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Operability, reliability and economic benefits of CSP with thermal energy storage: first year of operation of ANDASOL 3

F. Dinter[a,]*, D. Mayorga Gonzalez[b]

[a]*Dr-Ing. Frank Dinter, former Chief Technical Officer (CTO) of Marquesado Solar S.L., Central Termosolar Andasol 3*
[b]*B.Sc. Wirt.-Ing. Daniel Mayorga Gonzalez, Technische Universität Dortmund*

Abstract

This current paper gives a short overview on the results of the study we have conducted to illustrate the operability and reliability properties of CSP plants based on the experience acquired during the first operation year of the CSP generation unit with thermal energy storage (TES) Andasol 3.

Andasol 3 was commissioned in autumn 2011 under the leadership of the company “Marquesado Solar S.L.” and is the third of Solar Millennium developed parabolic trough power plants. The plant is located near Guadix in Andalusia, Spain and has an installed capacity of 49.9 MWe and a thermal storage tank with a capacity of 7.5 hours at full load. The power station was designed to reach a net annual energy production of 165 GWh at typical meteorological year conditions.

Andasol 3 as well as other solar power plants with TES, are not only providers of environmentally friendly solar electricity, but also power sources with operational capabilities that have the potential to support the continued reliability of the electric power system. Furthermore, the flexibility given by TES allows this type of plants to shift electricity generation meeting capacity needs and peak demand resulting in a rise of utility value due to increased revenues.

In order to demonstrate the properties mentioned above and to present the experience gained during the first operational year, Andasol 3 conducted a study based on actual economic and technical data collected during the period past. Our first priority was to explore several operating modes aiming to maximize the economic benefits of the plant and to gain an experience-based foundation that contributes to further developments. For this purpose several operational tests were conducted and anomalies owing to external and internal influence conditions were analyzed and evaluated.

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Keywords: Concentrating Solar Power, CSP, Solar Thermal Energy, STE, Thermal Energy Storage, TES, grid support, grid stability, energy on demand, operation, Andasol 3, parabolic trough

* Corresponding author. Tel.: +49 163 3736 943; Tel.: +27 76 117 2207.
E-mail address: frank.dinter@live.de

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1. Introduction

Renewable energies will play an important role in the energy systems of the future. However, the integration of these new technologies in the actual infrastructure represents a big challenge due to the volatility and lack of operability of renewable resources as PV and Wind. Solar-thermal power plants with TES can contribute to system flexibility supporting the continued reliability of the electric power system. This paper shows selected operational capabilities and advantages of CSP plants with TES that make this possible.

2. Solar-thermal power plant Andasol 3

The solar-thermal power plant Andasol 3 was commissioned in autumn 2011 under the leadership of the project company "Marquesado Solar SL". Andasol 3 is located in the Spanish municipalities Aldeire/La Calahorra – Granada and is the third of Solar Millennium developed parabolic trough power plants. Compared with Andasol 1 & 2 Andasol 3 has already some improvements. With an installed capacity of 49.9 MWe and a thermal storage tank with a capacity of 7.5 hours at full load, the general contractor guaranteed a net annual energy production of 165 GWh [1]. This is achieved thanks to the operation of 210,000 trough-shaped mirrors that collect and concentrate the solar radiation into a focus line, where receiver tubes are fixed. Inside the tubes a heat transfer fluid (HTF) is warmed enabling the transportation of heat from the collector field to a conventional water/steam cycle to run a steam turbine for electric power generation.

2.1. General plant description

The Solar Thermal Power Station consists mainly of the following parts:

- Solar field of parabolic mirrors
- Heat fluid system
- Thermal energy storage system
- Steam generating system and conversion into electricity with nominal output of 49.9 MW_e
- Auxiliary systems

A schematic illustration of the Facility is shown in Figure 1.

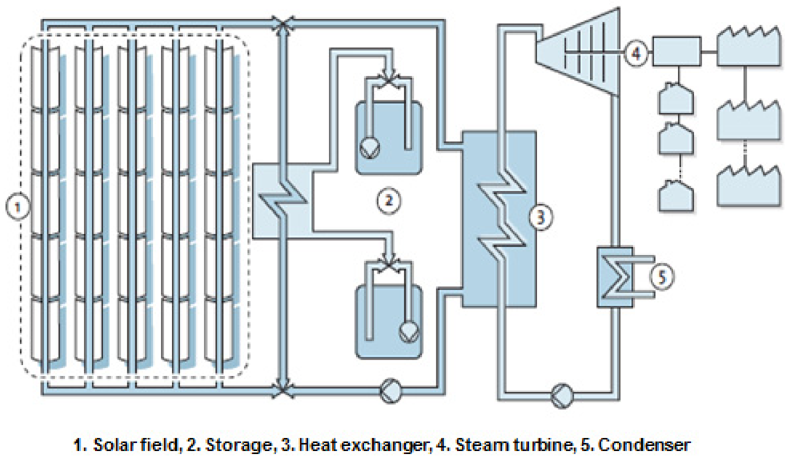

Fig. 1. Schematic illustration of Andasol 3.

Table 1 shows selected technical data of the Solar Thermal Power Station Andasol 3.

Table 1. Technical data of Andasol 3

Solar field	
Size of solar field	497,040 m²
No. of parabolic mirrors	204,288 mirrors
No. of receivers (Dewar tubes)	21,888 tubes, each 4 m long
No. of sensors	608 units
Annual direct normal irradiation (DNI)	2,136 kWh/m²a
Altitude above sea level	1,100 m
Thermal storage	
Storage capacity of heat store	28,500 t salt, 7.5 full load hours
Power plant output	
Turbine output	49.9 MW
Annual operating hours	approx. 4,000 full load hours
Forecast gross electricity generated	approx. 200 GWh/a
Estimated service life	At least 40 years

2.2. Thermal storage system

In order to increase the output of the plant, reduce interruptions resulting from the intermittency of the solar resource and to permit a flexible and controlled supply of electricity, the facility has a thermal storage system consisting of two insulated tanks. The actual storage medium is a molten salt mixture (60/40) of Sodium Nitrate ($NaNO_3$) and potassium Nitrate (KNO_3). During favorable weather conditions the solar energy collected by the solar field is partly used for thermal storage. The heat transfer fluid (HTF) coming from the solar field is diverted to the heat exchangers, where its thermal energy is transferred to the salt flow arriving from the cold tank, where salt is kept liquid at 282 °C . The salt is heated up to 386 °C and pumped into the insulated hot storage tank, where it is stored. For electricity production during the night or periods of reduced radiation, the process is reversed and salt from the hot tank is pumped through the heat exchangers, where the thermal energy of the salt returns to the HTF to be then transported to the conventional water/steam cycle to run the steam turbine. The entire storage system is designed for total 1010 MWh useful storage capacity, which corresponds to 7.5 full load hours. Due to the system's design the steam turbine can be operated between 10 MWe (approx. 36 h) to around 45 MWe (121 MWth for approx. 8.3 h) gross power output from thermal storage in discharge mode.

3. Advantages of CSP with TES

The main advantage of CSP with TES against other renewables energy technologies as PV or wind power is the capability to provide dispatchable energy and power by storing solar energy through thermal energy storage. Due to this feature, the power output of CSP with TES does not depend directly on weather conditions and electricity can even be produced at night or periods with insufficient radiation. Moreover the flexibility and predictability given by the thermal storage system allows generation units as Andasol 3 to provide many of the functions that are needed to support grid operation. In fact, the main difference between this kind of power plants and fossil fueled steam plants is the energy source. Therefore CSP with TES can offer similar operational attributes as conventional power plants. Table 2 shows selected advantages of CSP with TES which were confirmed during the first operation year of Andasol 3: [2, 3]

Table 2. Advantages of CSP with TES

Advantages of CSP with TES	Description
Avoidance of production interruptions resulting from the intermittency of solar radiation	In contrast to large scale PV, CSP power output does not depend directly on the current solar radiation so that the power feed into the grid can be held constant even with strong fluctuations in radiation. This fact gains significance since weather varies and is only partially forecast-able.
Generation of solar power decoupled from weather conditions and time	Conventional solar energy sources without storage produce energy only during the day and with optimal weather conditions. CSP with TES can still generate electrical energy from thermal storage in discharge mode regardless of the current solar situation.
Shifting of power generation to periods of highest demand and 24 hours per day continuous production capability	Energy demand is not constant and energy prices depend on current demand. The TES enable the shifting of power generation meeting demand peeks and avoiding periods of low or negative energy prices in order to generate energy during highest value hours.
Regulation and frequency response	Regulation and frequency response are ancillary services that are generally provided by conventional fossil-fuel generation. CSP generation units can provide this services in the form of either generation or demand reduction to be able to deal with actual demand being higher than forecast demand and plant breakdowns. This is possible through inertia and responsive governors.
Support for power quality	Power systems need reactive power to support and maintain operating voltage levels under both normal and emergency conditions. Furthermore, lower system inertia caused due to the integration of other renewable sources results in larger and faster frequency deviations after occurrence of abrupt variations in generation and load. CSP with TES operating conventional synchronous generators can support power quality through reactive power support, dynamic voltage support and inertia response.
Contribution to system flexibility supporting the integration of other RE sources	Regional system operator must be able to meet annual peak loads, as well as to have sufficiently flexible generation to ensure reliability during significant unplanned generator and transmission outages. With the increasing penetration of wind and solar PV generation, there is now growing variability of supply. CSP with TES can contribute to system flexibility supporting the integration of other RE sources.

These entire upper mentioned advantages are documented and proved by real operational data of Andasol 3 in the next chapter.

4. Operational flexibility of Andasol 3

Aiming to demonstrate the properties outlined above, several tests were conducted and anomalies due to external influence conditions were analyzed and evaluated. Selected results of the study made are presented below

4.1. Continuous generation – Base-load mode

Between September 11 and 18 2012 a test was performed to investigate the capability of Andasol 3 to produce energy continuously without interruptions. The objective of the experiment was to obtain concrete evidence of the Base-load capability of the plant. Over this period the plant generated energy in two different operating modes: During sun hours the heat collected in the field served to generate electric power feeding into the grid and the surplus heat was used to charge the thermal storage. Under these conditions the plant reached a gross power output of 35 MWe on average. During the remaining time the plant was operated in discharge mode. In this case, the required heat for steam production was provided by the thermal storage, reaching a gross power output of 25 MWe. Figure 2 gives an overview on the operation of Andasol 3 during the test. The yellow graph line shows the Direct Normal Irradiance (DNI) values given in W/m^2. The gross power output of the plant is given by the green graph line in MWe. The blue graph line shows the hot salt tank level in %.

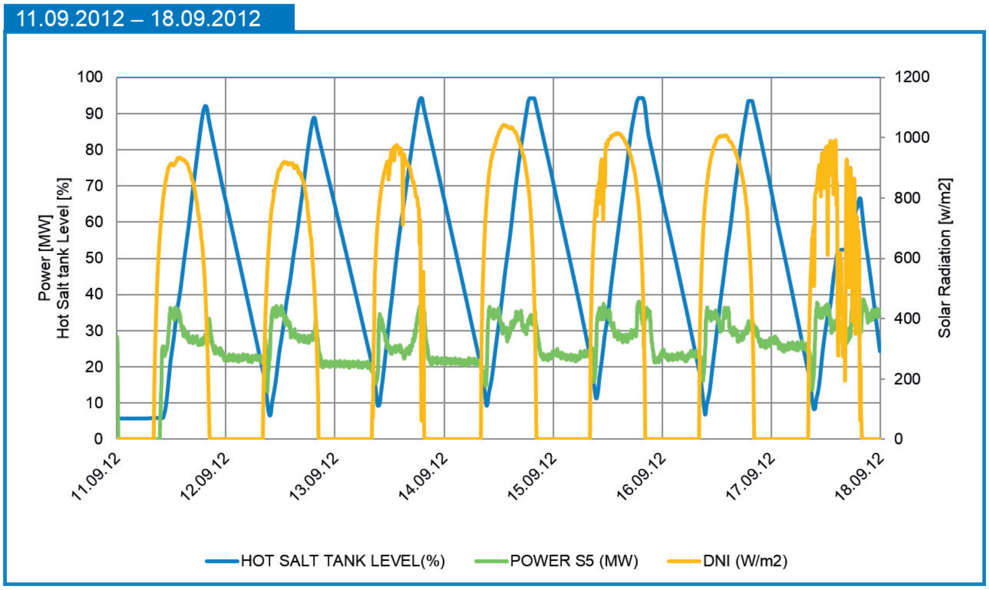

Fig. 2. 24 h continuous generation over several days.

4.2. Avoidance of production interruptions resulting from the intermittency of solar radiation

Thanks to the climatic conditions of September 17, the last day of the continuous generation test, it was possible to gather critical data to show a further feature of the power station Andasol 3. As shown in Figure 3, the Direct Normal Irradiance showed strong fluctuations during that day, reaching a minimum value of 192 W/m^2 at 16:15 in the afternoon. Figure 3 clearly shows that even during the collapse of the DNI the power output was maintained in an acceptable stable range. It is important to note that the jump of the green graph line registered between 9:00 and 10:00 is due to the operating mode change and it is a phenomenon that can be observed in all test days (see also

Figure 2). The cause of this malfunction was identified during the test. It caused during switching from storage to solar field and has been corrected directly after recognizing.

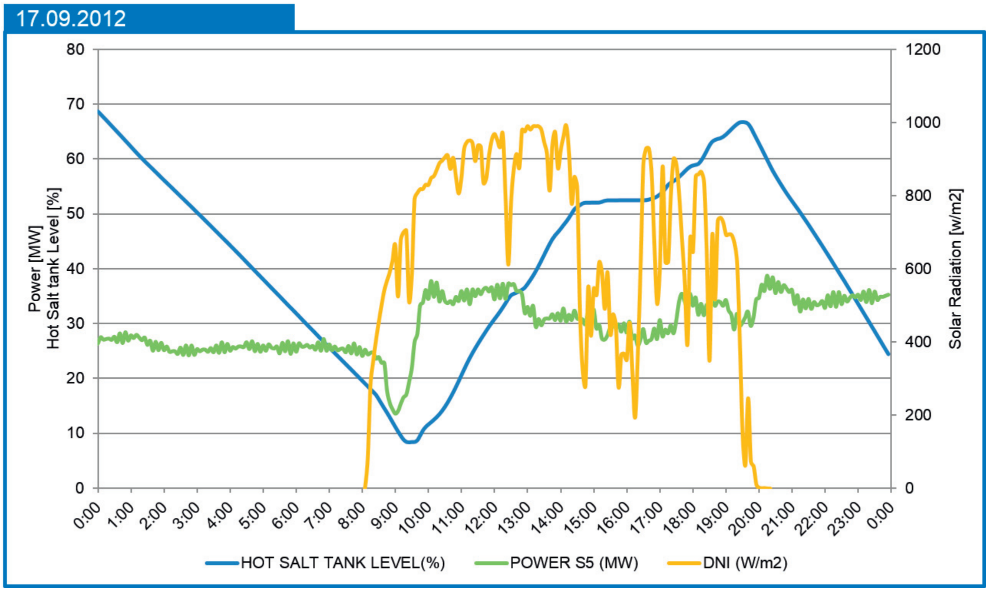

Fig. 3. Operation of Andasol 3 on 17 September 2012.

4.3. Dispatchability tests

Aiming to explore the ability of Andasol 3 to adjust its power output on demand, several dispatchability tests were conducted throughout March, 2012. In these trial runs the power station was operated according to an output plan, which was given by the grid operator. Figure 4 illustrates the planed output (blue bars) in comparison to the actual output (green bars) during the dispatchability test of 22 March 2012. The yellow shape highlights as a reference the period of time in which DNI values would be sufficient to operate the power station solely from the solar field. The bar chart clearly shows the suitable response of the power station at test conditions. All registered deviations represent an error rate below 5 per cent of the planned values. Moreover, the tests allowed to obtain evidence to proof the capability of Andasol 3 to efficiently shift energy and provide ancillary services. During the experiments done, ramp rates of up to 5.65 MW/min under stable conditions were recorded, demonstrating the operability of Andasol 3 by a preset output plan.

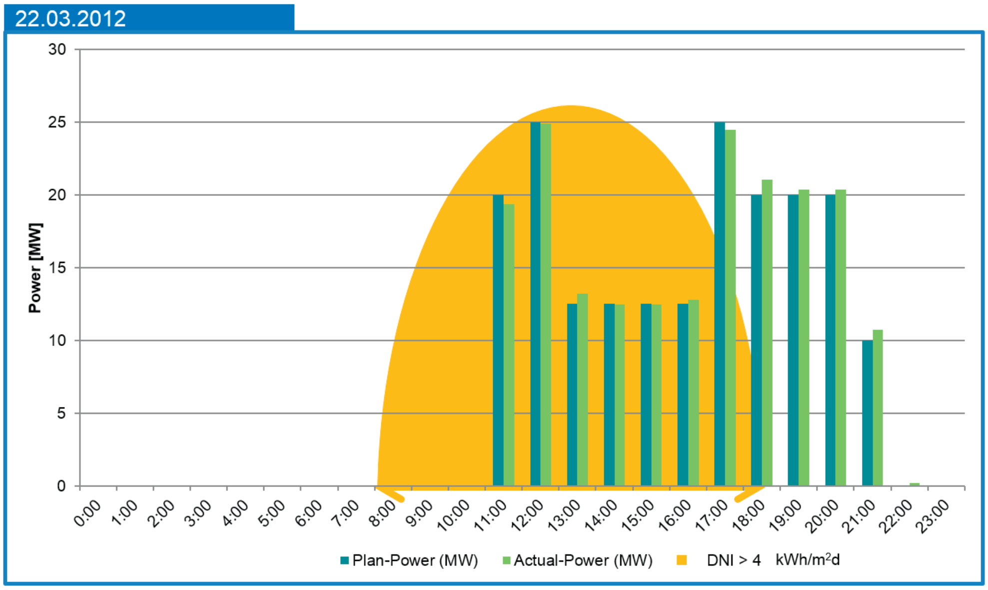

Fig. 4. Dispatchability test on 22 March 2012

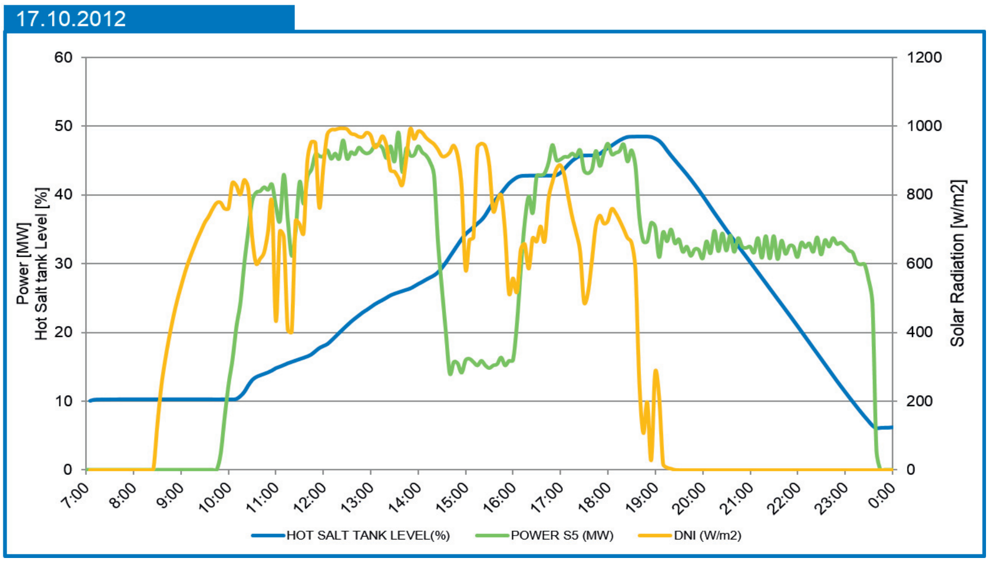

Fig. 5. Operation of Andasol 3 on 17 October 2012

4.4. Power reduction requests

The properties of Andasol 3 discussed above were demonstrated under controlled test conditions. In order to validate this results during the standard operation of the plant, further data was collected and analyzed throughout year 2012. Additional supporting evidence for the flexibility of the plant could be found through the power reduction requests, which were instructed by the Spanish grid operator. From September to December, there were 11 events where Andasol 3 was unplanned requested to reduce its net load to 15 MWe. Figure 5 gives an overview on the operation of the plant during the power reduction request of 17 October. The request started at 2:15 pm and ended at 4:00 pm. The bar chart in Figure 6 shows the gross power output of Andasol 3 during this event. It is important to point out that the heat collected during the power reduction request was not lost. It was used to charge the TES, so that this event did not lead to an output deficit as shown in Figure 5. The relation between generation dispatch and revenue impact is discussed in the next chapter.

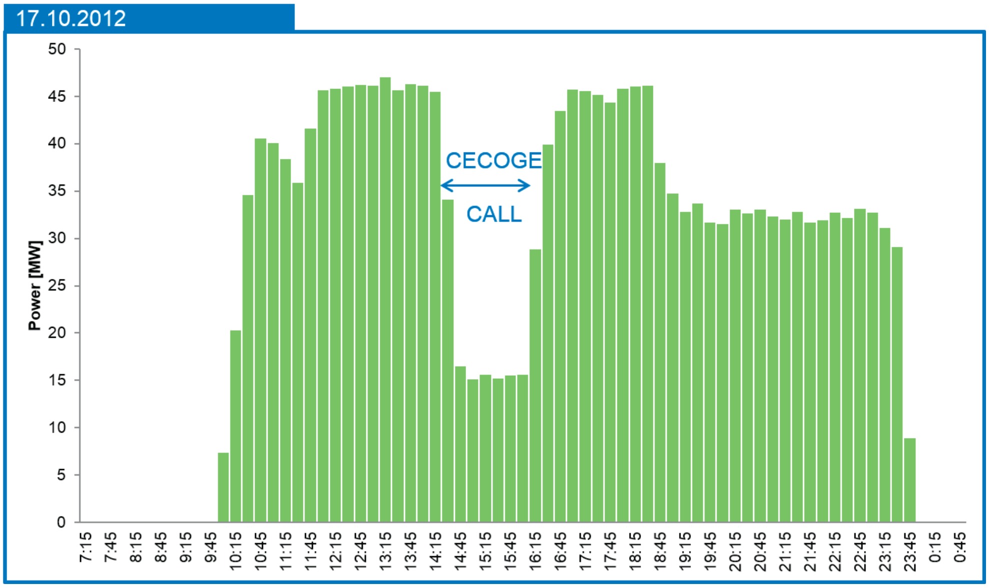

Fig. 6. Power gross output of Andasol 3 during power reduction request.

4.5. Economic value of dispatchable generation

In 2012 the Spanish legislation allowed operators of solar-thermal power stations to choose between a fixed price and a “premium” added feed-in remuneration system. The “premium” added alternative has the peculiarity of reflecting the MWh prices negotiated in the electricity market since the guaranteed feed-in remuneration is made up of the sum of the market price plus a prime established in the corresponding regulations. Under these conditions the operator of the plant has the capability of optimizing the revenues by shifting of generation to highest value hours. Figure 7 illustrates the behavior of the pool market price which is used to calculate the premium feed-in tariff for two selected days. As shown in this chart the market price on 1 July 2012 is marked by strong fluctuations reaching a minimum of 17 €/MWh and a maximum of 70 €/MWh.

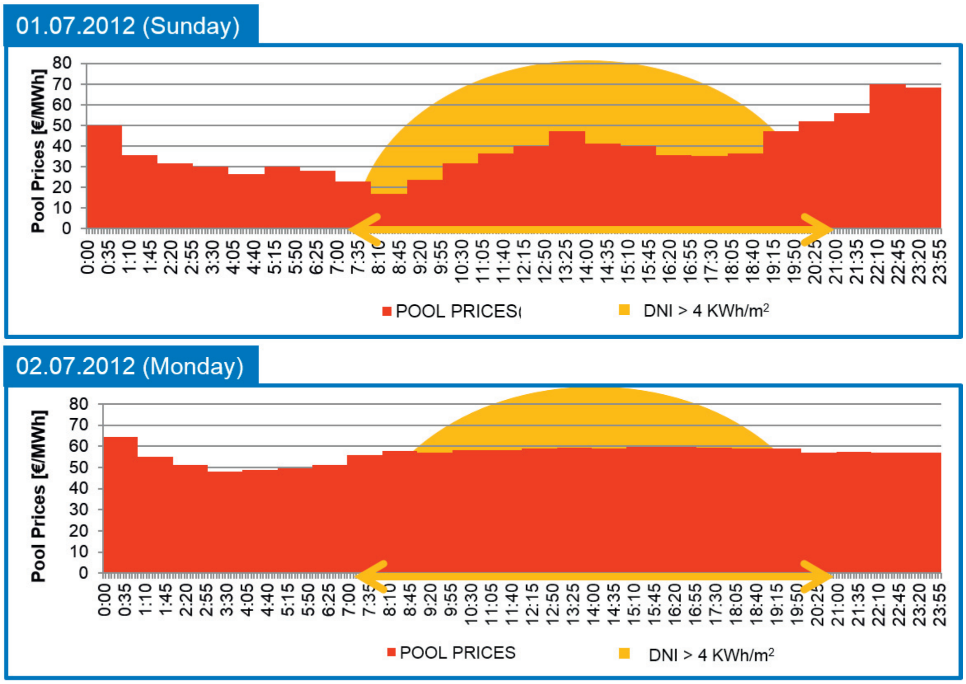

Fig. 7. Pool market price development

The actual operation of Andasol 3 at that day is shown in Figure 8. It can clearly be seen that the plant produced a high output and charged the storage to a certain level until DNI decreased. When this happened grid-connected PV systems also reduced their electrical output and the pool price increased during evening hours because of high electricity demand. Andasol 3 kept producing electricity with a relatively high output during higher pool price hours.

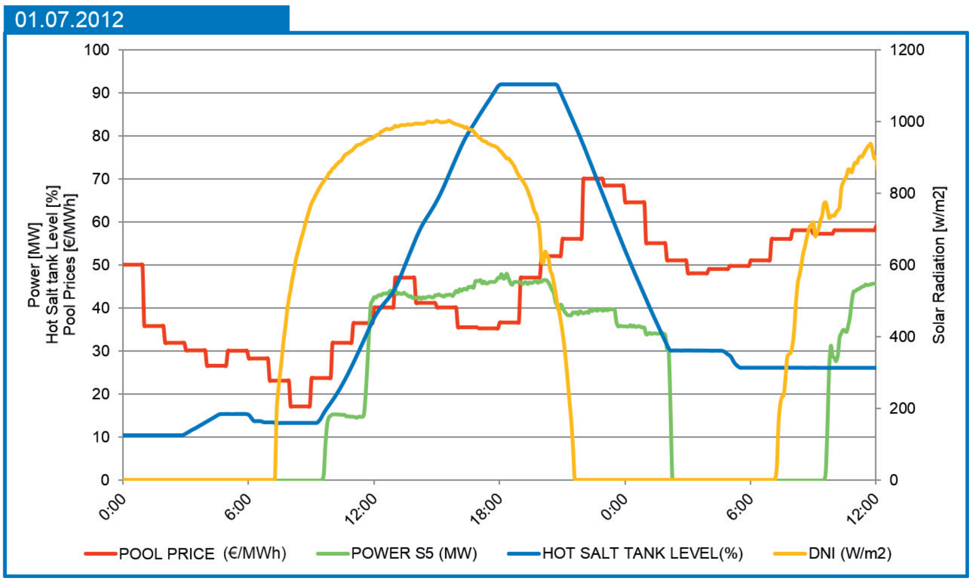

Fig. 8. Operation of Andasol 3 on 1 July 2012.

Figure 9 shows the effect of power shifting according to the market price development on that day. About 50 MWh were shifted from the low pool price morning hours while starting the plant with a lower output between 10 and 12 am, to a high pool price period in the evening hours. This generation shifting represents just 8 % of the total power output of that day resulting in a revenue increase of 1,500 € which means an increase of 5 % in this particular example.

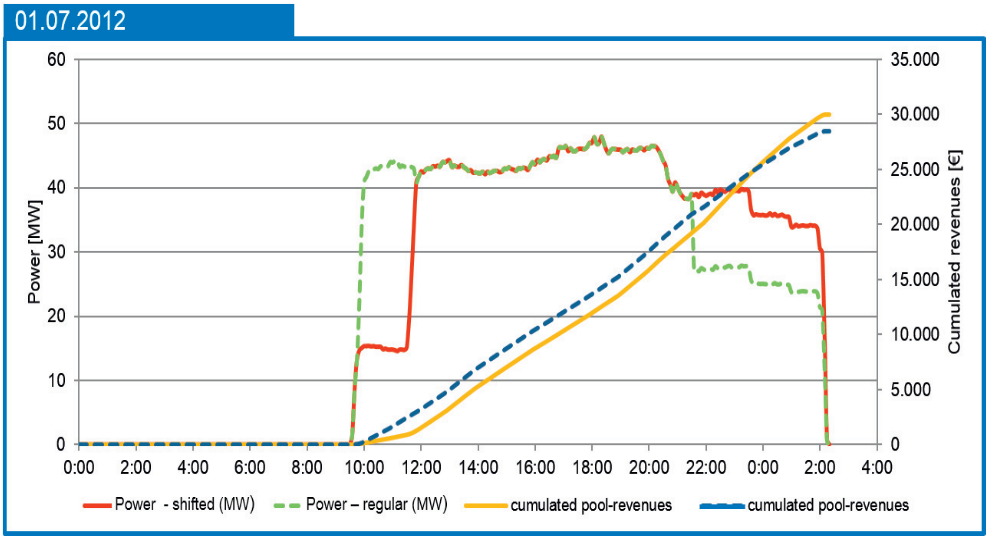

Fig. 9. Results of optimization

5. Conclusions

This paper demonstrates that CSP with TES has features, which allow a similar operability as a conventional fossil-fired power plant. It can deliver power on demand, adapt its output to the actual energy market situation through generation shifting and even produce electricity continuously and reliable during 24-hour operation cycles. Furthermore, due to this properties and the use of a conventional synchronous generator this kind of power units can provide ancillary services as regulation, frequency response and support for power quality in the local grid.

We thank the Andasol 3 team and especially the board members of Marquesado Solar S.L. allowing us to use actual data from the plant to show the benefits of CSP with TES.

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