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Small-scale CSP plant coupled with an ORC system for providing dispatchable power: the Ottana Solar Facility

Mario Petrollese*, Daniele Cocco, Giorgio Cau

Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Via Marengo 2, 09123 Gagliari, Italy

Abstract

This paper is focused on the ongoing studies at the Ottana Solar Facility, a new experimental power plant located in Sardinia (Italy). The facility consists of a 630 kW CSP plant and a 400 kW CPV plant. The CSP section includes a solar field based on linear Fresnel collectors using thermal oil as heat transfer fluid and a two-tank direct thermal storage system with a storage capacity of about 15 MWh_t. The electricity generation is carried out in the Turboden 6HR Special ORC unit. This paper presents a description of the CSP plant characteristics and an analysis of its expected performance. In particular, the results of the simulation activities aimed at assessing the influence of different operational strategies on the CSP plant behavior and, particularly, on the ORC performance are explained and discussed. The simulation models of the main sections of the CSP plant were developed in accordance with literature data and specific information given by the manufacturers. The results provide a useful basis for the future development of the management schemes during the experimental campaigns on the CSP plant.

Keywords: Solar ORC; Concentrating solar power; Linear Fresnel Collectors; Thermal energy storage

1. Introduction

Solar energy is a clean Renewable Energy Source (RES), which has attracted wide attention in recent years, as it is non-exhaustible, pollution-free and exploitable in most parts of the world. Photovoltaic (PV) conversion is the most mature and widespread used technology for electricity generation from solar energy. Concentrating Solar Power (CSP)

* Corresponding author. Tel.: +39 070-675-5741; fax: +39 070-675-5717.
E-mail address: petrollese@unica.it

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is another interesting technology for the exploitation of solar energy to produce electricity. Unlike PV systems, the operability of a CSP plant integrated with a Thermal Energy Storage (TES) section is comparable with conventional and dispatchable power plants. In fact, the inclusion of a TES system allows a power generation partially independent from the instantaneous solar radiation [1], coping uncertainty in solar energy availability, mitigating short load fluctuations and shifting or extending the energy supply period [2]. Nowadays, CSP technology is mainly used in large-scale plants (higher than 10 MW) where the thermal energy produced by the solar field is exploited by conventional steam cycles for power generation [2]. However, in recent years, the capabilities of small-scale CSP plant (from 50 kW to 5 MW) to meet the challenge of a significant share of solar energy in the electricity mix have been investigated [3]. The configuration of small-scale CSP plants significantly differs from that of large-size plants due to the lower temperature and pressure reached in the solar field. In this case, Organic Rankine Cycle (ORC) units are preferred to steam power plants [4], as they are a reliable technology for small size applications with low-grade heat conversion and with power outputs ranging from few kW to some MW [5]. Up to now, very few CSP plants using ORC technology are operating in the world [6,7] and, to the authors knowledge, very few studies are available in literature about the management of CSP-ORC power plants. This paper presents some results about the ongoing studies at the Ottana Solar Facility, a pilot power plant almost ready for commissioning service in Sardinia (Italy) [8,9]. The facility is based on a 630 kW CSP plant with thermal storage and a 400 kW concentrating photovoltaic (CPV) plant with electrochemical storage. The Ottana Solar facility has been designed with the aim to demonstrate the possibility to produce electricity from solar energy with scheduled profiles according to weather forecast as well as to provide ancillary services at distribution level. A detailed description of the main section characteristics, with a particular focus on the ORC unit, is carried out in this paper. Moreover, the control strategy adopted for determining the daily power profile is introduced and the expected performance of the CSP plant are presented and discussed.

2. The CSP section at the Ottana Solar Facility

The Ottana Solar Facility, located in the centre of Sardinia, Italy aims to integrate effectively solar concentrating technologies and energy storage systems for enhancing the dispatch capabilities of solar power plants. The CSP plant (of particular interest for the purpose of the present paper) includes three main sections:

- The Solar Field (SF), based on six lines of linear Fresnel collectors connected in parallel. The collector lines are aligned along the North-South direction and are equipped with a single-axis tracking system to follow the sun path. Each collector loop (200 m length and 9.0 m width for a net collecting area of 1432 m^2) includes 34 collectors. The primary mirrors concentrate the solar radiation onto the fixed receiver (7 m above the mirror plane) that includes a secondary reflector and the evacuated receiver tube. The Heat Transfer Fluid (HTF), a commercial Dowtherm®-T thermal oil, is heated up in the receiver tube, with a design inlet/outlet temperature of 165/275°C. Under nominal conditions (Direct Normal Irradiance of 900 W/m^2), the efficiency of the solar field is about 64% and its thermal power output is about 5 MW, corresponding to a Solar Multiple of 1.61.
- The Thermal energy storage (TES) section, based on a two-tank direct system using the same HTF as storage medium. The two cylindrical steel tanks are provided with a thermal insulation layer and the upper volume above the oil is filled with nitrogen to avoid oil oxidation. The Hot Tank collects the HTF heated by the solar field and supplies it to the ORC unit; the Cold Tank receives the oil coming from the power block and supplies it to the solar field. The two storage tanks are sized to contain about 195 tonnes of thermal oil at a maximum temperature of 275°C. The capacity of the storage system is equal to 15.2 MWh, corresponding to 4.92 hours of plant operation at nominal conditions.
- The Power block (PB), based on a Turboden 6HR Special ORC unit, which converts thermal energy into electrical energy by means of a regenerative Rankine cycle operated by an organic fluid. As shown in Figure 1, the thermal energy produced by the solar field feeds the ORC unit for heating and vaporizing the organic fluid. The condensation heat is removed by dry coolers and/or used for underfloor heating in control rooms and offices. The main components of the ORC module are: an axial turbine (rotational speed 3000 rpm), a multistage centrifugal feed pump coupled with an inverter controlled electric motor, shell & tube primary heat exchangers (evaporator and preheater), the recuperator (finned tubes heat exchanger), the condenser (shell & tube heat exchanger) and an electric generator (asynchronous type, air cooled).

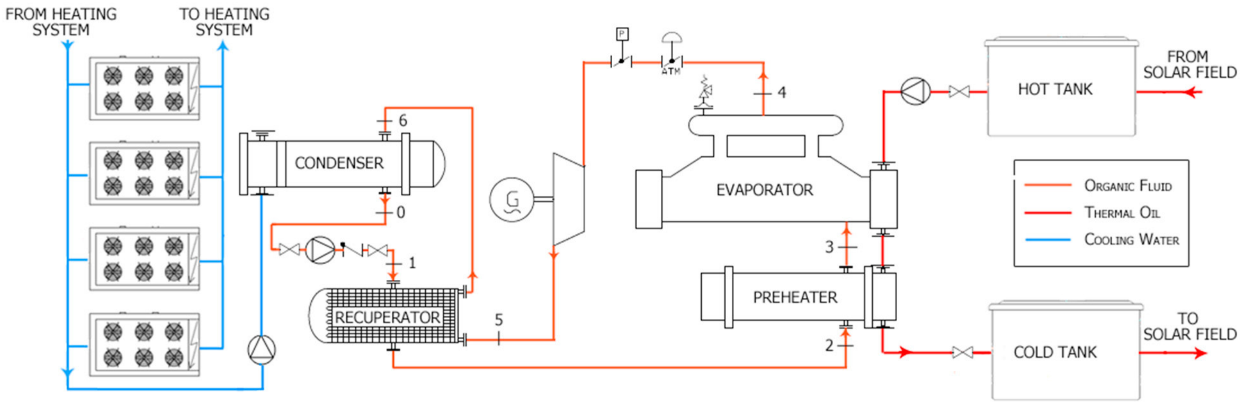

Figure 1 - Schematic view of the CSP section at the Ottana Solar Facility.

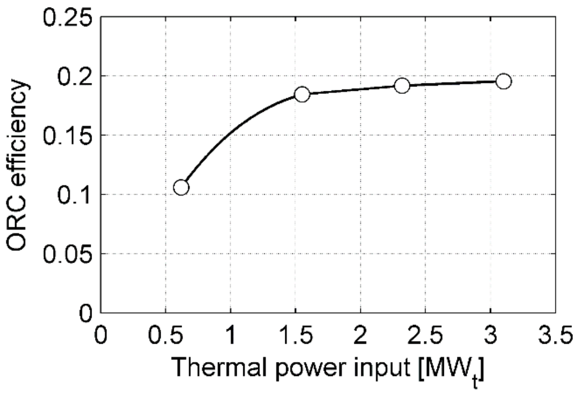

Figure 2 - ORC efficiency as function of thermal power input

Table 1 – ORC performance at reference conditions.

Thermal oil inlet temperature	275°C
Thermal oil outlet temperature	165°C
Thermal oil mass flow rate	11.05 kg/s
Thermal power input	3100 kW$_t$
Cooling water inlet/outlet temperature	25°C/35°C
Thermal power to condenser	2436 kW$_t$
Gross electrical power	664 kW
Captive power consumption	35 kW
Net electrical power	629 kW
Gross electrical efficiency	21.4%
Net electrical efficiency	20.3%

2.1. ORC performance

The 6HR Special ORC unit is designed to produce a net electrical power of 629 kW with a net efficiency of 20.3%. Table 1 reports the ORC unit performance at reference conditions. Obviously, the ORC can also operate at part-load conditions with a consequent efficiency decrease, as shown in Figure 2. Part-load operation is carried out by keeping constant the oil temperature and reducing the mass flow rate. The lower thermal power input results in a decrease of the mass flow rate of the organic fluid feeding the evaporator. The turbine adapts to the actual flow conditions with a decrease of the input pressure (sliding-pressure control) and the consequent decrease of the enthalpy drop and cycle efficiency. The sliding-pressure mode is applied at high partial loads while a combination of sliding pressure and throttling occurs at low partial loads, where the sliding pressure mode cannot be applied to avoid premature evaporation in the regenerator. The ORC performance also depends on the ambient temperature since the condensing heat is mainly removed by dry coolers and, subsequently, the water temperature at the condenser inlet side is directly related to the ambient temperature. Finally, because of the intermittent solar energy availability, a daily start-up and shut-down of the ORC turbogenerator is scheduled. After the shutdown phase, the ORC unit is kept warm by feeding it with a minimal thermal oil mass flow, in order to allow a fast start-up time during the following day (the so-called hot start-up). On the other hand, during some periods of the year, especially winter and mid-season, an ORC stop longer than one day may occur. In this case, a cold start-up is required with a longer warm-up period and a higher amount of energy demanded.

3. Determination of the daily power profile

The management of the CSP plant is entrusted to a supervision and control system of the integrated CSP+CPV plant, based on an innovative control strategy. As mentioned, the aim of the Ottana solar facility is not the maximization of the energy production (as in typical commercial solar power plants), but the study of the ability of the overall CSP+CPV system to deliver scheduled profiles in accordance with the weather forecasting. The achievement of this objective requires the development of a novel integrated control logic [9,10], different from that of conventional CSP plants [11]. In particular, the supervision and control system mainly consists of an appropriate one-day ahead scheduling procedure, which defines the set-point of the CSP+CPV power production for the following day, combined with a real-time control algorithm for the power profile tracking according to actual meteorological data. The hybridization of the two solar systems (CSP and CPV) occurs both during the daily operation, where the different dynamic response of the two systems to the DNI fluctuations (very fast for the CPV and relatively slow for the CSP) allows to obtain a more effective regulation of the scheduled profile, and during the start-up phases, where the batteries allow to supply the ORC ancillary consumption.

The determination of the daily power profile of the CSP plant, which is delivered 24 h ahead, is based on two main inputs: the state of the CSP plant at the end of the previous day and the weather forecast provided by a specific service. The first input refers to the State-of-Charge (SOC) of the hot tank, calculated in function of oil temperature and stored oil mass, and the on/off state of the turbogenerator in the previous day. The weather forecast data include the Direct Normal Irradiance (DNI), which directly influences the energy production of the solar field, and the ambient temperature, which affects the thermal losses in the solar field and the oil tanks as well as the ORC efficiency (η_{ORC}). Starting from these input data, the expected thermal energy production of the solar field is evaluated by using the simulation model presented in [10]. The overall thermal energy availability E_{IN} is determined as the sum of the expected daily energy production of the solar field and the stored energy in the hot tank from the previous day.

At this preliminary stage, the daily power output profile is simply represented by a constant ORC power output and it is defined by four parameters: the ORC on/off state, the net electrical power output P_{EL}, the corresponding duration period τ_{ORC}, and the start-up time t_{ON}. The control strategy adopted for the determination of the daily ORC profile is based on the trade-off between two conflicting goals:

1) The maximization of the ORC performance, achieved by operating it as close as possible to nominal conditions for high duration periods and with a low number of ORC start-up.
2) The maximization of the matching between CPV and ORC power delivery periods, exploiting the storage capacity of the CSP section to minimize the fluctuations in the CPV power production.

The first objective promotes the use of the ORC unit at design conditions with a starting time scheduled only if a high state-of-charge of the hot tank is reached (similarly to the control strategy currently adopted in large-size CSP plants). Vice versa, the hybridization of the two solar systems is pursued in the second objective. Consequently, it is required the operation of the ORC unit during daylight periods (that is simultaneously to the CPV), often at part load conditions, especially during days characterized by a partial cloud cover.

The main control variable that determines the trade-off between the two objectives is the clearness index K, which is defined as the ratio between the expected daily energy production from the solar field and the corresponding energy production in clear-sky conditions. Two K threshold values (K_{HIGH} and K_{LOW}) are introduced. Since high K values ($K>K_{HIGH}$) result in stable atmospheric conditions and the expected fluctuations on the CPV power production are limited, the role of the CSP section for supporting the CPV production is marginal. Therefore, the ORC can operate at nominal conditions ($P_{EL,nom}$) and the ORC state is set to ON-FULL. Vice versa, for low K values (that is $K< K_{LOW}$), due to the low solar energy availability, the ORC unit could only operate with low power outputs and for very low duration periods. In this case, the ORC unit is kept off (state OFF) and the thermal energy produced by the solar field is stored in the TES section. For intermediate values of K, the on/off state of the ORC unit is determined by evaluating the overall energy availability E_{IN} (in this case, the SOC of the hot tank at the end of the previous day becomes a fundamental parameter). In particular, the start-up of the ORC unit occurs only if the expected E_{IN} is sufficient to guarantee a minimum number of operating hours $\tau_{ORC,min}$ at nominal conditions. In this situation, the role of the CSP section for supporting the CPV production becomes fundamental and τ_{ORC} is set equal to the CPV delivery period (τ_{CPV}). The power level is subsequently calculated according to the overall energy availability and the imposed duration period (the ORC state is set to ON-PART). However, in order to avoid too low efficiency values, the minimum ORC power output ($P_{EL,min}$) is set to 50% of the nominal power and the delivery period is adjusted in order to satisfy this constraint (the ORC state is ON-MIN). Figure 3 summarizes the control strategy adopted for scheduling the ORC daily power profile. Finally, the start-up time t_{ON} is determined by evaluating the SOC of the hot tank. A threshold value of this SOC value is introduced (SOC_{START}) in order to guarantee the oil supply during the start-up phase, as well as to absorb the fluctuations in the thermal energy production during the day. If the state of charge of the hot tank at the end of the previous day (SOC_{PRE}) is enough for a safe ORC start up (SOC_{PRE}>SOC_{START}), t_{ON} is set equal to the first hour of the day where a share of the solar field production is expected. On the other hand, a restoration of the minimum level in the hot tank is required and t_{ON} is set equal to the first hour of the day when the hot tank state of charge is higher than SOC_{START}.

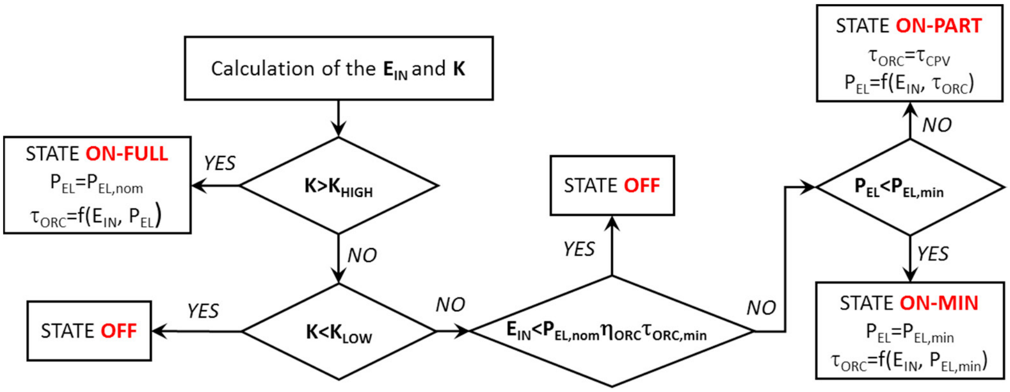

Figure 3 – Logic block diagram for the determination of the ORC daily power profile.

4. Expected performance of the CSP plant

In this section, the expected performances of the CSP plant are presented and analyzed. The SF thermal energy production is calculated as a function of solar radiation and solar position by using a dedicated simulation model [10], for given values of the main geometrical and technical characteristics of the solar collectors and of the HTF thermodynamic properties. The annual thermal energy produced by the solar field is about 5.0 GWh_t. A share of the energy produced by the solar field directly feeds the ORC unit to produce electricity while the surplus is stored in the TES section for a deferred use. When the solar radiation is high, the PB is at full load and the hot tank is fully charged, then some mirrors are defocused to maintain the thermal power balance. This originates an excess energy neither used nor stored, which leads to the so-called defocusing energy losses.

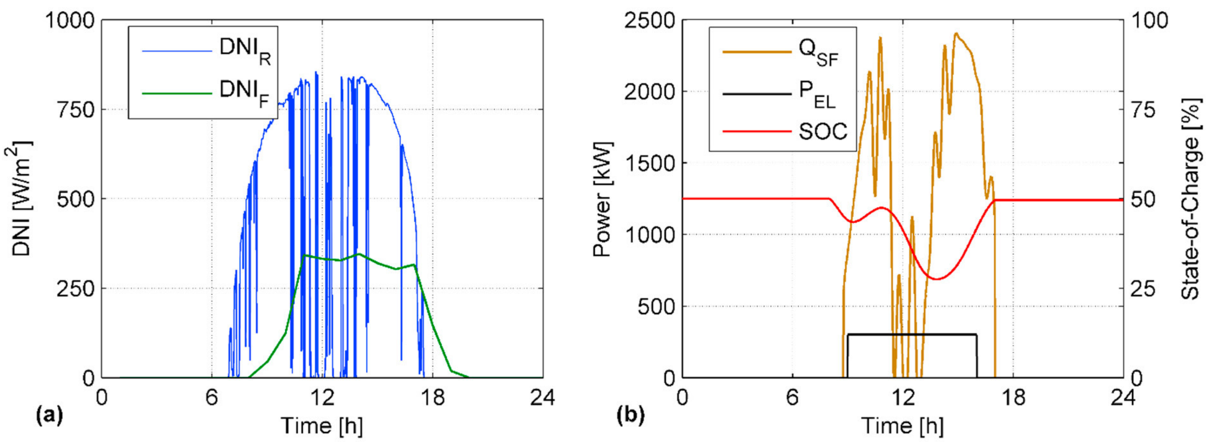

Figure 4 – (a) Real DNI (DNI_R) and forecasted DNI (DNI_F) and (b) energy flows occurring in 15/10/2016.

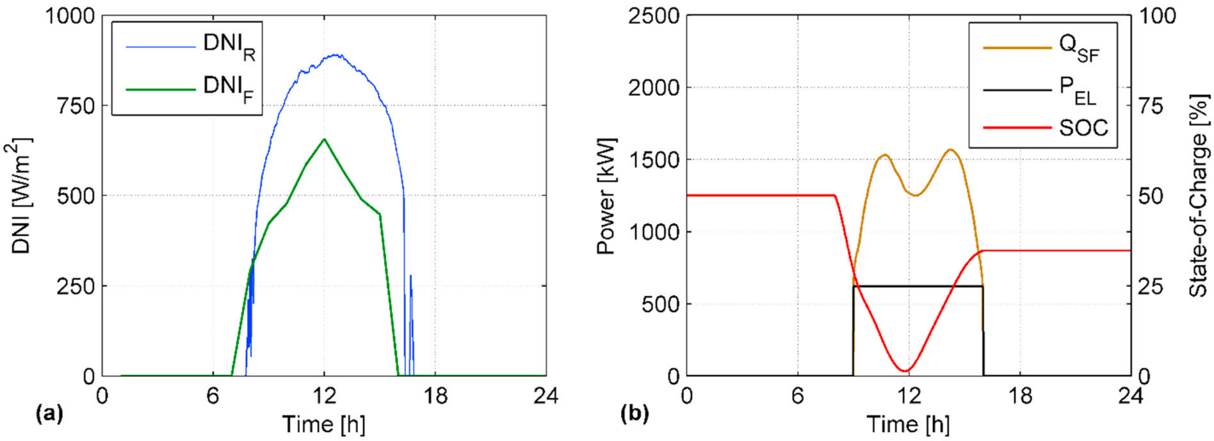

Figure 5 – (a) Real DNI (DNI_R) and forecasted DNI (DNI_F) and (b) energy flows occurring in 31/11/2016.

Table 2 – Expected annual performance of the CSP plant

Solar energy availability[MWh_t]	14650	Mean ORC efficiency [%]	19.1%
Solar field energy output [MWh_t]	5076	Mean ORC power level [kW]	430
Defocusing energy losses [MWh_t]	160	ORC running time [h/year]	2188
ORC power production [MWh]	941	Number of ORC start/stop	217

For the Ottana site is currently available a weather forecast service and real data have been measured starting from October 2016. Figure 4(a) and Figure 5(a) show for two different days, the expected DNI provided by the weather forecast service (DNI_F) compared to the real DNI (DNI_R). High fluctuations on the beam solar radiation are observed in Figure 4(a), especially during the middle of the day, while clear sky conditions occur in Figure 5(a). For both days, the weather forecast service underestimates the DNI and innovative strategies for minimizing the effect of uncertainty in solar energy availability are therefore required. The corresponding power output profiles (P_{EL}), determined by the control strategy presented in the previous section, are shown in Figure 4(b) and Figure 5(b), together with the SF thermal power produced (Q_{SF}) and the State-of-Charge of the TES section. A different strategy is adopted in these two test cases as the ORC state is set ON-MIN in the first day (Figure 4(b)) and ON-FULL in the second one (Figure 5(b)). It is also observed the important role of the TES system for compensating both the fluctuations on the SF thermal energy production and the uncertainty in weather forecast.

The annual performance of the CSP plant largely depend on the main control parameters, that are: K_{LOW}, which determines the off state of the ORC unit during cloudy days, K_{HIGH}, which sets the working point of the ORC unit and $\tau_{ORC,min}$, which represents the minimum duration time of the ORC daily power profile. The expected annual performance of the CSP plant are reported in Table 2 by assuming K_{LOW}=0.1, K_{HIGH}=0.8 and $\tau_{ORC,min}$=2 h. The main energy losses occur in the solar field, which achieves an annual average efficiency (including both optical and thermal losses) of about 35%. The defocusing energy losses are marginal (about 3% of the solar field energy production) demonstrating a proper choice for both TES capacity and Solar Multiple, as well as the adoption of a suitable operational strategy for the management of the energy flows from/to the TES system. The ORC unit frequently operates at part-load with a consequent average efficiency lower than the nominal one. Moreover, for about 150 days the ORC unit is not operating due to the low solar energy availability, achieving a plant capacity factor of 17.3%. This value is lower than the typical capacity factors attained in CSP plants that usually operate with higher values of both Solar Multiple and storage capacity. However, it is worth noting that the Ottana solar facility is an experimental facility plant, which was not designed to maximize the energy production.

Finally, a preliminary analysis on the expected performance of the plant in function of K_{LOW}, K_{HIGH} and $\tau_{ORC,min}$ has been carried out. Figure 6 shows the ORC operating states during the annual simulation by varying these three main control parameters, while Figure 7 shows the capacity factor of the CSP plant together with the average ORC efficiency (a box plot is added indicating the variability of the efficiency during the year). Figure 6(a) proves that an increase of K_{LOW} results in a decrease of the number of ORC start-up and in a reduction of the ORC operating hours at minimum load. As shown by Figure 7(a), the effect is twofold: an increment of the average ORC efficiency, as the latter operates closer to its nominal conditions (even a decrease of box size occurs) and, at the same time, a reduction of both the annual electrical production and the CSP capacity factor. As shown in Figure 6(b), since the K_{HIGH} control parameter is not involved in the determination of the ORC state during days characterized by low K values, the percentage of occurrence of both OFF and ON-MIN states remain almost constant by increasing K_{HIGH}. On the other hand, low values of this parameter increase the percentage of occurrence of ORC operating states at full load conditions. However, the effect on the ORC performance is marginal and both the mean value and the variability of the ORC efficiency remain almost constant. Finally, the effect of $\tau_{ORC,min}$ on the on/off ORC operating state is similar to K_{LOW} one, but the decision also involves the SOC of the TES section at the end of the previous day. Therefore, the ON-FULL state remains constant and the rise in the $\tau_{ORC,min}$ increases the percentage of occurrence of the OFF state although the clearness index in these days is higher than K_{LOW} and the solar energy production is not negligible. Consequently, a rise in the state-of-charge of the hot tank at the end of these days occurs and the remaining stored energy in the hot tank is used in the following days.

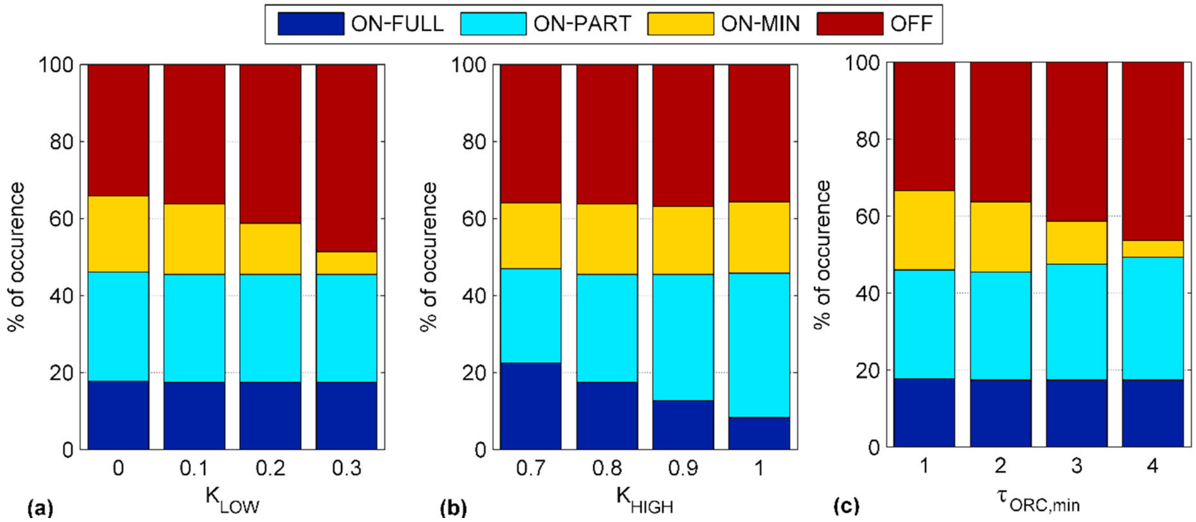

Figure 6 – Influence of the (a) K_{LOW}, (b) K_{HIGH} and (c) $\tau_{ORC,min}$ on the ORC state.

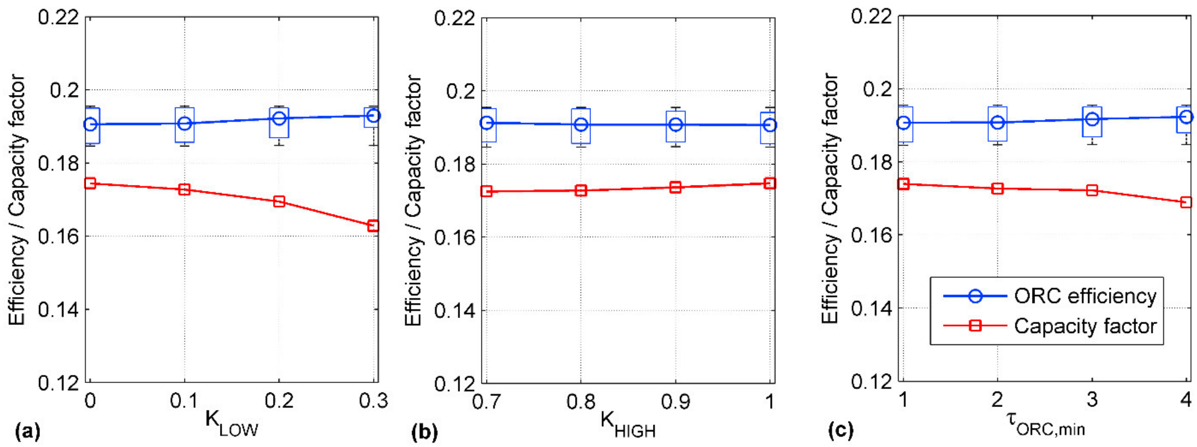

Figure 7 –Influence of the (a) K_{LOW}, (b) K_{HIGH} and (c) $\tau_{ORC,min}$ on the ORC efficiency and CSP capacity factor.

Finally, the determination of the daily power output profile is based on the expected solar field energy production, which usually differs from the actual one due to weather forecast uncertainty. Despite this aspect is not analysed in this paper, the decision of starting up the ORC unit when a low solar energy availability is foreseen increases the risk of a complete emptying of the hot tank and the consequent non fulfilment of the power output profile.

5. Conclusion

This paper was focused on the ongoing studies at the Ottana Solar Facility, a new experimental power plant located in Sardinia (Italy). The innovative configuration of the solar facility, with the integration of a CSP plant with a CPV system, demands the development of a novel control strategy for the achievement of a semi-dispatchability of the plant. After a description of the main components of the CSP section, the paper introduces the control strategy implemented for the definition of the daily power profile of the ORC turbogenerator. The expected performance are then presented through the simulation of two days characterized by different weather conditions, highlighting the fundamental role of the thermal energy storage and the frequent operation of the ORC turbogenerator at part load and with variable input conditions. Finally, the expected annual performance are investigated pointing out the importance of three control parameters on the ORC power profile, which affects the plant capacity factor and the turbogenerator efficiency.

Acknowledgements

The Ottana Solar Facility is founded by the Regional Government of Sardinia (Italy) in the framework of the operational program ERDF 2007-2013. The institutional supervisor of the project is the Industry and Energy Office of Sardinian Regional government. The design and the building of the plant were entrusted to ENAS, the Sardinian Water Company. Sardegna Ricerche, in collaboration with the University of Cagliari, will develop the research activities on the facility. ENAS will be in charge of the operation and management of the pilot plant.

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