ANALYSIS OF THERMAL ENERGY STORAGE SOLUTIONS FOR A 1 MW CSP-ORC POWER PLANT

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ABSTRACT

Organic Rankine Cycle (ORC) power generation blocks have been principally used in the past couple of decades to recover medium grade heat from sources such as geothermal steam, biomass boilers and the exhaust of a realm of different industrial processes. In the past few years, a new philosophy of integrating thermal solar energy to an organic Rankine cycle has been assessed, the purpose of which is to develop a compact, water free and decentralized solution that offers the advantages of solar thermal power with low intermittency and the possibility to extend power generation to the night time at a relatively reasonable cost. To achieve these objectives, a proper storage system that is thermodynamically fit to the heat profile captured by the solar collector and to that of the power cycle must be identified.

This paper covers the selected criteria and the analysis done to identify the potential storage solutions adapted to a thermal solar – ORC system operating at temperature range between 170 C min and 300 °C max, while receiving energy in the form of sensible heat from the collector in order to eventually deliver it to a power organic Rankine cycle (ORC) that uses Cyclopentane as a working fluid. The system so developed will be integrated in the 1 MWe CSP-ORC facility based on Fresnel technology which is currently under construction at Iresen's facilities in Morocco.

The paper covers the optimisation process carried out to best match the characteristics of the thermal Energy storage system to the features of the ORC power block. Two alternative solutions are looked into: sensible heat storage and latent (phase-change) heat storage. A parallel analysis is presented from a multiple fold perspective (technical, economic…) showing that both technologies have particular advantages.

1. INTRODUCTION

The recognized need for electrical energy storage is not new, and many methods of storing energy have been devised over the years. Early last century, a U.S. patent application for a "*System of Storing Power*" was filed on June 7, 1907, by R.A. Fessenden and a patent (No. 1247520) was granted on November 20, 1917. In it, Fessenden stated: "*The invention herein described relates to the utilization of intermittent sources of power and more particularly to natural intermittent sources, such as solar radiation and wind power, and has for its object the efficient and practical storage of power so derived […]. It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were devised for storing power derived from the intermittent sources of nature […]. These sources are, however, intermittent and the problem of storing them in a practicable way, i.e., at* *a cost which should be less than that of direct generation from coal, has for many years engaged the attention of the most eminent engineers, among whom may be mentioned Edison, Lord Kelvin, Ayrton, Perry, and Brush*".

In spite of this acknowledgeable efforts, the problem of storing large amounts of accessible energy in a cost-effective and efficient manner has nevertheless remained one of the most difficult scientific and engineering problems known to date. Thus, as foreseen by Fassenden (1907), the advent of modern renewable energy sources greatly improved our ability to generate energy for several decades but not to store all of what we could produce. In the light of the fore cited arguments, the search for robust and cost-effective energy storage means has intensified in the last ten years.

The Research Institute for Solar Energy and New Energies (IRESEN) is currently developing a solar platform where research activities can be carried out in an environment with unmatched boundary conditions. Amongst different initiatives aiming to foster the development of solar power generation technologies, a 1 MWe Organic Rankine Cycle power system based on indirect vapor generation with linear Fresnel collectors is worth noting. This technology makes use of a heat transfer fluid (typically mineral or synthetic oils) which carries thermal energy from the solar field to a dedicated heat exchanger where organic superheated vapor is produced. This power generation facility is currently under construction and will expectedly come into operation in 2016. Performance specifications are given in Table 1.

Table 1: Performance specifications of the 1 MWe ORC power plant

Parameter	**Units**	**Rated value**
Rated Direct Normal Irradiation	W/m^2	850
Net Rated Power Output	kWe	900
Net Rated Efficiency of the ORC (Solar to electricity)	%	18
Collector type	-	Linear Fresnel
Number of solar field loops and total aperture area	- / m2	7/11400
Efficiency of solar field all losses included	%	53
Solar field heat output	MWth	5000
Working fluid of power block	-	Cyclopentane
Reference dry bulb temperature (Dry cooling)	°C	30

The original design of the power plant does not incorporate thermal storage capabilities other than a buffer tank where a certain amount of hot heat transfer fluid is stored. Nevertheless, this system cannot be regarded as a true energy extending or shifting storage system as it only stores energy (sensible heat) for about twenty minutes and thus it is aimed at compensating for fast-passing clouds over the solar field only. Therefore, the buffer tank does not enable extended operation of the plant after sunset.

The aforecited characteristics of the power plant prevent it from delivering dispatchable electricity, hence eliminating one of the differential features of solar thermal electricity with respect to other renewable energy technologies like wind or photovoltaics. It is thus a primary target for IRESEN to develop thermal energy storage systems that could be integrated into these intermediate scale ORC power systems which are too large to consider electric batteries and too small to directly downscale the commercial technologies currently used in large CSP power plants (>50 MWe). The temperature difference between the steam cycle used in the latter and the ORC power block existing in the reference plant reinforces this statement.

With all the previous arguments in mind, this article approaches the design of a thermally-efficient and cost-effective thermal storage system to be integrated into the 1 MWe CSP-ORC power plant in Benguerir. The analysis starts off with the principles of energy storage and, then, a comparison amongst the different technologies available is presented before coming to conclusions with respect to the best candidate(s).

2. THERMODYNAMIC PRINCIPLES OF ENERGY STORAGE

To optimize the design and operation of the thermal energy storage (TES) system, this must be analyzed in terms of the First and the Second Laws of thermodynamics. The First Law yields the energy efficiency, which is the ratio from the energy delivered by the storage device during discharging to the energy supplied to it during the charging phase. This approach is interesting to detect two main inefficiencies:

- Heat losses to the surroundings. This is particularly important for systems that operate at very high temperature
- Residual energy not being delivered by the storage system. This is mainly due to temperature gradients between the energy source (typically a heat transfer fluid at high temperature) and the storage medium of the TES system.

This first law efficiency might nevertheless be misleading as it only accounts for the total amount of different forms of energy being transferred to and recovered from the TES system but it does not take into consideration how useful this energy is (energy quality); i.e. the potential to produce useful work in the power conversion system to which it is connected. Another complementary approach is thus needed, based on the second law. This provides a rational measure of the quality of this energy being transferred.

Figure 1 presents an elementary TES system whereby a heat transfer fluid, hereinafter called HTF, provides energy (E_{in}) to the tank during the charging process whilst the same or another fluid extracts a fraction (E_{out}) of the energy stored in the tank (E_{stored}).

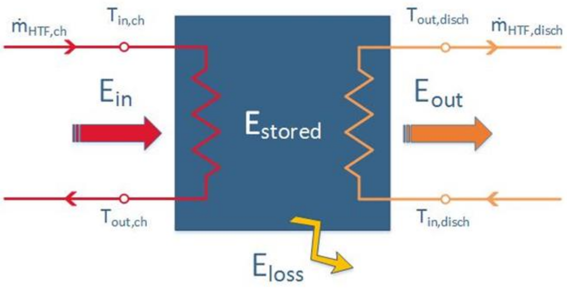

Figure 1: Scheme of an elementary TES system

The first law applied to the system in Figure 1 is equated as follows:

$$E_{in} = E_{out} + E_{loss} \tag{1}$$

Based on this balance, there are many different though valid definitions of the energy efficiency of TES systems. For example, Equations (1) and (2) provide valid definitions of energy storage efficiency:

$$\eta_{TES} = \frac{Energy\ delivered\ by\ TES}{Energy\ supplied\ to\ TES} \tag{2}$$

$$\eta_{TES} = \frac{Energy\ delivered\ by\ \ TES + Energy\ remaining\ in\ TES\ after\ discharge}{Energy\ supplied\ to\ TES + Residual\ energy\ originally\ in\ TES} \tag{3}$$

These equations have a similar foundation but they might yield different values under similar operating conditions. Therefore, many authors define different efficiencies for the charging and discharging phases:

$$\eta_{TES,charging} = E_{stored}/E_{in} \tag{4}$$

which describes the fraction of the total energy input (energy supplied plus pumping power) required to charge the storage tank that is effectively stored in it. A low value of $\eta_{TES,charging}$ indicates an ineffective heat transfer or a large amount of energy (sensible heat) carried by the hot fluid leaving the tank.

The discharging efficiency can be defined in a similar manner:

$$\eta_{TES,discharging} = E_{out}/E_{stored} \tag{5}$$

which describes the ratio of the energy delivered by the storage tank relative to the energy stored in it. The combination of charging and discharging efficiencies yield the overall efficiency of the TES system, which can be developed further with the introduction of Equation (1):

$$\eta_{TES,overall} = \eta_{TES,charge} \times \eta_{TES,discharge} = E_{in}/E_{out} = 1 - E_{loss}/E_{in} \tag{6}$$

On the other hand, as opposed to energy, exergy represents the maximum amount of work that can theoretically be performed by a system as this comes into equilibrium with its environment (once equilibrium is reached, the system no longer has the potential to perform work). If the process is ideal, then the work developed is highest; if on the contrary the process is irreversible, exergy is destroyed[1]. It becomes therefore evident that exergy yields added value to reflect the thermodynamic and economic value of the storage system application. A second law analysis of the system is out of the scope of this work due to space limitations. It will thus be released in due time along with the techno-economic feasibility study.

3. ANALYSIS OF THERMAL ENERGY STORAGE OPTIONS

3.1 Layouts

Most thermal energy storage systems make use of a parallel configuration which means that the hot stream coming from the solar field is split: the main stream is used to drive the power block whilst the secondary flow is directed towards the thermal energy storage system, Figure 2 (top). The main advantage of such layout is the very high temperature achievable by the storage medium which, in turn, ensures that the efficiency of the power plant in discharge operation is closest to or even at the rated value.

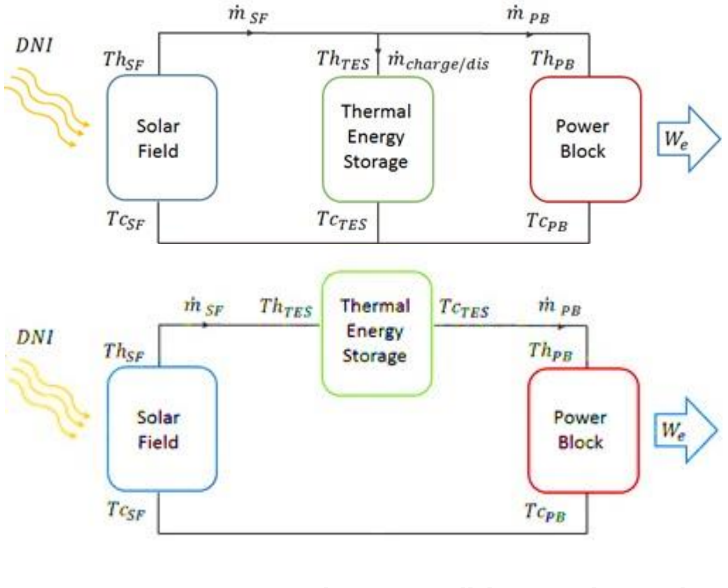

Figure 2: TES system integration layouts: parallel (top) and series (bottom).

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[1] Note that, whilst energy is always conserved, exergy can be destroyed.

This layout is currently used by most commercial TES's and is particularly suitable for sensible heat storage, whether it be with of the single (thermocline) or multiple tank type. Ideally, a good design should yield equal or very similar return temperatures from TES (Tc_{TES}) and power block (Tc_{PB}) so that the temperature of the heat transfer fluid at the inlet to the solar field (Tc_{SF}) remains constant regardless of the type of operation (TES charge/discharge or power block only). Based on this rationale, the parallel layout is not advisable for latent heat storage inasmuch as the temperature drop of the heat source (hot heat transfer fluid) is much lower than in sensible heat solutions. For this reason, a series layout is preferred wherein the TES is placed upstream of the power block, Figure 2 (bottom). The main drawback of such layout is a reduction in live vapor temperature, though this is only effective when the TES system is being charged and, even in this situation, it can be attenuated by increasing the time needed to charge the system (i.e., reducing the HTF temperature drop and hence the heat transfer rate to the storage medium). Based on these standard configurations, four types of thermal energy storage systems are studied in this work:

- Sensible heat storage: thermal energy is stored by increasing the temperature of a storage medium. This can be either the heat transfer fluid used in the solar field (direct) or a different heat transfer medium (indirect). Also, for the latter case, two options are available:
    - Single tank configuration (thermocline). A storage tank with stratified temperatures.
    - Two tanks configuration. Hot storage medium with high energy content is stored in a hot tank from where it is pumped to a cold one when energy is demanded.
- Latent heat storage medium. In this case, the storage medium stores and releases energy by changing phase. Even though solid-liquid and liquid-gas storage is possible, the former is preferred for its higher energy density.

The main features of the four storage systems considered in this work are given below (note that a common specification to all of them is the capacity to operate the power plant at full load for one hour):

- Two tanks direct. The hot and cold tanks are located upstream and downstream of the vapor generator respectively. Their respective HTF levels are left free to vary between 15% and 98% so the ratio from useful HTF volume to vessel volume is 0.83 (Pacheco, 2002).
- Two tanks indirect. The storage medium is a HITEC binary molten salt with $C_{p,salt}$=1.56 kJ/kg and ρ_{salt}=1900 kg/m^3. The sizing criterion of the hot and cold tanks remains the same.
- Single tank indirect (thermocline). The filler material is quartz rock and sand with a void fraction of 0.22 (Pacheco *et al.*, 2002). The properties of the filler are $C_{p,fill}$=1.075 kJ/kg and ρ_{fill}=2600 kg/m^3. The tank is divided in 50 slices with similar height, where the energy balance equations are applied in each time step. The system is designed to keep the thermocline region during the charge/discharge cycles.
- Phase change storage. The properties of the storage medium are similar to those of sodium nitrite ($NaNO_2$) even if with a slightly higher melting temperature (280ºC). This is done for generality and will have to be double checked and updated in future feasibility analyses. The properties of interest are λ_{PCM}=212 kJ/kg (latent heat) and ρ_{PCM}=2260 kg/m^3. The ratio from PCM volume to vessel volume is 0.7375 (Laing et al., 2010).

3.2 System model

The analysis presented in this document is based on elementary lumped volume models for the main components in the plant. The system is resolved in five minute steps (time discretization), meaning that the models are considered quasi stationary.

Turbine model

The Organic Rankine Cycle is of the recuperative type and operates with superheated live vapor. Given that cyclopentane is a dry fluid, the exhaust vapor from the turbine is also in the superheated region and hence its sensible heat is transferred to the subcooled liquid delivered by the pump. Such layout increases the thermal efficiency of the cycle though at the expense of a higher circulating mass flow rate through the solar field. This higher auxiliary power consumption is nevertheless compensated for by a lower duty of the condenser which operates slightly above atmospheric pressure under any operating conditions (thus preventing oxygen infiltration). As a consequence of the recuperative layout, the vapor quality at condenser inlet is always lower than one.

The vapor turbine operates in sliding pressure mode and hence the next equation for live vapor conditions holds true

$$k_t = \dot{m}_{lv} / \sqrt{p_{lv}/v_{lv}} \tag{7}$$

where k_t is the flow function and remains constant for power settings higher than 25%. For lower loads, live vapor is throttled across the main stop valve to keep turbine inlet pressure constant.

TES system model

These models of the energy storage systems are based on elementary energy balances already described in section 2. First law applications result in Equation (8) for sensible heat systems and Equation (9) for phase change storage (these are the practical application of Equation (1):

$$\dot{Q} = \dot{m}_{TES}\, C_{p,TES}\left(T_{h,TES} - T_{c,TES}\right) = \frac{dE_{TES}}{dt} = \frac{d}{dt}\left[M_{TES}\, C_{p,TES}(T_{h,TES} - T_{c,TES})\right] \tag{8}$$

$$\dot{Q} = \dot{m}_{TES}\ \lambda_{PCM} = \frac{dE_{TES}}{dt} = \frac{d}{dt}\left[M_{TES}\, \lambda_{PCM}\right] \tag{9}$$

Where T_h and T_c stand for hot and cold temperatures, M is the mass of storage medium and λ_{PCM} is the latent heat of the phase change material (storage medium). For direct systems, no additional heat transfer equations are needed as it is the heat transfer fluid flowing across the solar field which is stored in an insulated vessel. In this case, if no heat losses take place, the stored energy is available at the standard temperature level (i.e. live vapor temperature in discharge operation remains at the rated value). On the contrary, for indirect sensible heat systems, there is an inevitable reduction in the achievable live vapor temperature in discharge operation due to the terminal temperature difference of all heat exchangers. These heat transfer equipment are modelled with a simple ε – NTU approach.

Solar field model

The model of the solar field is based on the common approach making use of *incidence angle modifiers* IAM for the transversal (θ_t) and longitudinal (θ_l) incidence angles, which are provided by the manufacturer to correct the reference optical efficiency of the solar field at noon ($\eta_{SF,0}$). These correction factors are applied to the incidence angle of the reference location (Benguerir, Morocco) to calculate the solar energy collected and they are then complemented by temperature dependent terms to account for heat losses (Haberle *et al.*, 2002)

$$\eta_{SF} = \eta_{SF,0}\, IAM(\theta_t)\, IAM(\theta_l) - a_1 \frac{(T_{SF,out} - T_{amb})}{DNI} - a_2 \frac{(T_{SF,out} - T_{amb})^2}{DNI} \tag{10}$$

where a_1 and a_2 are empirical coefficients. The net solar energy collected is then used to heat up the heat transfer fluid whose temperature at the outlet from the solar field ($T_{SF,out}$) is calculated by merely applying first law calculations.

3.3 Operating strategy

The operating strategy of the thermal energy storage system is not straightforward and it depends largely on the electric market where the power plant is operating. Thus, some operators opt for as fast as possible start-ups of the plant prior to TES lading. This maximizes the annual yield though it increases the risk that the TES system is not fully loaded at the end of the day when the environmental conditions are not good (for instance, hazy or cloudy sky and/or short winter days in the northern hemisphere). On the contrary, some operators decide to charge the TES system to full capacity before plant start-up. This ensures the extended operation but influences the annual yield negatively. This operation might make sense though, if electricity prices in the morning are substantially lower than in the evening (Silva *et al*, 2011).

The first strategy is adopted in this work whereby the plant starts up as soon as possible in the morning and, once it is operating at full capacity, the TES system is loaded. It must be noted though that, for plant start-up, the minimum DNI needed to produce positive net power and the minimum stable load are case-specific and hence they are very difficult to model with simple approaches. Thus, at this preliminary stage of the analysis, the following assumptions are made:

- Minimum DNI for plant start-up: 500 W/m^2. The minimum DNI depends on two factors:
    - Minimum stable load: the value of 500 W/m^2 is based on the experience of the authors.
    - Energy required to preheat the solar field and power block. The solar energy collected between sunrise and DNI=500 W/m^2 is used to preheat the system.
- Start-up time. Given the size of the plant, the expected start-up time will be fairly short and thus it is assumed that it falls within the time-step of the solver. It is here noted that this is still a conservative approach inasmuch as no electricity is produced until DNI=500 W/m^2.
- For DNI>500 W/m^2, the load increases up to the rated value. At this point, a fraction of the hot HTF coming from the solar field is diverted towards the TES system.
- Once the TES system is fully loaded, no more HTF is necessary and thus the surplus hot flow is used to increase the output of the plant to 110% the rated value (common industry practice).
- When DNI falls below 500 W/m^2, the storage system is discharged and used to keep the plant at full capacity for one additional hour.

These considerations apply to parallel configurations only. For integration in series (phase change), heat is supplied to the TES system when DNI reaches 500 W/m^2 (it is assumed that below this DNI the peak temperature achieved in the solar field is not high enough).

4. RESULTS

4.1 Daily performance

Figure 2 summarizes the most relevant features of the power plant incorporating a TES system of the direct type. The solar energy collected by the solar field and transferred to the heat transfer fluid (Q_{SF}) is directed towards the power block (Q_{PB}) to generate electricity once the minimum DNI is exceeded. The electric output (W_{ORC}) increases from this point up to full capacity and, then, thermal energy is progressively supplied to the thermal energy storage system (Q_{TES}). Once storage is completed, the plant output is increased to 110%.

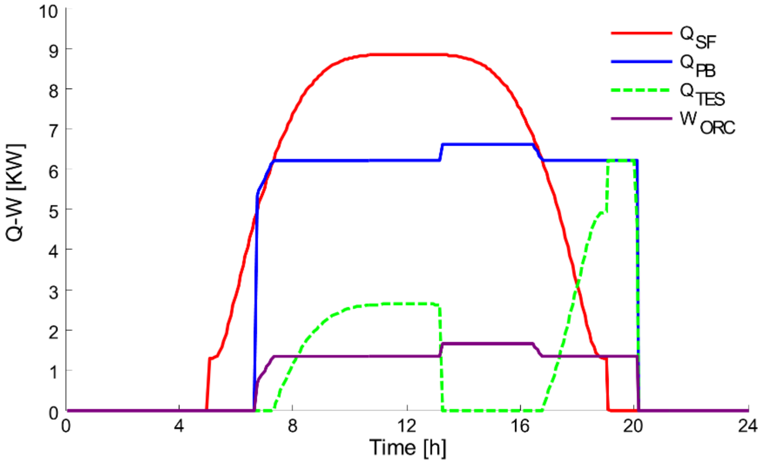

Figure 3: Performance of the direct sensible heat TES system.

In the evening, energy is dragged from storage to keep the plant operating at full capacity. It is worth noting in this regard that, rather than exhausting the storage system in order to further extend the operation of the power block (at part load), the plant is shut-down when operation in rated conditions is no longer possible. This enables a faster start-up in the next morning as the storage system is not completely used up. The information displayed in Figure 3 is qualitatively applicable to all the systems based on sensible heat.

Figure 4 shows the performance of the latent heat system. Three salient differences are observed:

- Owing to the series integration (TES system upstream of the power block), electricity production and TES charging start at the same time. It is not possible to achieve full capacity prior to the charging phase. Note that even if this could be avoided by bypassing the TES system initially, it would lead to a more complicated operation of the vapor generator.
- It takes more time to charge the TES system completely. This is because the temperature drop of the HTF (energy carrier) across the TES system, i.e. the heat transfer rate, is much lower than in the other systems with parallel integration. There are two alternative solutions to compensate for this effect:
  - Increase the mass flow rate of hot HTF coming out from the solar field. This would increase pumping power at the solar field, therefore reducing net output.
  - Adopt a parallel integration. This would inevitably increase the HTF return temperature to the solar field, inasmuch as PCM storage systems take advantage of a very small temperature drop of the hot HTF. Pumping power would in turn be increased.
- Even if values will be provided later, it can be observed that more energy is dumped from the system than in the sensible heat arrangements (dumped energy is the fraction of available energy at the solar field that is not used by the power plant, neither for the power block nor for the storage system).

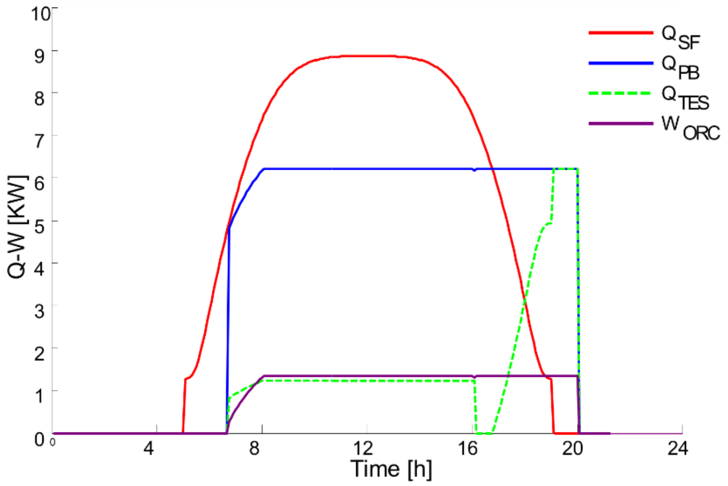

Figure 4: Performance of the indirect latent heat TES system.

4.2 Energy management

A comparison is provided in this section to show how energy is managed by the different TES systems, Figure 5. It is to note first that a common solar multiple of 1.5 is selected for all cases, which explains why the energy collected by the solar field (E_{SF}) and effectively transferred to the HTF leaving it (E_{EFF}) is constant in the cited figure. This effective energy is then split into two different streams. The majority of it drives the power block (E_{PB}), which produces electricity (W_{ORC}) whilst the smaller fraction charges the storage system (E_{Ch}). The surplus energy that cannot be used is dumped out of the system (E_{Dum}). This occurs when the storage system is already charged and the turbine operates at 110% load.

The most relevant observations in Figure 5 follow:

- All three sensible heat systems produce roughly the same electricity in a day, in spite of the slightly different heat addition to the power block. This is explained by the different power block efficiencies brought about by the operation in discharge conditions, Table 2. In other words, the live vapor conditions that are achievable during discharge are dissimilar.

- This can be confirmed by comparing, for these three systems, the amount of energy supplied to the power block (E_{PB}) and to the storage system (E_{Ch}). The indirect system exhibits lower values than the direct and thermocline solutions.
- Further to the previous point, it is also observed that dumped energy is highest for indirect systems. This makes sense in the light of the common solar field size and dissimilar energy demand by power block and storage.
- For the case of latent heat storage, the lower live vapor temperature brought about by the series integration has a visible negative influence on the efficiency of the power block. This influence is reflected in a lower electricity yield (W_{ORC}).
- The most remarkable difference between sensible and latent heat storage systems is the much higher dumped energy in the latter, due to the particular characteristics of the series integration and very low temperature drop of the HTF across it.

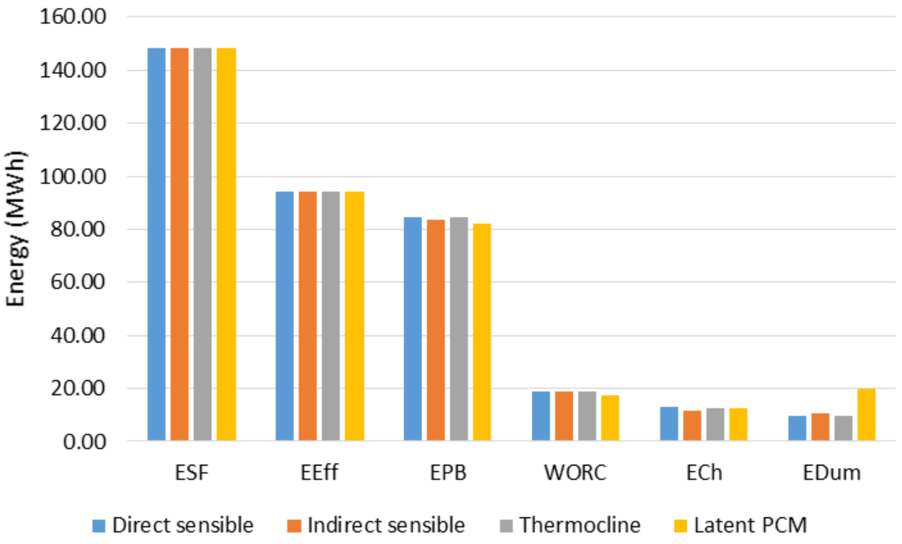

Figure 5: Energy management comparison.

Table 2: Daily average efficiency of power block

TES type	Direct sensible	Indirect sensible	Thermocline	Latent PCM
Average thermal efficiency of power block	22.25	22.29	22.13	21.23

4.3 Volume of storage medium

The thermal performance discussed so far provides a very useful insight into the benefits and drawbacks of each storage system. Nevertheless, when it comes to energy storage in the form of either sensible or latent heat, it is of capital importance to consider other techno-economic features. The first of these is the charging/discharging rate, which favors sensible heat storage, in particular of the direct type as already discussed previously. This can be ascertain by merely comparing he charging times in Figures 3 and 4.

On the other hand, the amount of storage medium is a critical factor affecting the economics of the TES system. Installation costs comprise two contributions: specific cost (€/ton) and total volume of the storage medium. Whilst the former is actually beyond the scope of this work (techno-economic analyses will be presented in future publications), the total volume of storage medium needed for each configuration is presented in Table 3. It is observed that in spite of the inherent simplicity and thermodynamic advantages, direct sensible heat storage is not interesting for it requires an extremely large volume of storage medium. This is because of the characteristics of the HTF and has a dramatic impact on the cost of the storage vessel.

On the other hand, PCM storage steps forth as a very interesting solution volume-wise. Nevertheless, the poorer thermodynamic performance and longer charging time are not compensated for by this advantage. Therefore, thermocline solutions are identified as the most interesting candidate with conventional two tank indirect storage solutions behind.

Table 3: Volume of storage medium

TES type	Direct sensible	Indirect sensible	Thermocline	Latent PCM
Volume of storage medium (m^3)	420	315	200	125

5. CONCLUSIONS

The main conclusions drawn from the work presented in this analysis are:

- Sensible heat storage systems enable faster charging processes and more agile operation.
- Latent heat systems exhibit poorer thermodynamic performance in comparison with sensible heat storage. This is most relevant when the energy dumped out of the system is compared.
- Direct sensible heat storage systems request a prohibitive amount of storage medium. It is thus not feasible in practice for the extended operating time required.
- Latent heat systems require the lowest amount of storage medium.
- Thermocline storage steps forward as the most leveraged solution, offering the best trade-off between thermodynamic performance and volume of storage medium

Future work include performing optimization analyses based on second law efficiencies and entropy analysis to identify where the main irreversibilities are located. Also, a more detailed analysis of operational aspects of the proposed solutions will result in a more clear picture of the reliability and agility of each TES system. This features are of paramount importance for the owners of these mid-scale facilities.

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