and condensed. After the condenser, the organic fluid is compressed by the feeding pump and then preheated in the regenerator. The condensing heat is removed by dry coolers due to the lack of cooling water.

The TES section is based on a two-tank direct system, which includes a low-temperature and a high-temperature storage tank (the cold and hot storage tanks, respectively). The thermal oil from the cold tank flows through the solar field, where it is heated and sent to the hot tank. Depending on the solar radiation, the control system regulates the oil mass flow to keep constant the solar field exit temperature. When required, the hot thermal oil is pumped to the power block, where it is cooled and sent back to the cold storage tank.

Table 1 reports its main design specifications at reference conditions (DNI 900 W/m^2, air temperature 17 °C, elevation 17°, azimuth 0°).

Table 1. Main design parameters of the CSP plant.

SOLAR FIELD		ORC UNIT	
Loops (200 x 9.0 m)	6	Thermal power input	2970 kW
Solar field collecting area	8400 m^2	Thermal oil temp. (in/out)	263/153 °C
Solar field conversion efficiency	62.0 %	Thermal oil mass flow	11.1 kg/s
Collector area A_C	865.5 m^2	Gross conversion efficiency	18.8 %
Thermal oil mass flow	17.3 kg/s	Gross power output	559 kWe
Thermal power output	4690 kW	Condenser power output	2385 kW
THERMAL ENERGY STORAGE		OVERALL CSP PLANT	
Storage volume (each tank)	330 m^3	ORC internal consumption	20 kW
Thermal oil mass	195 t	Solar field internal consumption	30 kW
Thermal storage capacity	14.6 MWh	Net power output	550 kW

2.2. Concentrating photovoltaic power plant

Concentration Photovoltaic (CPV), in particular High Concentration Photovoltaic (HCPV), is currently the solar technology with the highest conversion efficiency [7-8]. The main advantage of CPV is represented by its ability to increase the efficiency reducing at the same time the active material and therefore the cost of electricity production. Presently, most of commercial CPV modules employs refractive optics (such as Fresnel lenses) because of their cheapness and minor complexity [9]. The Fresnel-based technology has recently reached the technological and commercial maturity and was therefore adopted for the Ottana pilot plant. The CPV power plant is based on 36 two-axes solar trackers, with an overall power output of about 400 kWp. Each solar tracker includes 72 modules, subdivided in two strings which are connected to a dedicated three-phase DC/AC converter integrated with two independent MPPT (Maximum Power Point Tracking) systems. The tracking system is equipped with a four quadrants solar sensor and an on-board meteorological station, which measures DNI and wind speed. Such data are used by the tracker controller to continuously follow the sun position, together with the information about the astronomical ephemerides. Table 2 reports the main design parameters of the CPV plant. The electrical energy storage system is based on Sodium-Nickel (NaNiCl) batteries [10]. The NaNicl battery operates at high temperature (close to 300 °C) in order to improve the conductivity of the electrolytes.

Table 2. Main design parameters of the CPV plant.

CPV MODULE		TRACKING SYSTEM	
Optics technology	Refractive	Tracking technology	Two axes
Solar cells technology	Triple-junction	Pointing accuracy	0.1 °
Geometric concentration factor	500 suns	Azimuth range	0°-360°
DC efficiency	27.2%	Elevation range	6°-90°
Maximum DC power	165 Wp	Dimension	7.3m x 7.4m
DC/AC CONVERTER		OVERALL CPV PLANT	
Nominal Efficiency	97%	Overall efficiency	24%
N° independent MPPT	2	Net peak power output	400kW$_p$ @850W/m^2

Thanks to the ceramic electrolyte, the battery has no electrochemical self-discharge and the electrodes are not involved in side-reactions, resulting in a coulombic efficiency of 100% [11]. The design of batteries was carried out in order to allow a programmable generation of the CPV system in 30 seconds-time intervals and compensate forecasting errors.

3. System modelling and assumption

The present study was carried out using a data set for a typical meteorological year obtained from the Meteonorm® software [12] for the site of Ottana (40°25'00''N, 9°00'00''E), in Sardinia (Italy). The meteorological data set includes Direct Normal Irradiation (DNI), solar azimuth and elevation, ambient temperature, relative humidity and wind velocity. Figure 3a-b shows the monthly values of average air temperature and DNI. Overall, the annual DNI is about 1790 kWh/(m^2·yr). The reference design conditions of the CSP plant are represented by a DNI of 900 W/m^2, an air temperature of 17 °C, an elevation angle of 17° and an azimuth equal to 0°.

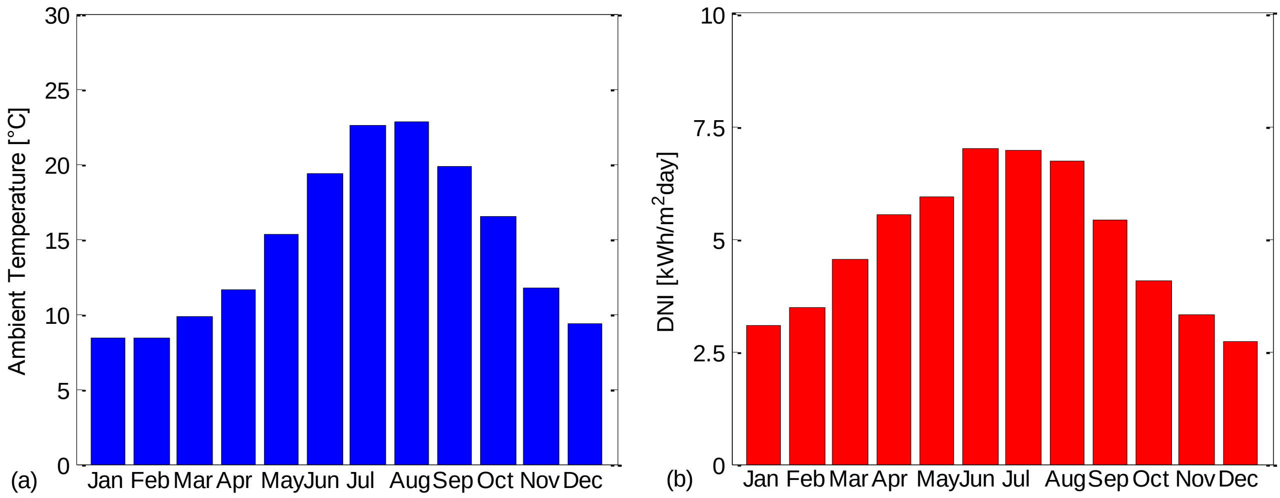

Fig. 3. Monthly average values of air temperature (a) and daily DNI (b).

Since past forecasting data on a yearly basis were not available, a random perturbation of both DNI and ambient temperature was introduced to generate fictitious forecasting data. In particular, a normal distribution on the difference between real and forecasting data is supposed with a mean value equal to 0 and a standard deviation (σ) which value represent the error between forecasting and real data. Therefore, the generic forecast condition (Forecast) as a function of the real value (Real) is given by:

$$\text{Forecast} = \text{Real} \cdot (1 + \sigma\xi) \tag{1}$$

where ξ is a pseudorandom number in the range [-1,1] drawn from the standard normal distribution.

3.1. CSP plant section

The solar field includes the 6 lines of Fresnel collectors, the cold and hot header pipe (one for distributing the cold oil throughout the collector loops and the other for collecting the hot oil), the main pipes, valves, fittings and pressure, temperature and flow meters. The simulation model of the solar field evaluates the net thermal power output on an hourly basis as a function of solar radiation and solar position for given values of the main geometrical and technical characteristics of the solar collectors, as well as for assigned thermodynamic properties of the heat transfer fluid. According to [13], the thermal power concentrated onto the received tube Q_{RCV} is a function of the solar power input Q_{SOL} reduced by the optical losses of the solar concentrator Q_{OPT} and can be evaluated by means of the following equation:

$$Q_{RCV} = Q_{SOL} - Q_{OPT} = A_C \cdot DNI \cdot \eta_{OPT,R} \cdot IAM(\theta) \cdot \eta_{END} \cdot \eta_{CLN} \tag{2}$$

where $\eta_{OPT,R}$, η_{END} and η_{CLN} are the reference optical efficiency, the end-loss optical efficiency and the cleanliness efficiency respectively. According to [13], $\eta_{OPT,R}$ and η_{CLN} are constant and equal to 0.75 and 0.98 respectively while η_{END} is a function of the incidence angle θ.

Due to the receiver thermal losses and the piping thermal losses Q_{THR}, the thermal power transferred to the thermal oil, that is the effective output power from the solar field Q_{SF}, is lower than the receiver available power Q_{RCV}:

$$Q_{SF} = m_{oil} \cdot c_{P,oil} \cdot \left(T_{oil,out} - T_{oil,in}\right) = Q_{RCV} - Q_{THR} \tag{3}$$

Thermal losses are evaluated by means of the following equation:

$$Q_{THR} = \left[(a_1 \Delta T + a_2 \Delta T^2) + q_{pipe}\right] \cdot A_C \tag{4}$$

Where the receiver thermal losses are a function of ΔT (the difference between average oil temperature in the receiver tube and the ambient temperature) approximated with a second-order polynomial with a_1 and a_2 equal to 0.056 W/m^2K and 2.13E-4 W/m^2K^2 respectively, whereas the specific piping losses q_{pipe} was assumed equal to 0.5 W/m^2.

During the day, the power produced by the solar field can be directly used to feed the ORC power block (Q_{DIR}) producing electricity or stored in the TES system ($Q_{TES,in}$). However, if the latter is fully charged, the excess energy not directly used by the ORC unit is lost (Q_{EX}). Therefore the thermal energy balance the control strategy must satisfy is:

$$Q_{SF} = Q_{DIR} + Q_{T.i} + Q_{EX} \tag{5}$$

As previously mentioned, the TES system is based on two identical thermal oil tanks. Starting from the power produced by the solar field, the control system manages the input and output thermal energy flows from the TES system. Because of thermal energy losses due to a not-ideal tanks insulation, the stored thermal energy is lower than the overall thermal energy sent to the TES system. The state-of-charge of the TES section is the ratio of its thermal energy content to the thermal storage capacity (Q_{TES}). Therefore, the state-of-charge at a give time t (TES_t) can be expressed in function of the state-of charge at the previous time step (TES_{t-1}), and the input and output thermal energy flows ($Q_{T,i}$ and $Q_{T,o}$ respectively):

$$TES_t = TES_{t-1} + \frac{(Q_{T,i}\eta_{TES} + Q_{T,o})\Delta t}{Q_{TES}} \tag{6}$$

Where Δt is the applied time step and η_{TES} represents the stored energy efficiency (a value of 98% was considered in this study). Obviously, the maximum value of the TES level is 100% (full charge of the hot storage tank) and vice versa, a minimum value of the TES level is imposed (equal to 1% in this study).

Finally, the thermal power supplied to the ORC unit (Q_{ORC}) is given by the power coming from the solar field conveniently integrated with the power provided by the TES system:

$$Q_{ORC} = Q_{DIR} + Q_{T.o} \tag{7}$$

The performance of the ORC unit strongly depends on the thermal input load with a maximum efficiency reached at nominal thermal load. Because of condensing heat is removed by dry coolers, the water inlet temperature of the condenser is directly proportional to the ambient temperature. Therefore, for given values of the air temperature difference in dry coolers (10°C) and the minimum air-water temperature difference (about 6-7°C), the increase of the ambient temperature results in an increase of the condenser temperature with a corresponding decrease of the Rankine cycle efficiency.

The performance of the ORC unit were evaluated with reference to data provided by the manufacturer and Fig. 4 shows the ORC efficiency as a function of the thermal load (cooling water at 25°C) and air temperature (thermal input of 2970 W). A minimum thermal load equal to 20% of the rated one was also assumed [14]. Furthermore, rapid changes in the electrical output may lead to increased maintenance costs. Consequently, safe ramp up and ramp down rates are provided by the manufacturer, especially during the start-up phase.

Finally, a minimum up time and down time of the CSP plant is usually imposed in order to restrict the number of start-up and shut-down of the ORC unit during a day [4]. In particular, 2 hours of minimum up/down time is imposed as constraint in the control strategy.

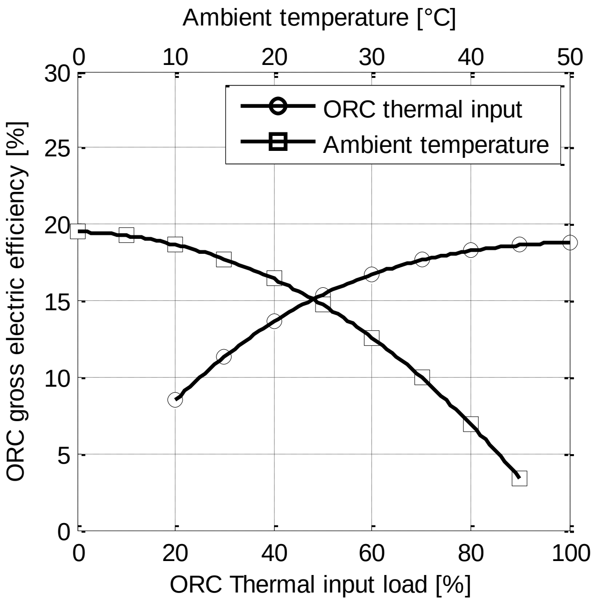

Fig. 4. Efficiency curves of the ORC unit.

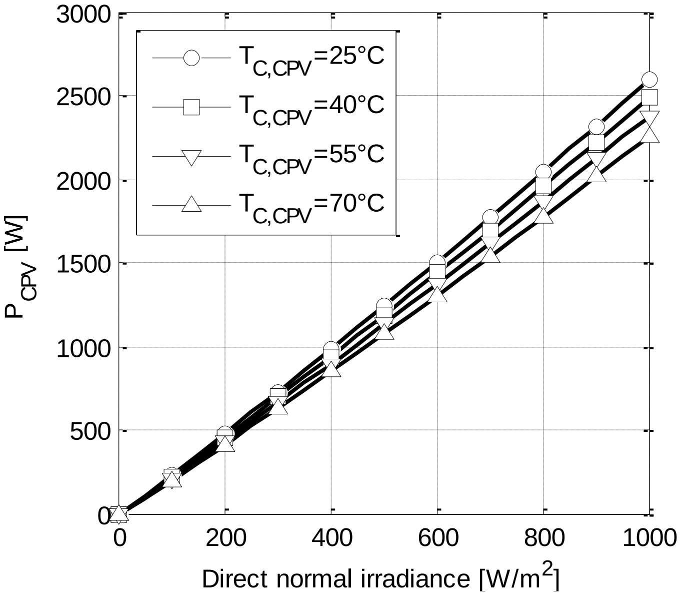

Fig. 5. CSP power production curves

3.2. CPV plant section

Modelling the electrical behaviour of HCPV cells and modules is a fundamental task for the design, monitoring and energy prediction of these systems. Several models are presented in literature with different levels of complexity and accuracy. Because of only the determination of the maximum power point as a function of the different atmospheric conditions is important in this analysis, a simple model for the estimation of the power produced by the CPV (P_{CPV}) is used. The power produced by the HCPV modules is influenced by different atmospheric parameters, such as direct solar radiation (DNI), air temperature (T_{AMB}), air mass (AM) and wind speed (v_{wind}). In particular, the working point of CPV modules can be estimated in accordance with the characteristic curves provided by the manufacturer. As shown in Fig. 5, the power produced by the HCPV units is directly proportional to the DNI but decreases with the increase of the cell temperature [15]. However, the determination of this temperature is a complex task due to the unique feature of such a module [16]. The linear coefficients method proposed by [17] is used in this work to estimate the mean cell temperature of the module ($T_{C,CPV}$):

$$T_{C,CPV} = T_{AMB} + a\,DNI + b\,v_{wind} \tag{8}$$

where a and b are empirical parameters obtained through a regression analysis of the outdoor monitored data. Despite this method does not take into account the spectral effects that affect the behaviour of modules containing multijunction solar cell, it can be used for the estimation of the cell temperature with an acceptable degree of accuracy [18]. Because of the impossibility to carry out experimental activities, a and b are estimated according to values presented in literature obtained in similar atmospheric conditions with the location under examination [17] (a=0.0601 °Cm^2/W and b = -1.46 °C s/m).

Batteries are introduced for the short-term energy storage and to smooth the fluctuation in the CPV power production. Therefore, they have a low storage capacity (about 1 h) unlike the TES system, which is more suitable for a medium-term energy storage. In addition to that, the batteries are used to fill the gap between the real and the expected power production. However, the batteries are not always able to cover this gap and several times during the year they reach their complete charge or discharge. Vice versa, if the batteries are completely discharged and a deficit in the power production occurs, a fraction of the scheduled power production is unmet (P_{UN}). Therefore the energy balance of the CPV plant is:

$$P_{OUT} + P_{UN} + P_{BC} = P_{CPV} + P_{BD} + P_{EX} \quad (9)$$

Where P_{OUT} represent the effective power output of the CPV plant and P_{BC} and P_{BD} are the charging and discharging power flows of the batteries. The capacity of the battery (Q_{BATT}) is 430 kWh with a maximum power of 300 kW ($P_{B,MAX}$). The available energy content of batteries is commonly evaluated by the state-of charge (SOC). The latter is the ratio between the stored energy and its nominal storage capacity and it is determined by monitoring the charging and discharging power flows over time:

$$SOC_t = SOC_{t-1} + \frac{(P_{BC}\eta_{BC} + P_{BD}/\eta_{BD})\Delta t}{Q_{BATT}} \quad (10)$$

Where η_{BC} and η_{BD} are the battery efficiencies during charge and discharge phases, respectively ($\eta_{BC} = \eta_{BD} = 0.93$). These parameters are assumed constant and equal to the nominal battery efficiency provided by the manufacturer. Moreover, the batteries are managed by assuming that the initial battery's state of charge is preserved at the end of the simulation time-horizon. Finally, as suggested by the manufacturer, a maximum SOC (SOC_{MAX}) of 90% and a minimum SOC (SOC_{MIN}) of 10% are also considered.

3.3. Control strategy

An innovative optimal EMS is applied to the integrated CSP-CPV system based on the combination of an Optimal Scheduling Procedure (OSP) and a Real-Time Control algorithm (RTC). In particular, the OSP represents the first level of the control strategy and defines the one-day ahead power production profile established through technical and economic criteria. The optimal power profile is then used as reference profile during the following day when the RTC is used to track the power production curve and to compensate for the deviations of the actual production profile from the forecasted one. In this way, the proposed EMS allows to enhance the exploitation of solar energy and to improve the programmability and reliability features of such power plants based on a variable and intermittent renewable energy source.

The determination of the optimal power production is found through the resolution of an optimization problem, which objective function is defined according to the goal of the control strategy. In this work, an energetic criterion is used and the power profile is chosen in order to maximize the energy production and to minimize the energy losses (in other words, to maximize the overall plant efficiency). Weather forecast are used as input data and the CSP and CPV power production is therefore foreseen. Starting from these data and the status of the two storage systems, the control strategy determines the optimal distribution of the main energy flows. For instance, if the DNI is low and the TES has enough charge, the energy produced by the solar field can be integrated with a proper amount of energy coming from the TES so that the ORC power unit can work close to its nominal power. Otherwise, if the TES charge level is low, this energy can be stored for a later use.

Furthermore, different equipment constraints must be considered in the assessment of the day-ahead power profile, especially for the CSP plant. The constraints in the ORC power rate are introduced to avoid high thermal stress. Minimum up-time and down-time constraints are also introduced to minimize the number of ORC start-up and shut down during the day. Obviously, the energy balance of both CSP and CPV power plants must be satisfied.

Because of the main input data (weather forecast) are subject to uncertainties and errors, the power production profile found with a deterministic approach differs from the optimal one when the real meteorological conditions occur. For this reason, a stochastic approach is also investigated and a scenarios tree method [19] is used to manage with the uncertainties of the solar radiation. Starting from the weather forecast, different evolutions of the solar radiation affected by uncertainty are generated with a corresponding probability and the different weather evolutions are aggregated in a scenario tree.

In order to take into account all the possible scenarios, up to the first 24 hours the power production profile is the same for all scenarios. In this way, the output power profile could be non-optimal for some scenarios but the optimum power profile takes into account the weighted average of all the possible weather evolution (the weights are the probabilities of the event occurrence). In other words, this approach allows to obtain a more robust power profile than the simple deterministic case.

4. Results of the performance analysis

The performance evaluation of the integrated CSP-CPV plant was carried out on a yearly basis by comparing five different case studies. The first case ("Ideal Case"), refers to the performance of the system with a control strategy based on real meteorological data (in other words the weather forecast data exactly corresponds to real data). Obviously this control strategy achieves the best performance in term of maximization of power production and minimization of energy losses. However, in real applications, meteorological data cannot be predicted exactly and this case is used only as a reference benchmark. The second case refers to the performance achieved by the integrated CSP-CPV system by considering a deterministic approach to determine the power production profile and an error between real and forecast data with a standard deviation of 0.2 ("Det σ=0.2 Case"). A stochastic approach instead a deterministic one is used in the third case and the corresponding control strategy takes into account not only the errors in weather forecast but also 2 additional scenarios where solar radiation varies by ± 5% with respect to the corresponding foreseen value ("Stoc σ=0.2 Case"). Finally the forth ("Det σ=0.4 Case") and the fifth ("Stoc σ=0.4 Case") cases refer to a control strategy based on the deterministic and stochastic approach respectively with a standard deviation equal to 0.4 (that is a higher mismatch between foreseen and actual meteorological conditions) in order to evaluate the effect of the forecast errors in the optimal EMS.

Figure 6 shows the energy flows occurring during a three day summer period for the “Stoc σ=0.2 Case”. As shown by the upper part of Fig. 6, the CSP power profile is characterized by a constant power output corresponding to the ORC nominal power. The TES system compensates for the DNI fluctuation and guarantees a constant ORC thermal power load. Overall, during the three day period, the thermal energy contained in the TES section (the initial state-of-charge was near to 100%) is largely used. As shown by the bottom part of Fig. 6, the CPV power profile is less regular and constant during the three day period. The power output of the CPV section follows the CPV module power production and the batteries compensates for the contingent fluctuation. Although the role of the batteries shown by Fig. 6 seems marginal, they play a key role in ensuring a constant hourly power supply to the grid. This fact is emphasized by Fig. 7, where the minute variations of the energy flows during the first day are shown. Figure 7 highlights the large fluctuations of the power produced by the CPV modules that are directly related to the DNI variations due to the occasional passage of clouds. The batteries are able to cover the gap between the desired power profile and the real power production of the CPV plant during almost all the day.

However, at the end of the day the battery SOC reach its minimum value and the batteries are unable to further cover the scheduled power profile and a small amount of unmet power is observed. Figure 8 shows the main results of the performance analysis in terms of yearly energy production. As expected, the maximum energy production, about 1800 MWh is reached in the Ideal case. Only a minor decrease in the yearly energy production is achieved with the use of a stochastic approach (Stoc σ=0.2 and Stoc σ=0.4 cases) and the increase of the standard deviation of the forecast error only leads to little differences. On the other hand, larger differences are observed with the adoption of a deterministic approach (Det σ=0.2 and Det σ=0.4 cases) where a reduction of 3-5% in the yearly energy production with respect to the Ideal case occurs. Therefore, the use of the scenarios approach allows to achieve a more robust scheduling of the integrated power plant with a minor influence of the forecast errors. For all the cases, the CPV energy production accounts for about 55% of the overall energy production.

Figure 9 shows the main thermal energy flows of the CSP power plant, that is the energy directly supplied to the ORC unit (E_{DIR}), the energy supplied to the TES section ($E_{T,C}$), the energy supplied by the TES section to the ORC unit ($E_{T,D}$) and the energy losses due to solar field defocusing (E_{EX}).

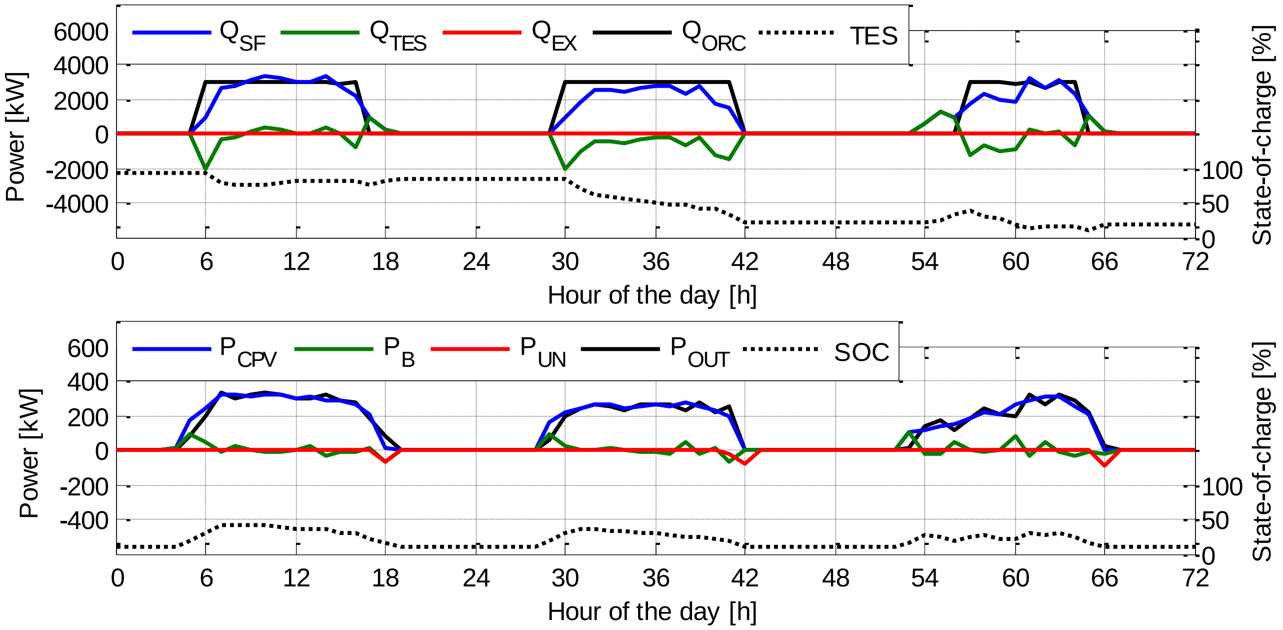

Fig. 6. CSP-CPV energy flows during three summer days

Figure 9 demonstrates that a higher use of the TES system occurs in the stochastic scheduling cases with respect to the deterministic ones. In fact, the control strategy based on the statistical approach faces the uncertainties of solar radiation by storing large amounts of thermal energy, thus avoiding the complete discharge of the TES system. Therefore, only a minor amount of the thermal energy produced by the solar field is directly sent to the ORC unit. Figure 10 shows the main energy flows of the CPV power plant. Unlike the results obtained for the CSP plant, for the CPV section the implementation of a deterministic control strategy lead to an higher use of the batteries owing to the higher gap between the desired power profile and the actual CPV power production. Moreover, because of a worst management of the battery bank, the adoption of a deterministic approach leads to an increase of the overall unmet and excess energy flows. Finally, the main results in terms of energy flows, efficiency and operating hours are reported in Table 5. As expected, the Ideal case reaches the best performance in terms of average yearly efficiency. Despite the higher energy production, the EMS based on a stochastic approach gives a lower average CSP efficiency with respect to the deterministic one. Therefore, an increase of the CSP operating hours occurs together with the increase of the annual number of ORC start/stop. For an economic point of view, this is a disadvantage for the control strategy as an increase of the operating costs is achieved.

5. Conclusion

In this paper, the annual performance of an integrated CSP-CPV power plant with energy storage was investigated. Suitable simulation models were developed for the evaluation of the power production of the CSP and CPV power systems and the energy behaviour of the TES system and the battery bank. In order to test the effective ability of the integrated system to produce electricity with scheduled profiles, two different energy management strategies were implemented and compared. Despite the requirement of higher computational resources, the adoption of a stochastic approach has demonstrated better results in term of maximization of the yearly energy production and reduction of the unmet power. In particular, an improvement by about 3-5% of the yearly CSP-CPV energy production is expected with respect to the use of an EMS based on a deterministic approach. However, the adoption of a stochastic approach also leads to an increase of the ORC operating hours and the number of the ORC starts/stops. Therefore, some economic drawbacks, as the increase of the ORC operating costs, can arise by adopting this approach. For this reason, future developments in the EMS of these CSP-CPV integrated power plants will involve the introduction of economic criteria in the definition of the objective function of the control strategy.

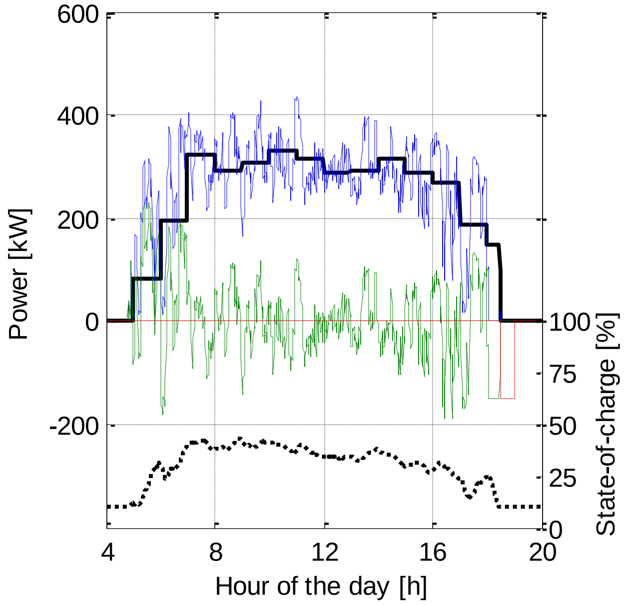

Fig. 7. Minute based CPV energy flows.

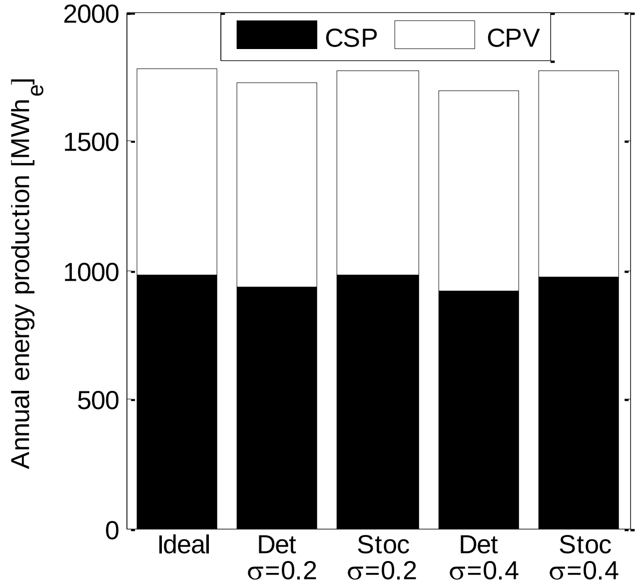

Fig. 8. Yearly CSP-CPV energy production.

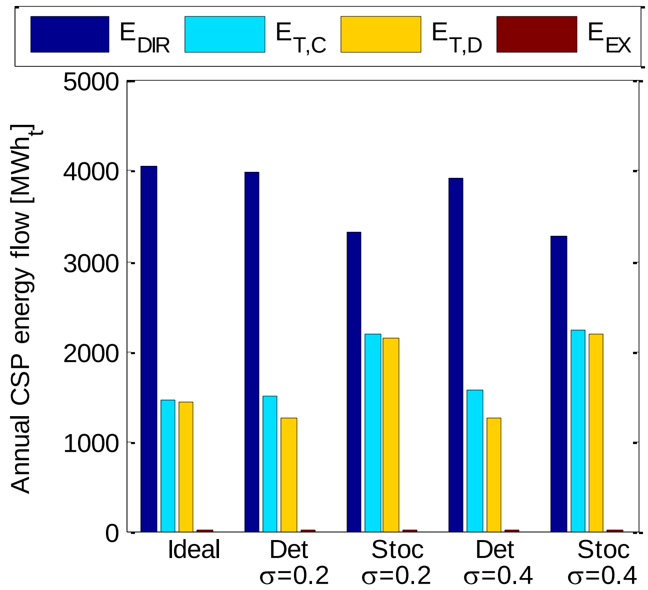

Fig. 9. Yearly CSP thermal energy flows

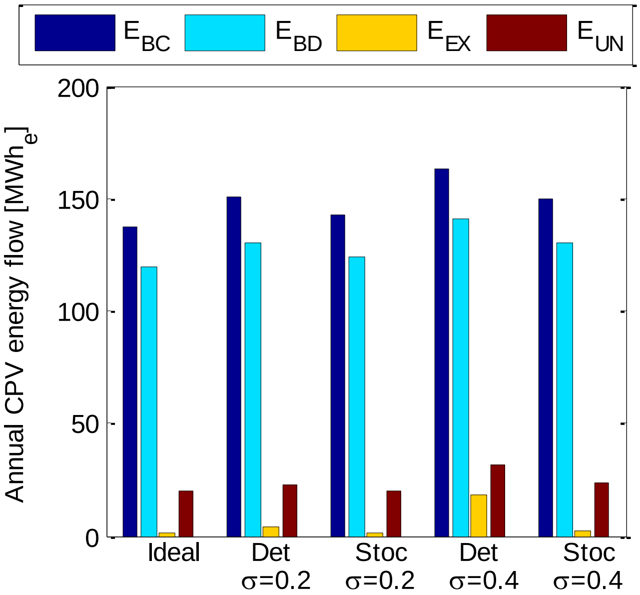

Fig. 10. Yearly CPV energy flow.

Table 5. Main results for different control strategy

	Ideal	Det@σ=0.2	Stoc@σ=0.2	Det@σ=0.4	Stoc@σ=0.4
Solar field energy output [MWh_t]	5520	5520	5520	5520	5520
ORC power production [MWh_e]	980.0	936.0	978.6	921.9	979.1
Mean ORC efficiency [%]	17.78	17.76	17.69	17.78	17.69
ORC running time [hr/yr]	1916	1840	1928	1812	1930
Number of ORC start/stop	427	403	423	417	419
CPV Power production [MWh]	797.2	792.4	796.3	775.5	794.1

Mean CPV efficiency [%]	23.44	23.3	23.41	22.8	23.35
CPV unmet energy [MWh_e]	20.2	23.0	20.3	31.2	23.6

References

[1] Giuntoli M, Poli D., Optimized Thermal and Electrical Scheduling of a Large Scale Virtual Power Plant in the Presence of Energy Storages, IEEE Transactions on Smart Grid 2013;4:942–55.
[2] Usaola J., Operation of concentrating solar power plants with storage in spot electricity markets. IET Renewable Power Generation 2012;6:59–66.
[3] Madaeni S., 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. IEEE Trans Power Syst 2013;28(2):1205–15.
[4] Dominguez R., Baringo L., Conejo A.J., Zendehde N., Karimpour A., Optimal offering strategy for a concentrating solar power plant, Applied Energy 2012;98:316–325.
[5] Pousinho, H., Contreras J., Pinson P., Mendes V., Robust optimisation for self-scheduling and bidding strategies of hybrid CSP–fossil power plants. Int. J. Electrical Power & Energy Systems 2015;67:639-650.
[6] Camerada M., Cau G., Cocco D., Damiano A., Demontis V., Melis T., Musio M., A pilot power plant based on concentrating solar and energy storage technologies for improving electricity dispatch, Proceedings of the 69 ATI National Congress, Milan, 10-12 September 2014.
[7] Wiesenfarth M, Helmers H, Philipps SP, Steiner M, Bett AW. Advanced concepts in concentrating photovoltaics (CPV), 27th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC), Frankfurt, Germany, September 22-23 2012.
[8] Kinsey GS, Bagienski W, Nayak A, Liu M, Gordon R, Garboushian V. Advancing efficiency and scale in CPV arrays, Journal of Photovoltaics, 2013;4:873-3.
[9] Chong KK, Lau SL, Yew T, Tan PC. Design and development in optics of concentrator photovoltaic system, Renewable and Sustainable Energy Reviews 2013;3:598–612.
[10] Lu X, Xia G, Lemmon JP, Yang Z. Advanced materials for sodium-beta alumina batteries: Status, challenges and perspectives, Journal of Power Sources, 2010;195(9):2431-42.
[11] Restello S, Lodi G, Miraldi AK. Sodium Nickel Chloride Batteries for telecom application: A solution to critical high energy density deployment in telecom facilities, Proceedings of Telecommunications Energy Conference (INTELEC), Scottsdale, USA, Sept. 30-Oct- 4, 2012, IEEE 34th International 1/2012.
[12] Meteonorm, Version 6.0, Meteotest, Bern (CH), 2010.
[13] Cau G., Cocco D., Comparison of Medium-size Concentrating Solar Power Plants based on Parabolic Trough and Linear Fresnel Collectors, Energy Procedia, 2014;45:101-110.
[14] http://www.turboden.eu, Last accesses October 2013.
[15] Helmers H., Schachtner M., Bett A.W. Influence of temperature and irradiance on triple-junction solar sub cell. Solar Energy Materials & Solar Cells, 2013;116: 144-152.
[16] Rodrigo P., Fernández E.F., Almonacid F., Pérez-Higueras, P.J. Models for the electrical characterization of high concentration photovoltaic cells and modules: a review. Renewable and Sustainable Energy Reviews, 2013;26:752-760.
[17] Almonacid F., Pérez-Higueras, P.J, Fernández E.F., Rodrigo P., Relation between the cell temperature of a HCPV module and atmospheric parameters. Solar Energy Materials & Solar Cells, 2012;105:322-327.
[18] Fernández E.F., Almonacid F., Rodrigo P., Pérez-Higueras P.J, Calculation of the cell temperature of a high concentrator photovoltaic (HCPV) module: a study and comparison of different methods, Solar Energy Materials and Solar Cells, 2014;121:144-151.
[19] Cau G., Cocco D., Petrollese M., Kær, S. K., Milan, C., Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system. Energy Conversion and Management 2014;87:820-831.