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A pilot power plant based on concentrating solar and energy storage technologies for improving electricity dispatch

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Abstract

This paper presents the main features and the expected performance of the pilot solar power plant under construction in Ottana (Sardinia-Italy). The facility is based on a 600 kWe concentrating solar power (CSP) plant with thermal energy storage, and a 400 kWe concentrating photovoltaic (CPV) plant with electrochemical storage. The CSP plant uses linear Fresnel collectors, thermal oil as heat transfer fluid, a two-tank direct storage system and an ORC module. The CPV plant consists of 37 dual-axis trackers integrated with Sodium-Nickel batteries. The facility is characterised by the integration of different concentrating solar and storage technologies. The pilot power plant has been designed in order to produce electricity with scheduled profiles according to weather forecast.

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Keywords: CSP plants; Linear Fresnel Collectors; Thermal energy storage, Concentrated photovoltaics; Electrochemical storage

1. Introduction

The increasingly widespread use of renewable energy sources (RES), supported by economic subsidies and environmental policies, is changing the structure of the electric power system and is contributing to the spreading of

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the distributed generation (DG). The variability, intermittency and poor predictability of the electricity production from RES and the decentralization of power generation raises serious challenges related to the reliability, control and power quality of the electrical power grid. Coping to these challenges requires the development of active distribution power systems and, in some countries such as Italy, to reinforce the balancing service at distribution level. Currently, a unique and comprehensive operational strategy to overcome these issues has not been assessed yet and intensive research is worldwide devoted to the development of new models, structures and control algorithms [1-3].

For these reasons, the Regional Government of Sardinia (Italy), in the framework of the POR FESR 2007-2013 Program, is supporting the realization of three pilot facilities based on small scale concentrating solar power (CSP) plants integrated with other RES technologies and energy storage systems. This paper focuses on the first pilot facility which will be installed in the industrial district of Ottana. Its design has been developed with the scientific support of Sardegna Ricerche and the University of Cagliari with the aim to effectively integrate solar concentrating technologies and energy storage systems and therefore enhance the dispatch of solar power plants. Overall, the Ottana pilot plant will be able to produce electricity with scheduled profiles according to weather forecast as well as to provide ancillary services at distribution level. In particular, the facility consists of a Fresnel-based CSP plant (600 kWe), a two-tank thermal energy storage (TES) system (capacity of about 15 MWht), a concentrator photovoltaic (CPV) power plant (400 kWe) and an electrochemical storage system with a capacity of 430 kWhe. The plant control system has been designed with the aim to manage the predictable and unpredictable daily power fluctuations that occur in solar power plants in order to ensure the accomplishment of scheduled profile in accordance with the weather forecasting and the planned electricity ancillary services at distribution level.

2. Main design specifications

The main design specifications of the integrated power plant were represented by an overall power output of about 1 MWe, 600 kWe for the CSP section and 400 kWe for the CPV section. Moreover, since the power plant will be able to produce electrical energy with scheduled profiles, suitable thermal and electrical storage devices were included.

The site selected for the construction of the experimental facility is Ottana (40°25’00’’N, 9°00’00’’E), in the center of the Sardinia island, at about 160 m asl. The design was carried out by using a data set for a typical meteorological year obtained from the Meteonorm® software [4]. Figure 1a-b shows the monthly values of air temperature and Direct Normal Irradiation (DNI). Overall, the annual DNI is about 1685 kWh/(m^2·yr).

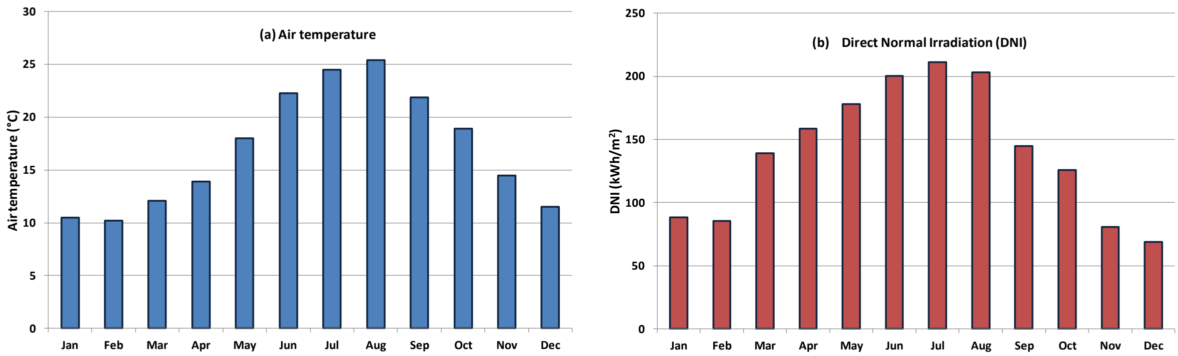

Fig. 1. Monthly values of air temperature (a) and DNI (b).

3. Concentrating solar power plant

Currently, for the design of CSP plants, different options are available for solar field, power block, heat transfer fluid and thermal energy storage [5-6]. For the power output here considered (600 kWe), the most interesting alternative is represented by Organic Rankine Cycles (ORC), that require thermal energy inputs with temperature levels in the range of 250-350 °C [7-8]. For such temperature levels, Linear Fresnel Collectors (LFC) may be a viable alternative to parabolic trough collectors because they have a simpler design, show lower land requirements and lower capital costs; on the other hand, they show a lower optical efficiency [9]. Moreover, the most suitable choice for the TES section is based on a two-tank direct system, where thermal oil is used as heat transfer fluid and storage medium [10]. Figure 2 shows a simplified diagram of the CSP plant and Table 1 reports its main design specifications at reference conditions (DNI 900 W/m^2, air temperature 17 °C, elevation 17°, azimuth 0°).

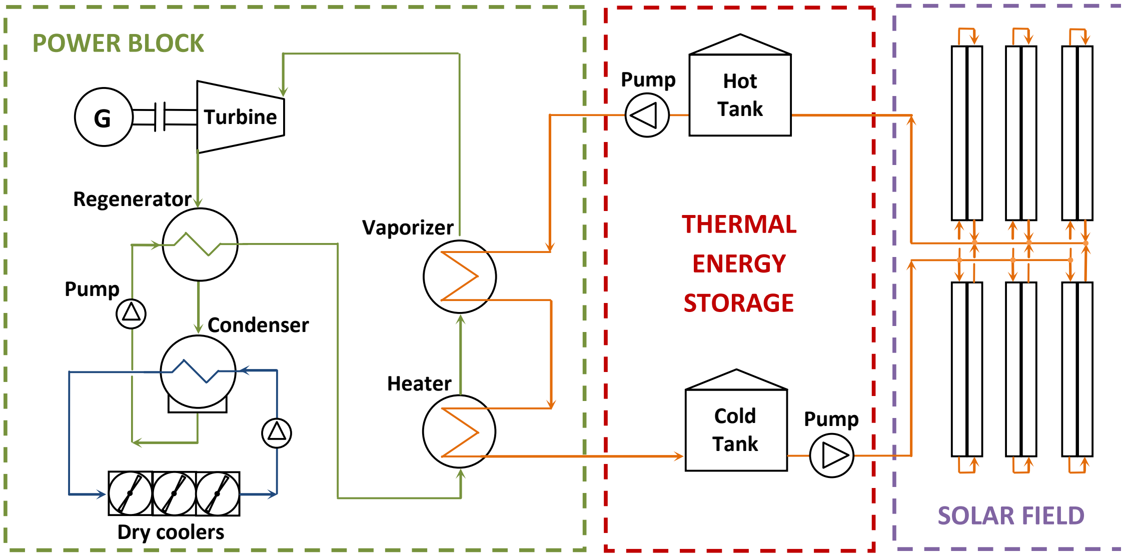

Fig. 2. Process flow diagram of the CSP plant.

Table 1. Main design parameters of the CSP plant .

SOLAR FIELD		ORC UNIT	
Loops (200x9.0 m)	6	Thermal power input	3000 kW
Solar field collecting area	8400 m^2	Thermal oil temperatures (in/out)	260/150 °C
Solar field land area	10800 m^2	Thermal oil mass flow	11.1 kg/s
Solar field conversion efficiency	62.0 %	Gross conversion efficiency	20.0 %
Thermal oil mass flow	17.3 kg/s	Gross power output	600 kWe
Thermal power output	4690 kW	Condenser power output	2350 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

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. The condensing heat is removed by a dry cooling system due to the lack of cooling water in the site. The ORC unit requires a thermal power input of about 3000 kW, that is supplied by cooling the thermal oil from 260 °C to 150 °C.

The solar field is based on 6 "U" loops of LFC connected in parallel to achieve the required thermal power output. Each collector loop (200 m length and 9.0 m width for a collecting area of 1400 m^2) includes 50 collector modules. The primary mirrors are mounted on a fixed steel structure placed at about 1.0 m above the ground and 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 solar collector lines are aligned along the North-South direction and are equipped with a single-axis tracking system to follow the sun’s path. The conversion efficiency of the solar field at design conditions is 62% with a corresponding thermal power output of about 4690 kW and therefore a solar multiple of 1.56.

The excess thermal energy produced by the solar field during periods of high solar availability is stored in the TES section using the same thermal oil as storage medium. In particular, the thermal oil from the cold tank (150 °C) flows through the solar field, where it is heated, sent to the hot tank (260 °C) and subsequently pumped to the ORC unit. The size of the TES section was evaluated in function of the required storage capacity (about 5 hours of ORC thermal supply) and the thermodynamic properties of thermal oil (an average specific heat of 2.5 kJ/(kgK) and a density of 700 kg/m^3 at 260 °C were considered).

4. Concentrating photovoltaic power plant

Concentration Photovoltaic is currently the solar technology with the highest conversion efficiency [11]. Recently, CPV modules achieved values of conversion efficiency of about 35% [12]. In particular, High Concentration Photovoltaic (HCPV) represents the most advanced CPV concept, which has already demonstrated its reliability and efficiency. The main advantage of this technology is represented by its potential to increase the efficiency reducing at the same time the active material and therefore the cost of electricity production. Based on the geometry of the optics, CPV systems can be divided in refractive (such as Fresnel lenses) and reflective (such as parabolic mirror) optics based systems [13]. Presently, the main part of commercial CPV modules employs refractive optics because of their cheapness and minor complexity. In fact, Fresnel lenses are usually made with low cost Poly-methyl methacrylate (PMMA) lenses characterized by a typical thickness of 4-5 mm. Thanks to these features the Fresnel-based technology has recently reached the technological and commercial maturity, as proved by the global cumulative installed capacity which hit about 100 MW at the end of 2013, with extra 200 MW expected to be installed by 2014 [14]. This optic configuration was therefore adopted for the Ottana pilot plant.

The CPV power plant is based on 37 two-axes solar trackers, with an overall power of about 400 kWp. Each solar tracker includes 48 modules, subdivided in two strings which are connected to a dedicated three-phase DC/AC converter integrated with two independent MPPT systems. This solution allows to enhance the reliability of the CPV plant, ensuring continuity of the energy supply when faults and brownouts occur only in a section of the CPV plant. Figure 3 shows the picture of a typical solar tracker.

Fig. 3. Solar tracker unit.

The dual-axis 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. In fact, the trackers accuracy relies on a hybrid tracking mode, ensuring a very low tracking error (about ± 0.1°) compatible with the divergence angle of most CPV modules currently in the market [15]. Table 2 reports the main design parameters of the CPV plant.

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	25% (IEC 62670-1)	Elevation range	6°-90°
Maximum DC power	225 Wp	Maximum wind speed	40 m/s
Open-Circuit Voltage	36.4 V	Wind stow condition	15 m/s
Short-Circuit Current	8.3 A	Tracking control mode	Hybrid
Cooling system	Passive	Communication interface	PLC
DC/AC CONVERTER		OVERALL CPV PLANT	
Conversion unity type	Inverter PWM	DC/AC conversion losses	2.80%
European conversion efficiency	97%	Overall efficiency	22%
N° independent MPPT	2	Net peak power output	400kWp_AC @ 850W/m^2 DNI

5. Electrochemical storage system

In the pilot plant, CSP and CPV systems are integrated with the final purpose of trading electrical energy or to provide system support services. Nevertheless, this task can be accomplished only if these solar energy-based generators are combined with electrical storage devices (ESDs) in a synergic and complementary way. Among all available electrical storage technologies, electrochemical batteries are currently considered one of the most efficient and suitable ESD solutions for smart grid applications. In particular, in this project a Sodium-Nickel (NaNiCl) battery has been proposed [16]. The NaNicl battery operates at relatively high temperature close to 300 °C in order to achieve adequate battery performance by melting both electrodes and improving the conductivity of the solid electrolyte (β''-alumina) and of the secondary electrolyte (sodium chloroaluminate in liquid state). 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% [17]. Since ESD are generally characterized by high investment costs, their diffusion at the distribution grid level requires a careful evaluation and a correct sizing, calibrated on the real application's needs.

For the Ottana pilot plant, the rated power and capacity of the NaNiCl battery were determined considering the high variability and poor predictability of power production from CPV systems as well as their dynamics, which are much greater than those of the CSP plant. In particular, the design was carried out in order to allow a programmable generation of the CPV system in 30 seconds-time intervals and compensate forecasting errors. Moreover, the size of battery was calculated by assuming that the initial battery's state of charge (SOC) was preserved at the end of the simulation time-horizon and with reference to a maximum SOC of 80%. Overall, the capacity of the battery is 430 kWh with a maximum power of 300 kW.

6. Supervision and control system

The supervision and control system, which is summary described by the scheme of Fig. 4, is based on an innovative optimal control strategy applied to the integrated renewable and storage systems. The proposed optimal management strategy mainly consists of an appropriate one-day ahead Optimal Scheduling Procedure (OSP) combined with a Real-Time Control algorithm (RTC): the OSP synthesizes an optimal combined RES-storages power profile one-day ahead on the basis of technical and economic criteria, by taking into account forecasted RES power production profile, storages status and availability, as well as electricity market and grid constraints. Then, in the next day, this optimal power profile is tracked by means of the proposed RTC, which has to compensate for the deviations of the RES actual production profile from the forecasted one. As a result, the proposed optimal RES management will enhance RES exploitation and integration, by improving programmability and reliability of RES power plants at the same time.

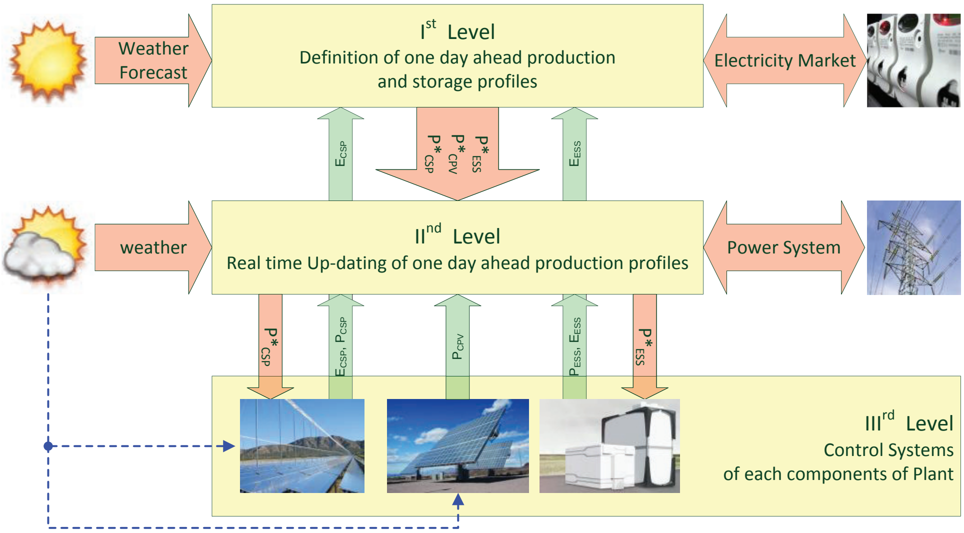

Fig. 4. Scheme of the supervision and control system.

7. Expected performance of the pilot plant

The Ottana pilot plant is currently under construction and Fig. 5 shows a 3D representation of its layout. As mentioned, the expected performance of the plant was evaluated on an hourly basis with reference to a typical meteorological year.

In particular, the performance of the CSP plant was calculated as a function of solar radiation and solar position by using a devoted simulation model [18], for given values of the main geometrical and technical characteristics of the solar collectors, thermodynamic properties of the heat transfer fluid as well as design and off-design performance of the ORC module. Figure 6a shows the thermal power output of the solar field over the year. Because of the low solar multiple, the thermal power output exceeds that required by the ORC unit (at design condition) just for few months, when irradiance reaches high levels. For the same reason, as illustrate by Fig. 6b, the charge percentage of the storage tank rarely exceeds 50%. However, the availability of an high thermal storage capacity is very useful in view of the experimental purposes of the pilot plant.

Moreover, a devoted algorithm was developed in order to simulate the optimum management of the battery according to the CPV power output, desired power profile and battery SOC. Figure 7 reports the desired power profile, the CPV power production, the battery power and energy flows on a daily basis, considering weather conditions with partially overcast sky and highly variable DNI, which are the most challenging for the battery compensating CPV power fluctuations. Overall, the expected electricity production is around 1600 MWh per year, 900 MWh/yr from the CSP section and 700 MWh/yr from the CPV one.

Fig. 5. 3D representation of the Ottana Pilot Plant.

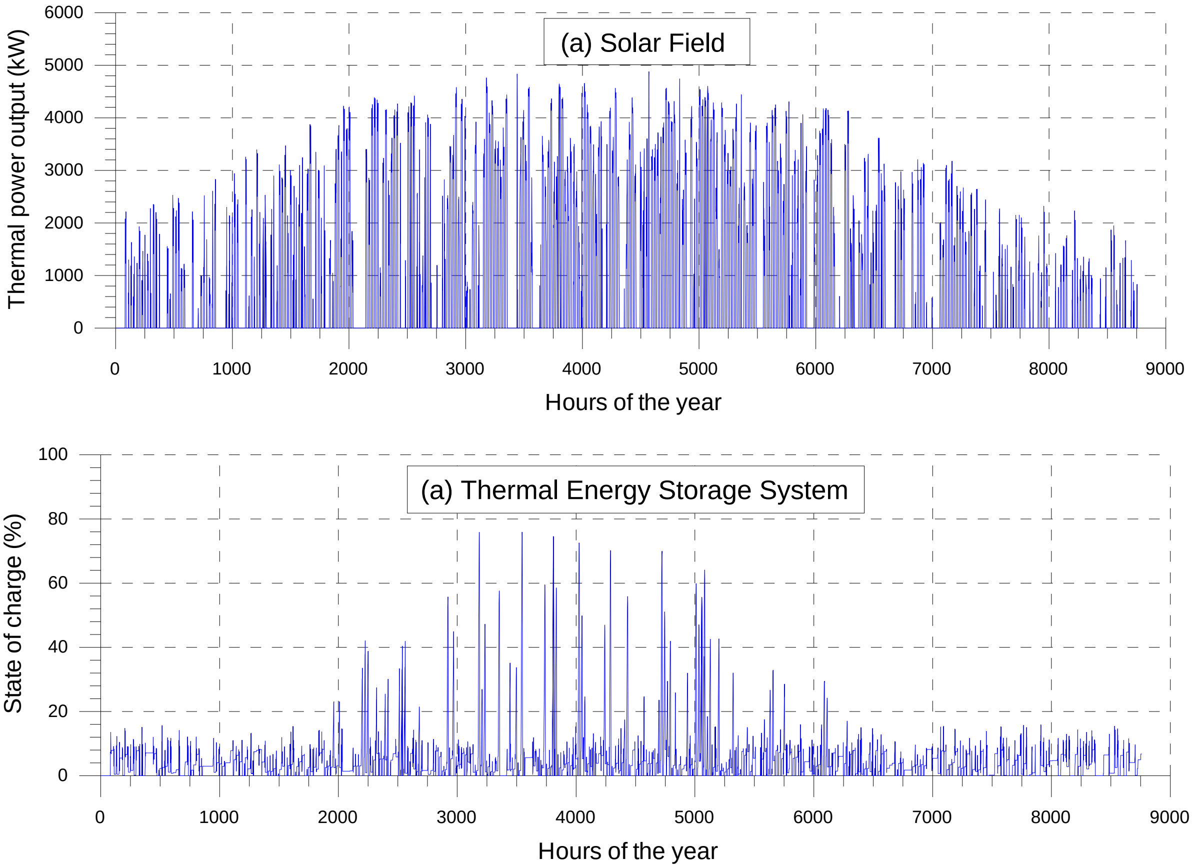

Fig. 6. Thermal power output of the solar field (a) and State of charge of the TES system (b).

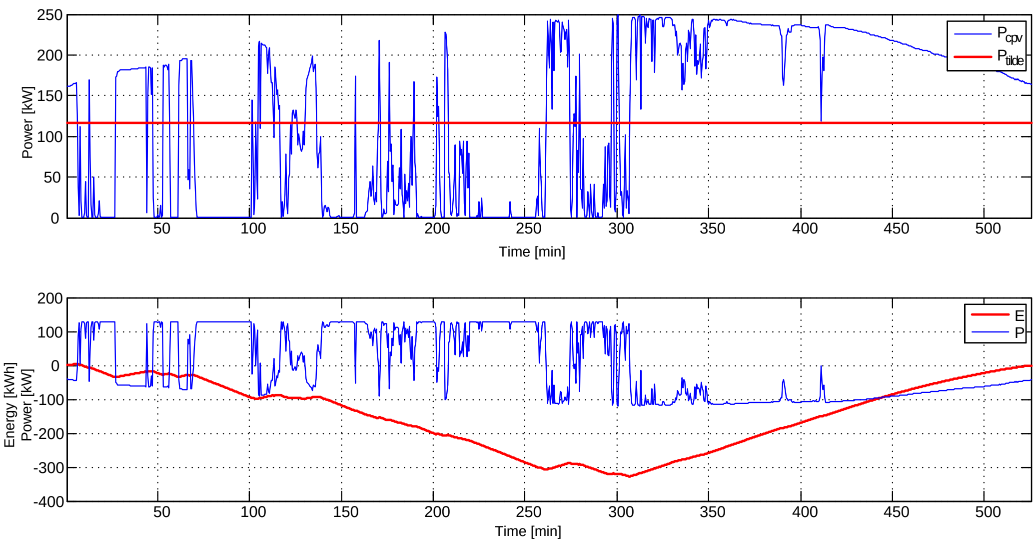

Fig. 7. Evolutions of the CPV power (top graph-blue line), constant delivered power (top graph-red line), battery energy and power (bottom graph-red line and blue line, respectively).

8. Conclusions

A pilot plant based on concentrating solar thermal and photovoltaic power plants integrated with thermal and electrochemical energy storage systems is under construction in the industrial district of Ottana (Sardinia). The main aim of the facility is to demonstrate the possibility to produce electricity form a high variable renewable energy source, such as solar energy, with scheduled profiles as well as to provide ancillary services at distribution level.

In particular, the facility consists of a Fresnel-based CSP plant (600 kWe), a two-tank direct TES system with a capacity of about 15 MWht, a concentrator photovoltaic plant (400 kWe) and an electrochemical storage system with a capacity of 430 kWhe. A specifically developed control systems was developed with the aim of produce electricity with desired power profiles in accordance with weather forecasting. Overall, the expected electricity production is around 1600 MWh per year, 900 MWh/yr from the CSP section and 700 MWh/yr from the CPV one.

Acknowledgements

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