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THERMAL ENERGY STORAGE WITH CONCENTRATED SOLAR POWER FOR A MORE RELIABLE AND AFFORDABLE ELECTRICITY TO INDUSTRIAL APPLICATIONS

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Abstract

The implementation of Concentrated Solar Power for industrial applications has become a topic of high interest both for CSP plants developers and potential client industries. The integration of CSP for industrial processes can be done follow various needs ranging from power generation to steam generation, drying, heating and even cooling applications. Although the interest for the latter "less common" applications has gained more importance for researchers over power generation, this options has still a lot of interest for industrials especially when this power generation can be more flexible and cheaper thanks to a good Thermal Storage System integration and to encouraging market conditions and availability of the solar resource.

In this paper we studied the possibility for large industrial facilities to exploit small scale CSP plants as fossil fuel and grid saving mechanism considering the variable grid pricing and an appropriate TES integration.

Keywords: *Concentrated Solar Power (CSP), Thermal Energy Storage (TES), industrial application…*

1. Context

Since its creation, IRESEN has placed small scale CSP-ORC systems among the main priorities. Such systems are considered as possible solutions for small power consumers (below 5MW). In this regard a first demonstration and research pilot CSP-ORC plant of 1MW capacity is being commissioned at the green energy park in Benguerir, Morocco.

During the project planning period, the development of an appropriate thermal storage add-on to increase the dispatchability of the plant, and help demonstrate the benefits of storage for this package and the potential clients.

Fig. 1: Picture of the 1MW CSP-ORC plant under commissioning in Benguerir, Morocco

Industry is out of doubt one of the most energy intensive sectors, standard energy needs for industry cover electricity for machines supplying, electrolyze processes, cooling, lightning and others. On the other hand, various needs for heat at various grades and on various ways (hot air for drying, high pressure steam, furnaces, processes preheating…), this heat is mostly obtained via the combustion of fossil fuels but can also be produced by electricity at higher cost while many industrial processes based on fossil fuel are being supported by others based on electricity such as for steel industry.

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The costs of fossil fuel have decreased significantly during the last few years, this has put CSP for heating applications in a less comfortable position, although this can be regarded as a temporary situation which can change following geopolitical conjuncture.

On the other side, electricity prices are more or less constant in many countries regardless of fossil fuel prices. The price of electricity from the grid are generally linked to the power demand or load either at a national or regional level. In Morocco for example, electricity from the national grid (ONEE) follows a time dependent pricing approach for industrial consumers (middle and high voltages), the highest prices correspond to the hours of higher power demand (peak hours and also super peak hours for high voltage consumers).

Tab. 1: ONEE power pricing in Morocco for middle and high voltage consumers (ONEE, 2016)

Pricing options 60kV	Yearly capacity price per	kWh price (MAD/€)			
	kW/year (MAD/€)	SHP	HP	HPL	HC
Very long use	1 933,23 / 172.45	0,8482 / 0.075	0,7725 / 0.069	0,6284 / 0.056	0,5733 / 0.051
Long use	773,96 / 69.04	1,6692 / 0.148	1,0457 / 0.093	0,7561 / 0.067	0,5733 / 0.051
Short use	386,97 / 34.52	2,2166 / 0.197	1,2280 / 0.011	0,8793 / 0.078	0,5989 / 0.053
Emergency use	343,30 / 30.62	2,5715 / 0.229	1,4246 / 0.127	0,9077 / 0.081	0,6029 / 0.054
Capacity Reduction Factor		1	0,8	0,6	0,4
Pricing options 150kV & 225kV	Yearly capacity price per	kWh price (MAD/€)			
	kW/year (MAD/€)	SHP	HP	HPL	HC
Very long use	2 160,77 / 192.75	0,8652 / 0.077	0,7881 / 0.071	0,6419 / 0.057	0,5908 / 0.053
Long use	865,31 / 77.19	1,7696 / 0.158	1,1087 / 0.099	0,7871 / 0.070	0,5908 / 0.053
Short use	431,82 / 38.52	2,4909 / 0.222	1,3800 / 0.123	0,9251 / 0.082	0,6195 / 0.055
Emergency use	383,09 / 34.17	2,8897 / 0.258	1,6010 / 0.142	0,9550 / 0.085	0,6236 / 0.056
Capacity Reduction Factor		1	0,8	0,6	0,4

In this configuration, the price of electricity during super peak hours can raise to more than three times the base price at off load hours. Peak and super peak hours are generally between 6:00 and 10:00 in the evening. This opens a large opportunity for large industries which have large power needs and whose processes are working continuously to integrate CSP with storage in order to use less electricity from the grid especially during the evenings.

By offering the possibility to extend a CSP plant production to the evening, thermal energy storage has then a double benefit if we consider a "grid saving" approach:

- Benefit of higher grid prices during the evenings allowing the operator to profit from a better competitiveness versus grid power;
- Benefit of generally lower ambient temperatures which contribute to a higher power cycle efficiency, hence a higher production and a better economic efficiency;

2. Methodology

The Noor-Ouarzazate 1 plant is seen as a breakthrough in terms of CSP competitiveness with a kWh price around 15 cents, nevertheless, this price might seem very high for basic Moroccan consumers which do not pay electricity on a time based pricing. For middle voltage and high voltage clients the variability of electricity price between peak and off peak hours offers a high potential for the integration of CSP with storage.

The aim of this paper is to study the impact of integrating a small CSP unit with thermal storage to supply an industrial installation. This can be achieved by simulating the CSP plant production with a home developed model at IRESEN based on the 1MW CSP-ORC plant of Benguerir. Although this model is very simple, it was successfully compared in many occasions with more proven tools such as GREENIUS (J. Dersch). The simulations will be integrated on an economical balance taking into account all consumers specifications and electricity pricing (V. Quaschning et al., 2011).

2.1. Plant simulation input

The simulations for production are based on three calculation modules:

- The solar field performance: the total heat production of the solar field is based on the weather conditions, mainly, the Direct Normal Irradiation or DNI, the ambient temperature and the solar angles (Azimuth and Elevation) combined with the solar collector performances (A. Soteris Kalogirou, 2004).
- Storage and heat dispatch: this module defines the amount of heat to be stored and the share to be dispatched, it also calculates the charging level of the storage system based on the solar field output and the dispatched heat (J. Pacheco, 2002).
- ORC module: the ORC performance is calculated using the supplier's correction curve, the ambient temperature and the amount of heat dispatched by the solar field and storage.

Among the available weather data sets, actual measurements data were preferred over satellite data, the data set used for the simulations contains a measurement value for each 10 second and was obtained with a high precision tracker based weather-station.

Concerning the solar field, the adopted configuration consists of 16 loops with 4 linear Fresnel collectors on each, the total surface area of the mirrors is 26500m^2, and the nominal solar field capacity is 11.3MW$_{th}$ at a reference DNI of 750kWh/m^2 (A. Haberle et al., 2002). The heat transfer fluid enters each solar field loop at 185°C and exits at 315°C.

The storage technology is thermocline with Quartzite rocks bed, the heat capacity is 27MWh equivalent to 5 storage hours. Charging of the storage system is given priority over ORC operation, which is similar to a partial production shifting mode.

Discharging is oriented to the peak hours while the charging rates are based on the season and the average solar irradiation for the few hours preceding the calculated time slot, this means that during winter for example, a full production shifting occurs to the peak hours while in summer there is only a partial charging of the storage during the first hours of operation and depending on the amount of heat produced by the solar field.

The ORC set used on the simulations has a nominal net capacity of 1MW at an ambient temperature of 20°C and heat input of 4.8MW. The efficiency of the power cycle varies proportionally to the heat input and inversely to ambient temperature.

2.2. Economic configuration

The selected potential client for the simulated plant is an industrial unit connected to the national grid at high voltage with a medium/long consumption contract (3500 to 6000 hours per year). In this case the price of electricity will follow 4 different time slots as presented on figure.

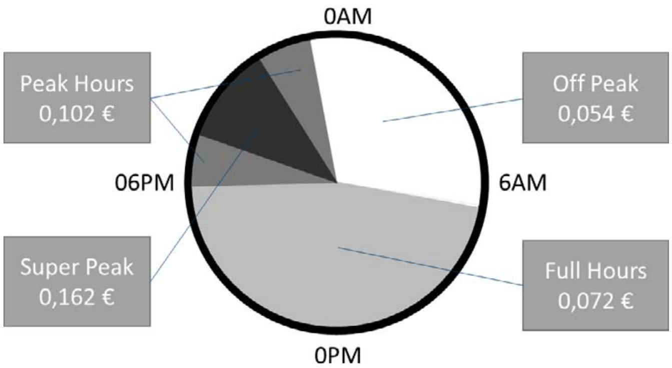

Fig. 2: Power pricing for middle/long consumption at high voltage connection (150 & 225kV)

For the following calculations we assume that the industrial client can sustain the full investment, meaning an equity ratio of 100% (this might be likely with small CSP units requiring relatively reduced investments). In addition, it is also assumed that the required land surface is owned by the client, hence land costs are not considered in calculations.

Tab. 2: Plant main properties and components cost

Plant main properties			Main components specific costs		
Solar field total mirrors area	26500	m²	Solar Field specific cost	240	€/m²
ORC nominal capacity	1000	kWe	ORC specific cost	1600	€/kWe
Thermal storage capacity	27000	kWh	Thermal Storage specific cost	35	€/kWh
Total required surface area	2.5	ha	Operation & Maintenance costs	0.01	€/kWh

The total investment is 9.15M€ based on the information in table 2. The economic assessment is done over a period of 20 years, followed by another 5 years with higher maintenance costs (+50%).

Operation and maintenance costs are generally close to 0.015$/kWh (IRENA, 2012), in the CSP-ORC plant case, a specific configuration and particular design requirements were set to allow for maximal automation and minimum operation leading to much lower O&M requirements.

3. Simulation results and conclusions

The simulations were done for one complete year using hourly data (average values from 10 seconds values). However, two representative days were selected to show the impact of an operation strategy specifically oriented to the peak hours.

4.1 Results for representative days

When observing figures 3 and 4 a slight difference can be noticed in terms of power production, although the sum of the daily production is comparable with both approaches.

Regarding the cash flow curve, a strong difference between the two figures can be noticed despite being representative of the same day. This is mainly due to the production being shifted with the peak oriented operation strategy, while the second strategy only focuses on smoothing the production. Hence, a large share of the power is produced during the day, which means out of peak hours, and does not occur during hours with the highest pricing.

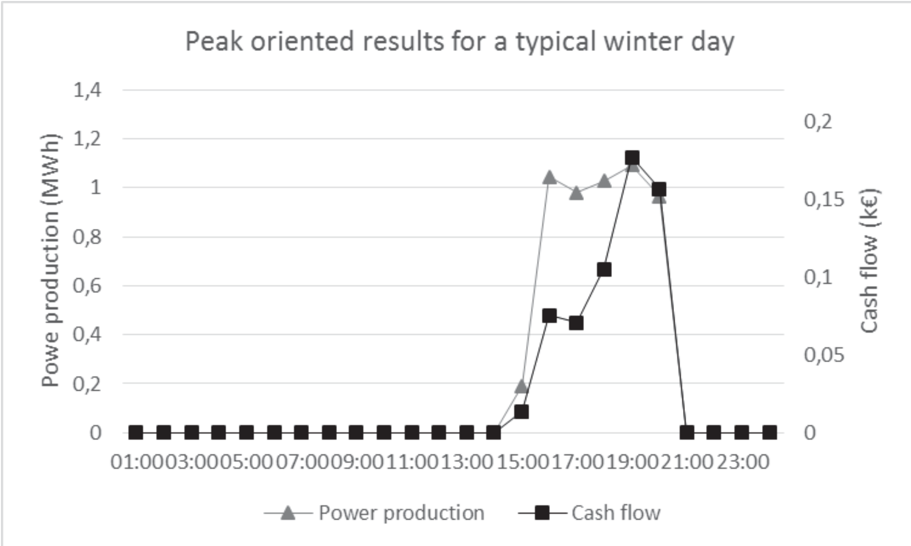

Fig. 3: Power production and cash flow results for a typical winter day with peak oriented operation

It is important to notice that the ORC efficiency increases with lower ambient temperatures until a certain limit, this is a reason not to shift the production beyond 11PM, as temperatures can go easily below 10°C which is a threshold for ORC operation. Moreover, the stored heat has to be completely discharged before 11PM as the pricing moves directly to off peak period leading to an intense drop of electricity pricing.

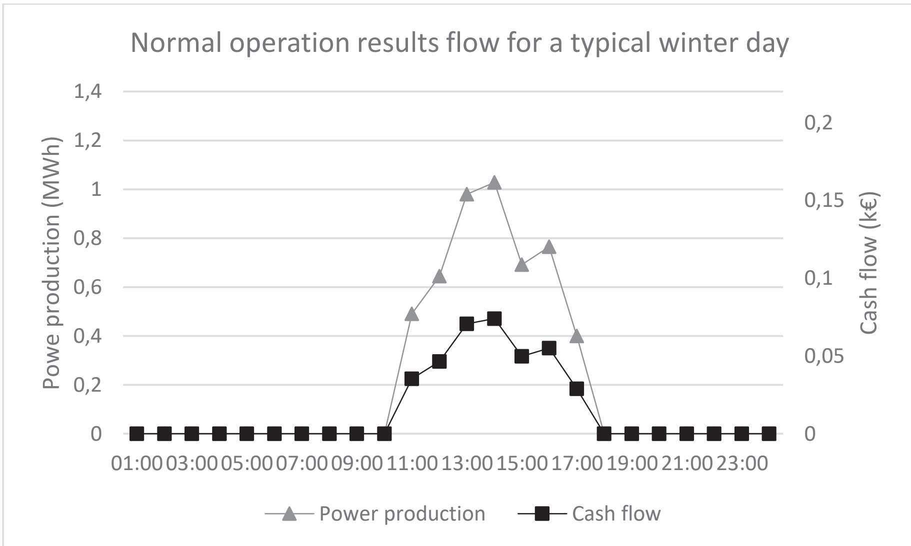

Fig. 4: Power production and cash flow results for a typical winter day with normal operation

During summer, the situation is quite different, when comparing figures 5 and figure 6, the overall shape of the power production curves of both figures is more or less the same. There is only a slight difference on the top of the curve (plateau shape), as the production is limited to 1MW before discharge and around 1.2MW after discharge for the peak oriented operation strategy, while the opposite happens with normal operation.

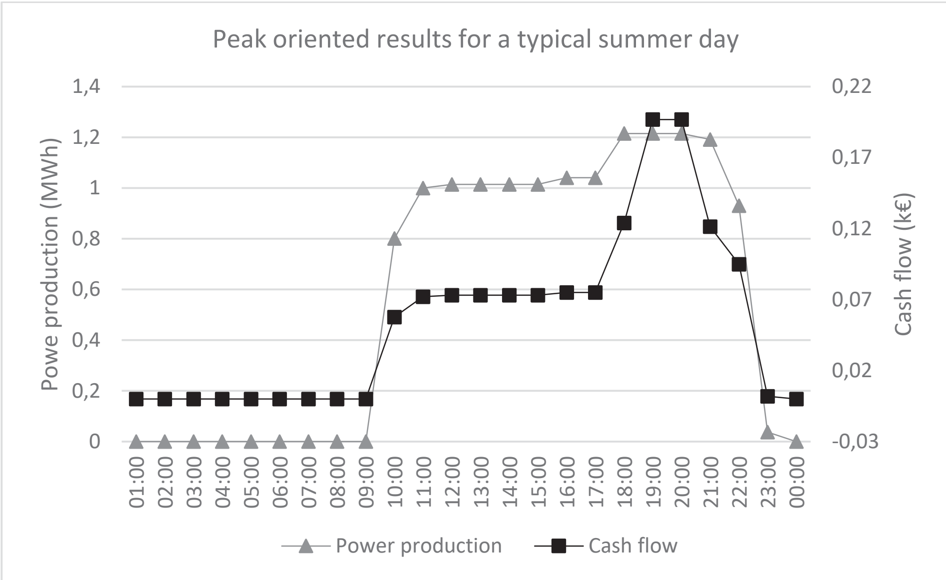

Fig. 5: Power production and cash flow results for a typical summer day with peak oriented operation

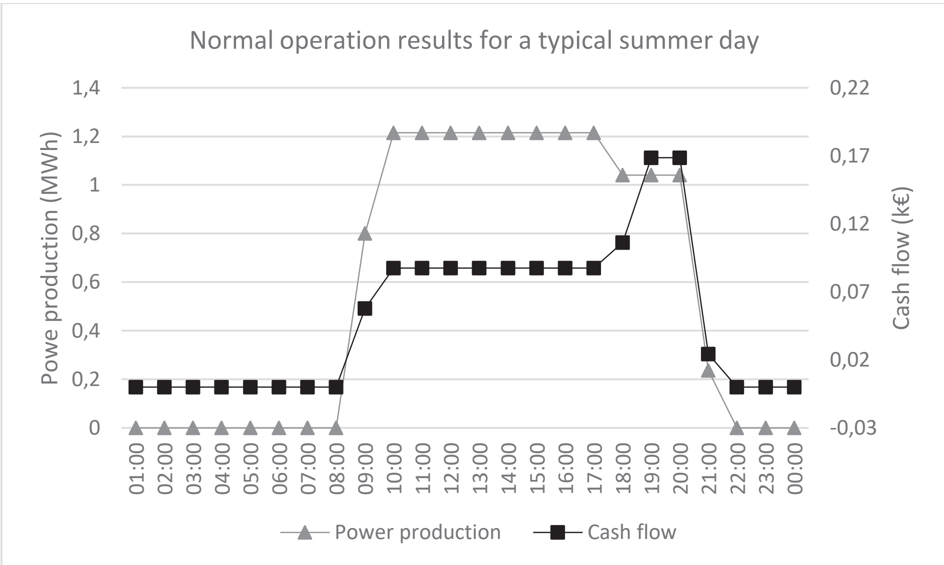

Fig. 6: Power production and cash flow results for a typical summer day with normal operation

In terms of cash flow, there is a certain difference between the two operation approaches, and this is due to the higher amount dispatched during the evening with the peak oriented operation. Nevertheless, this difference is not as important as for the winter example, simply because in this case both strategies tend to extend the production to the evening with different intensities.

4.2 Yearly results

Concerning the yearly simulations, there is slightly equivalent overall production. But when analyzing average values for the summer and winter period, it appears that there a larger increase of production in winter when applying the peak oriented strategy over the normal approach. This is due to the higher efficiency of the ORC with a controlled discharge at high ORC input over spread production with generally low heat input.

Tab. 3: Summary of the main simulation results

Simulated operation strategies	Yearly production		Average Summer day production		Average winter day production	
	Power generation (MWh)	Cash flow (k€)	Power generation (MWh)	Cash flow (k€)	Power generation (MWh)	Cash flow (k€)
Scenario with focus on peak hours	3637	356	15.09	1.34	5.3	0.59
Scenario with normal operation	3611	312	15.01	1.22	4.6	0.37

The cash flow results show an increase for both periods with respectively 10% for summer and 60% for winter, for an entire year the total cash flow gain is 14%.

The initial investment of the plant is set at 9,460,000€, over a period of 20 year, the total incremental costs are 10,020,000€, by extending the operation to 25 years, these costs reach 10,270,000€. In the studied case no debt financing was considered, otherwise, the total incremental costs would have largely exceeded the latter value.

After 20 years of operation, the plant should have produced 72GWh. With a normal operation, this production can generate 6,200,000€, while a peak oriented strategy can generate up to 7,100,000€ which represents 71% of the total incremental costs.

By extending the operation for further 5 years and increasing operation and maintenance costs by 50%, the figures can reach 8,900,000€ and 87%. A 10 years extension of the operation can drive the total revenues up to 10,680,000€ which exceeds the total costs (10,600,000€) including doubled operation costs for the last 5 years.

Such a plant operated with a classical approach would need 5 additional years for amortization, which tends to be difficult with the increasing O&M costs.

The objective of this work is not only to display applicability of small CSP units for industrial consumers, but also to demonstrate that the integration of thermal storage to such plants can help achieve better economic results. It is common to compare CSP projects LCOE with the base power pricing, however, in the case of systems with storage, the comparison is not as simple and must include some other parameters.

A plant with an LCOE of 0.18€ or 0.22€ (which is the average of small scale CSP units) might seem totally unfeasible with an average electricity price of 0.1€/kWh, it appears that such a plant when equipped with an appropriate storage system, can be amortized with a reasonably extended operation lifetime.

Although the approach followed in this study does not consider debt financing, no land cost and relatively long operation in comparison to average plants lifetime simulations, it is still sufficiently reliable to demonstrate the advantage of a peak oriented operation over normal production extension.

It also demonstrate the ability of CSP to supply reliable electricity during the peak periods and compensate for other energy sources especially with a high penetration of renewables on the grid (J. Jorgenson et al., 2014).

In any case, the obtained results show that a slight increase in electricity pricing in Morocco and the mastering of CSP technologies combined with economies of scale (when applicable) and with reasonably high fossil fuel prices can make small CSP applications able to enter the market within the coming few years.

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