Operation Experience of a 50 MW Solar Thermal Parabolic Trough Plant in Spain

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Abstract

This paper explains how a parabolic trough plant with storage system works and how it can support the grid operation. All requirements and experiences will be explained with the example of 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 MW_e and a thermal storage tank with a capacity of 7.5 hours at full load. This power station was designed to reach a net annual energy production of 165 GWh_e at typical meteorological year conditions.
Andasol 3 as well as other solar power plants with Thermal Energy Storage (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 to meet capacity needs and peak demands.
This paper presents the experience gained during the first operational years of Andasol 3.

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

1. Introduction

The world's largest source of renewable energy is the sun. The part of the earth directed to the sun is permanently exposed to a radiant power of $1.73*10^{11}$ MW, which is equal to the capacity of 173 million big coal power plants. Each year the sun emits over 1 billion TWh of energy to the earth, which is equal to 60,000 times the world's electricity needs. From a mathematical perspective, less than 3 % of the surface area of the Sahara would be sufficient to meet the world's energy demand with solar power plants. Unfortunately the utilisation of solar energy is not that easy due to the low power density. [1]

One big challenge of the renewable energies is the volatility and lack of operability of 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 some operational advantages of CSP plants with TES that make integration into current infrastructure possible.

2. Situation in Spain for Solar thermal power plants

The first commercial Solar Thermal Energy (STE) plants began operating in California in the mid-eighties; however, at the time the renewable energy market was paralyzed due to the fall in fossil fuel prices and the cancellation of public incentives. While other renewable resource based technologies for electricity generation began to receive support at the end of the nineties, it was only in 2004 that a framework making commercial power plant construction possible was established in Spain.

In the last years, STE in Spain has grown significantly. Its weight within the renewables environment is becoming relevant, but even more so, is its impact on economics, society and reducing energy dependence.

Although based on different models, this was also the case in the US. The first plants to go into operation were the solar tower plant PS10 in Spain at the beginning of 2007, and a short time later, the Nevada Solar One in the US.

This solar thermal renaissance in Spain and the US emanated from the response to the need to meet political renewable energy penetration targets and reduce energy dependence. Furthermore, interest in this technology was awoken by the establishment of a series of incentives, such as the premium feed-in tariffs for renewables, the requirement to use renewables, along with the existence of the resource in both countries.

Most of the plants are logically concentrated as the highest supply is available, especially Andalusia, in southern Spain. Spain now is the world leader in this technology. About 2.500 MW_e in TES power plants are installed in Spain as shown in Figure 1. [2]

Fig. 1. STE Power Plants in Spain and location of Andasol 3

3. 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 already has some improvements. With an installed capacity of 49.9 MW_e 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_e [3]. This has been achieved through the operation of 204,288 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.

3.1. 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 2.

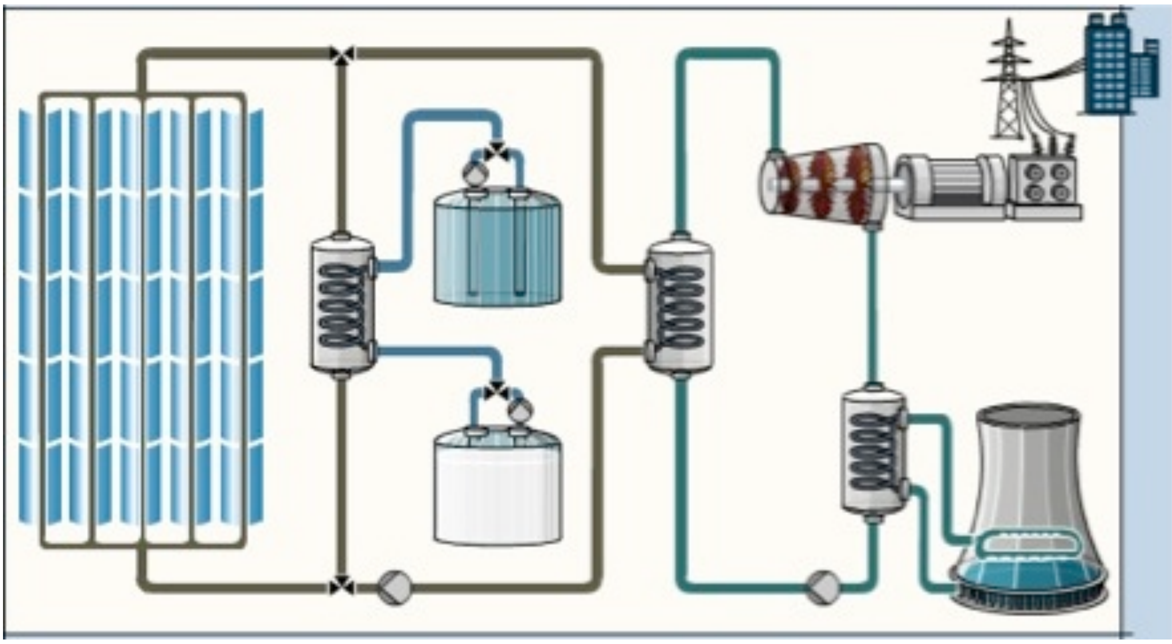

Fig. 2. Schematic illustration of Andasol 3

Table 1 shows selected technical data of the Solar Thermal Power Station Andasol 3. [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_e
Annual operating hours	approx. 4,000 full load hours
Forecast gross electricity generated	approx. 200 GWh_e/a
Estimated service life	At least 40 years

Table 1. Input parameters and performance indicators of exemplary configurations

3.2. 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 HTF coming from the solar field is diverted to the heat exchangers. There 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 then be transported to the conventional water/steam cycle to run the steam turbine. The entire storage system is designed to produce a total 1010 MWh_{th} storage capacity, which corresponds to 7.5 full load hours. Due to the system's design the steam turbine can be operated between 10 MW_e (approx. 36 h) to around 45 MW_e (121 MW_{th} for approx. 8.3 h) gross power output from thermal storage in discharge mode.

4. Operational flexibility of Andasol 3

This chapter explains why CSP with TES is becoming one of the electricity supply technologies for the future. The main advantage of CSP with TES compared to other renewable energy technologies such as PV or wind power, is the capability of CSP to provide dispatchable energy and power, by storing solar energy through TES. Due to this feature, the power output of CSP with TES does not depend directly on weather conditions. Electricity can even be produced at night or during 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 plant and a fossil fueled steam power plant is the energy source. Therefore CSP with TES can offer similar operational attributes as conventional power plants.

During the commissioning and first operation of Andasol 3, many tests and demonstrations of reliability were performed which are described in the following. [4]

4.1. Dispatchability tests

In Spain, CSP plants have to demonstrate the ability to adjust its power output on demand.
The Andasol 3 dispatchability tests were carried out in March, 2012. During these trial runs the power station was operated according to an output plan, which was given by the grid operator. Figure 3 illustrates the planned output (blue bars) in comparison to the actual output (green bars) during the dispatchability test of 22 March 2012. The yellow shaded reference highlights 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 enabled evidence to be obtained to prove the capability of Andasol 3 to efficiently shift energy and provide ancillary services. During the experiments, ramp rates of up to 5.65 MW_e/min under stable conditions were recorded, demonstrating the operability of Andasol 3 by a preset output plan. The plant very precisely produced the given forecast.

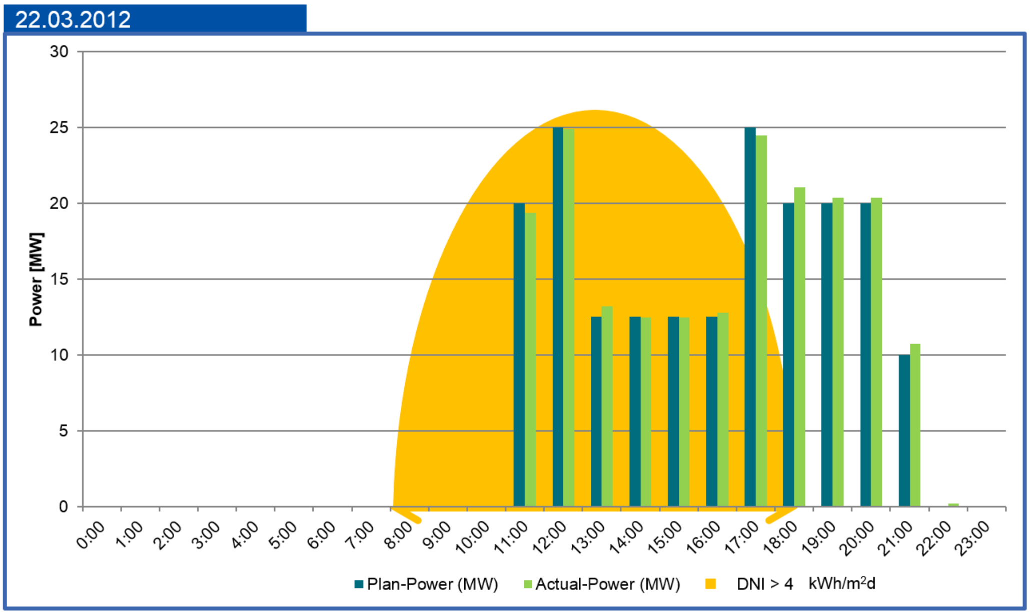

Fig. 3. Dispatchability test on 22 March 2012

4.2. Power reduction requests

CSP plants with TES have another restriction in operation. 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 unexpectedly requested to reduce its net load to 15 MW_e. Figure 4 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 4 shows the gross power output of Andasol 3 during this event.

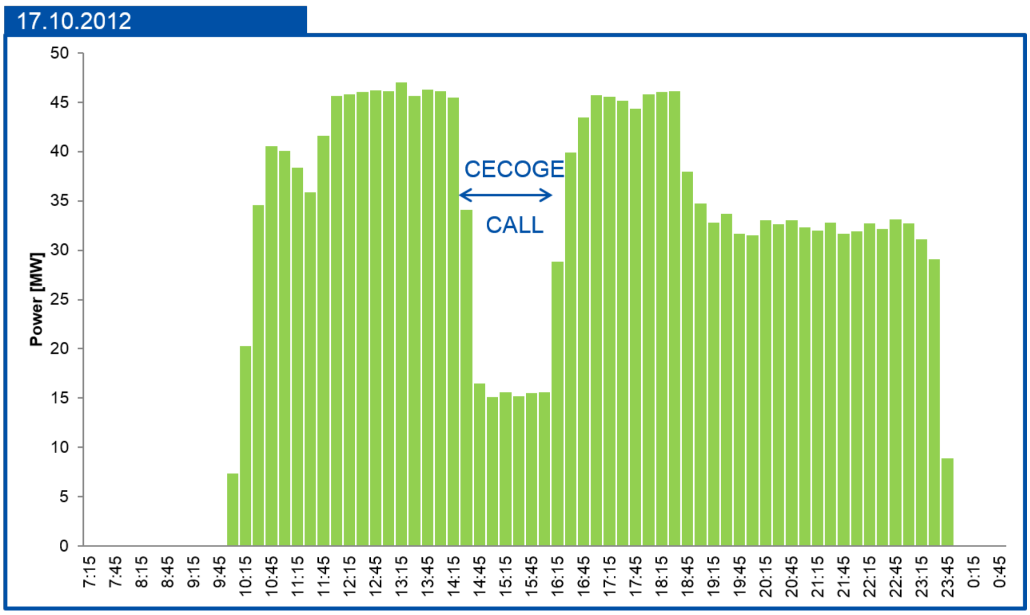

Fig. 4. Power gross output of Andasol 3 during power reduction request

It is important to point out that the heat collected during the power reduction request was not lost but used to charge the TES, so that this event did not lead to an output deficit as shown in Figure 5. The yellow graph line shows the Direct Normal Irradiance (DNI) values given in W/m^2. The green graph line gives the gross power output of the plant in MW_e. The blue graph line shows the hot salt tank level in %.

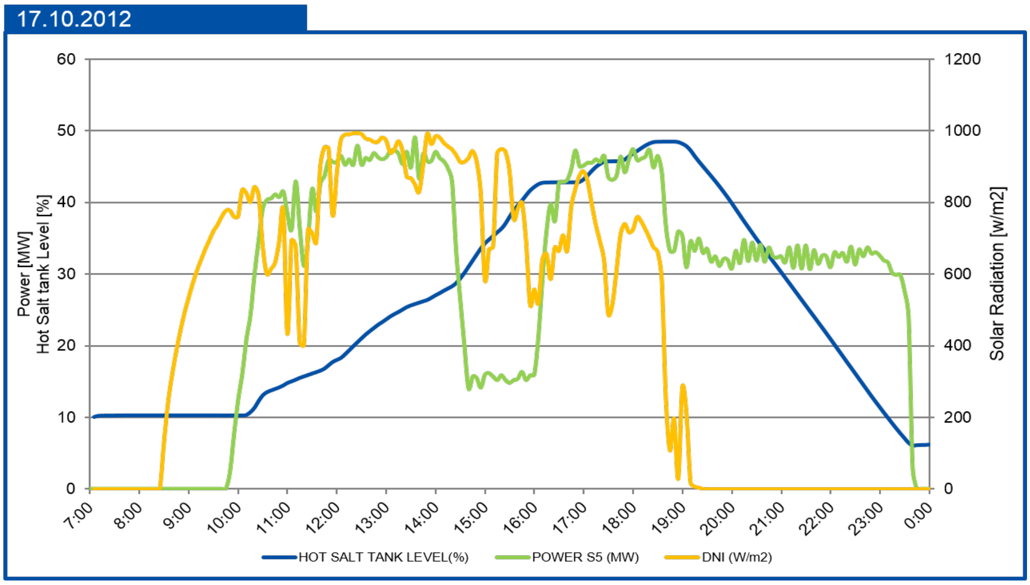

Fig. 5. Operation of Andasol 3 on 17 October 2012

4.3. Continuous generation – Base-load mode

Understandably the argument exists that renewable energies may be volatile in energy supply as wind can only deliver when the wind is blowing or PV only when the sun is shining. However STE plants with storage system can deliver a 24 h production without disruption as shown in the time period between September 11th and 18th 2012 (see Figure 6). The plant produced 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 MW_e 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 MW_e.

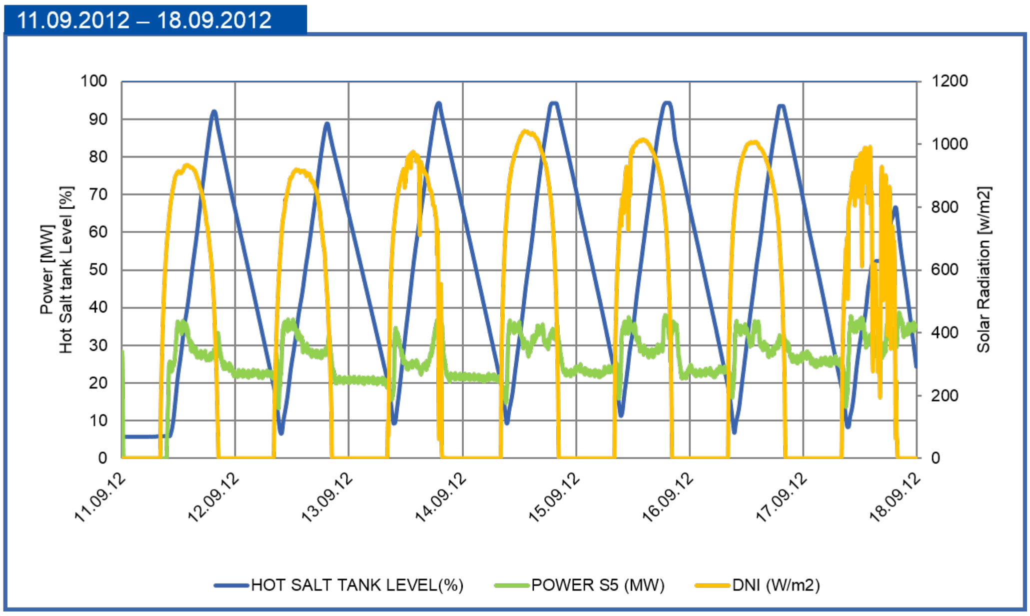

Fig. 6. 24 h continuous generation over several days

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

Due to the climatic conditions of September 17th, 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 7, the Direct Normal Irradiance (DNI) varied intensively during that day, reaching a minimum value of 192 W/m^2 at 16:15 in the afternoon. Figure 7 clearly shows that even during the collapse of the DNI the power output was maintained in an acceptably 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. The cause of this malfunction was identified during the tests as the result of switching from storage to solar field, but has been corrected directly after recognition.

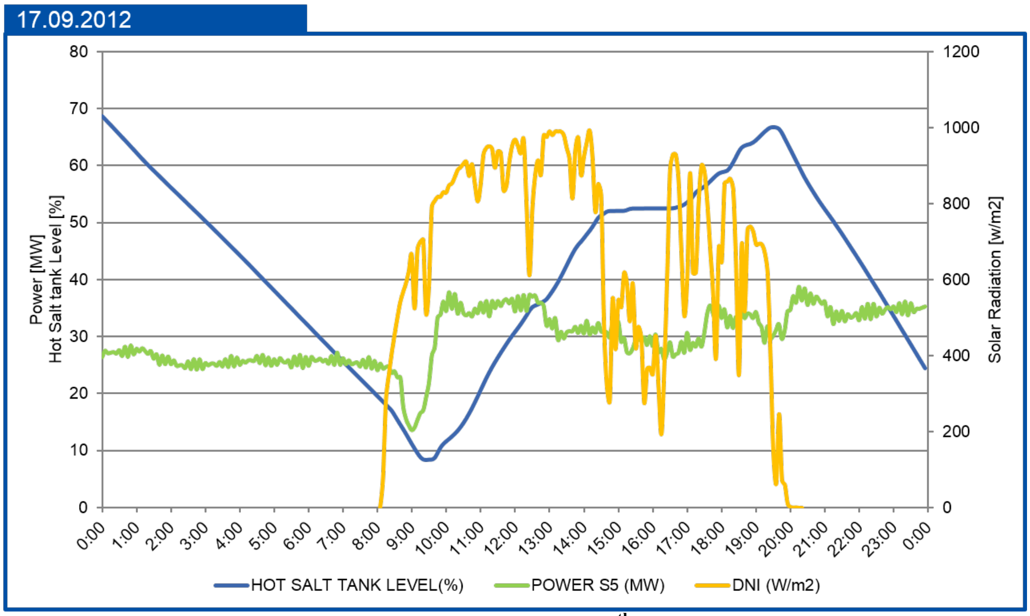

Fig. 7. Operation of Andasol 3 on 17th September 2012

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$_e$ 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.

The current operation of Andasol 3 on 1st July 2012 is shown in Figure 8. The red line in this chart shows the market price on that current day with strong fluctuations reaching a minimum of 17 €/MWh$_e$ and a maximum of 70 €/MWh$_e$. It can clearly be seen that the plant produced a high output and charged the storage to a certain level until DNI decreased. At the time grid-connected PV systems were already reducing 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.

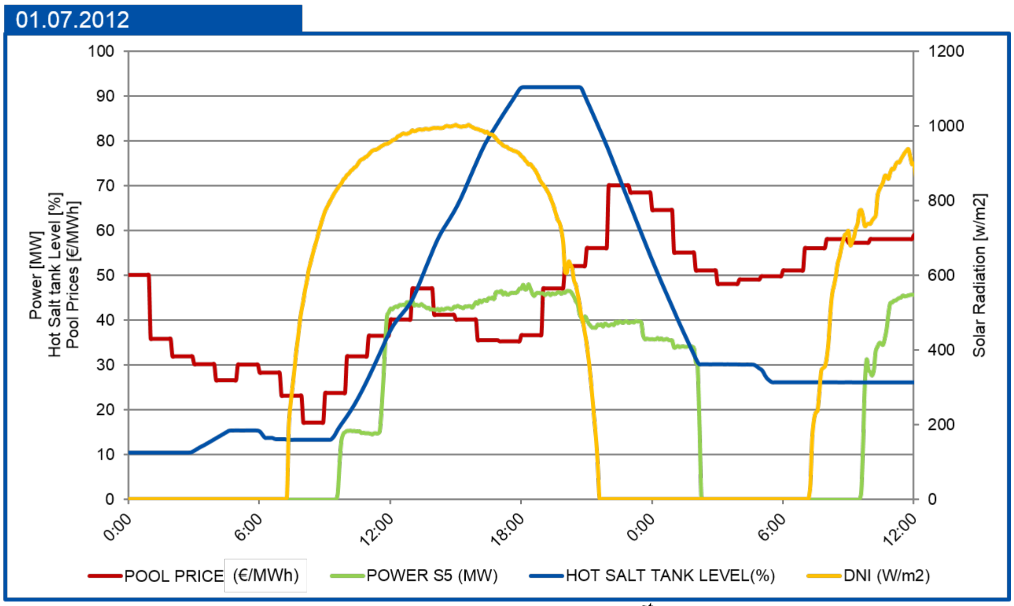

Fig. 8. Operation of Andasol 3 on 1st July 2012

Figure 9 shows the effect of power shifting according to the market price development on that day. About 50 MWh_e 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.

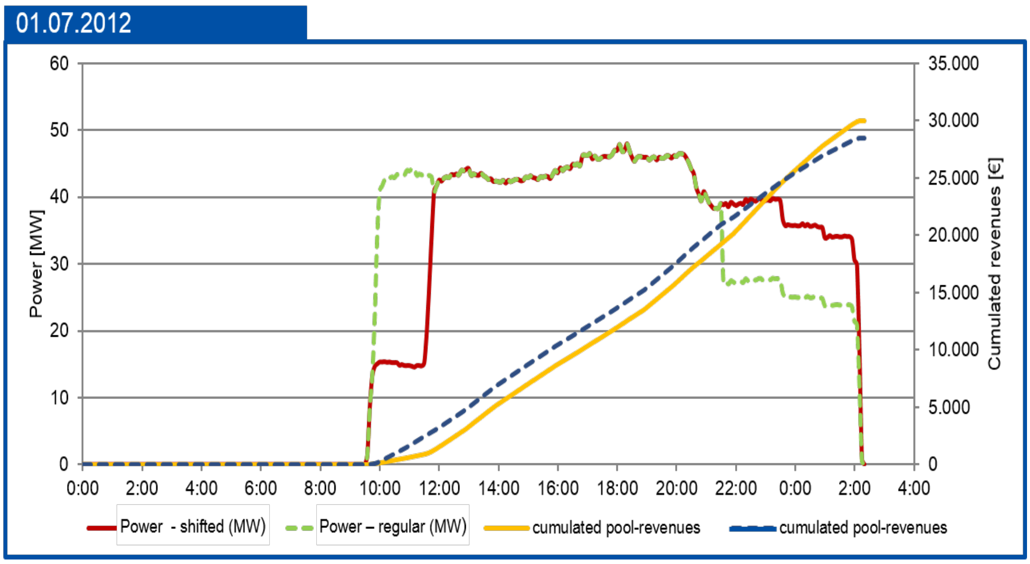

Fig. 9. Results of optimized operation

4. Conclusion

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 reliably during 24-hour operation cycles. Furthermore, due to these 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.

These advantages of CSP with TES will allow installing further CSP plants in the sunny regions of the world, especially at places with high DNI with more than 2,000 kWh/m^2a. These countries are predestined to use CSP for electricity production and for industrial heating purposes to reduce CO_2 emission and also for compatible energy supply. CSP is already compatible in technology and will soon also be in costs.

Acknowledgements

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