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Techno-economic Performance Evaluation of Solar Tower Plants with Integrated Multi-layered PCM Thermocline Thermal Energy Storage – A Comparative Study to Conventional Two-tank Storage Systems.

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Abstract. Solar Tower Power Plants with thermal energy storage are a promising technology for dispatchable renewable energy in the near future. Storage integration makes possible to shift the electricity production to more profitable peak hours. Usually two tanks are used to store cold and hot fluids, but this means both higher investment costs and difficulties during the operation of the variable volume tanks. Instead, another solution can be a single tank thermocline storage in a multi-layered configuration. In such tank both latent and sensible fillers are employed to decrease the related cost up to 30% and maintain high efficiencies. This paper analyses a multi-layered solid PCM storage tank concept for solar tower applications, and describes a comprehensive methodology to determine under which market structures such devices can outperform the more conventional two tank storage systems. A detail model of the tank has been developed and introduced in an existing techno-economic tool developed by the authors (DYESOPT). The results show that under current cost estimates and technical limitations the multi-layered solid PCM storage concept is a better solution when peaking operating strategies are desired, as it is the case for the two-tier South African tariff scheme.

INTRODUCTION

Concentrating solar power (CSP) plants are expected to increase their share in future electricity markets mainly due to their ability to integrate cost effective thermal energy storage (TES). Previous research by the authors have highlighted that such ability enhances the economic viability of CSP plants either by increasing the capacity factor or by allowing the solar input to be decoupled from the electrical output energy and thereby generate electricity during peak hours when revenues are highest [1]. However, TES integration is linked to a higher investment and thus techno-economic optimal plant configurations are to be identified. Nowadays, the most used TES technology is a two-tank configuration in which hot and cold molten salts are stored individually. The use of molten salts as both heat transfer fluid (HTF) and TES media in solar tower power plants (STPP) has led to cost reductions by avoiding the need of additional heat exchangers and related piping mechanisms. However, it has been suggested that the introduction of a single tank thermocline TES can further reduce TES costs by a third when compared to the costs of conventional two-tanks, whilst still offering the advantages of having molten salts as HTF and TES media [2]. In a thermocline TES both cold and hot fluids are stored in a tank simultaneously and are separated by a steep gradient of temperature, which prevents mixing [3]. Nonetheless, large tank diameters can cause a degradation of the gradient, for which a promising solution is to combine both sensible and latent fillers in different layers to create a porous medium. Such design has been suggested in previous research for parabolic trough applications [3]. Specifically, the

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design consists of two small layers of latent fillers (at the top and at the bottom of the tank), with sensible fillers in between (Multi-Layered Solid PCM (MLSPCM)). The design (presented in **Fig.2** in the Tank Design section) has been shown to be a viable solution to keep a high efficiency of the tank and decrease the amount of PCMs needed [3]. The work hereby presented aims at studying the applicability of such design for STPPs applications in which the temperatures reached by the HTF are higher. The methodology to carry the work involved first a modelling of the tank, then its integration in a dynamic simulation tool and finally a techno-economic analysis of the STPP. The study also compares the results with previous analyses performed by the authors based on STPPs with two-tank TES [1], stressing under which tariff structures the proposed TES is more attractive both economically and technically.

STORAGE MODEL

An essential step in order to introduce the MLSPCM tank model in the STPP layout is to simulate its thermal behavior and hence outlet temperature trend during charging and discharging processes. To do so, the energy conservation differential equations are modelled for the particular case and simplified as follows [3].

1. One dimensional fluid flow and temperature distribution
2. Conduction effect on the fluid considered negligible
3. One dimensional heat transfer in filler particles (conduction and convection for the PCM)
4. Spherical shape for the fillers
5. Heat conduction between particles and contact melting are considered negligible
6. Negligible heat losses through the tank and radiation losses

The differential equations are solved by means of Finite Volume Method (FVM). The tank is discretized axially and divided in N_x transversal cylindrical section of height Δx in which the temperature is considered uniform. In each section, a single filler is analyzed as all are affected by the same temperature of the fluid. The filler particles are discretized radially in N_r control volumes [2, 4]. Main discretized equations used are shown below in (1) and (2), followed by (3)-(7) which are the additional equations required to solve the energy balance of the latent fillers (2), based on enthalpy-temperature correlations. The method suggested by Regin et al. [5] is adopted in order to avoid the specific tracking of the solidification front and to simplify the solution.

$$\rho_f \varepsilon_i V_i Cp_f \frac{\partial T_{f_i}}{\partial t} = -\dot{m}\, Cp_f \left(T_{f_{i+\frac{1}{2}}} - T_{f_{i-\frac{1}{2}}}\right) - n_{fm_i}\left(\frac{T_{f_i} - T_{i_{Nr}}}{R_{conv} + R_{cond}}\right) \tag{1}$$

$$\rho_{fm} V_{i_j} \frac{\partial h_{i_j}}{\partial t} = \left(k_{fm} A \frac{\partial T}{\partial r}\right)_{i_{j+\frac{1}{2}}} - \left(k_{fm} A \frac{\partial T}{\partial r}\right)_{i_{j-\frac{1}{2}}} \tag{2}$$

$$\mathrm{h} - \mathrm{h}_0 = Cp_s(T - T_0) \qquad T \le T_s \tag{3}$$

$$\mathrm{h} - \mathrm{h}_0 = Cp_s(T - T_0) + f\,L \qquad T_s < T \le T_{sl} \tag{4}$$

$$\mathrm{h} - \mathrm{h}_0 = Cp_l(T - T_{sl}) + Cp_s(T_{sl} - T_0) + fL \qquad T_{sl} < T \le T_l \tag{5}$$

$$\mathrm{h} - \mathrm{h}_0 = Cp_l\,(T - T_{sl}) + Cp_s(T_{sl} - T_0) + L \qquad T_l \le T \tag{6}$$

$$f = \frac{T - T_s}{T_l - T_s} \tag{7}$$

In this case *f* represents the mass liquid fraction and ranges between 0 (pure solid) to 1 (pure liquid). By following this method only one value of enthalpy exists for each value of temperature and the energy balance can be expressed as solely function of T. In order to model the heat exchange between the particles and the fluid, the fluid-to-bed Nusselt number correlation by Wakao et al. [6] has been used to calculate the non-dimensional coefficient.

$$Nu = 2.0 + 1.1\, Re^{0.6}\, \mathrm{Pr}^{\frac{1}{3}} \qquad Re = \left(\frac{\rho_f v_f d_p}{\mu_f}\right) \tag{8}$$

The convection coefficient calculated from Nusselt is then used to calculate the convective resistance between the filler and the fluid. A discretization method was followed. For (1) a fully implicit method was adapted together with an upwind scheme for the advection term. In this way each section is influenced by the temperature of the fluid coming from the upstream direction calculated at the previous time step and less iterations are needed. For (2) a fully implicit method was used together with a central discretization scheme. The resulting tri-diagonal matrix of the discretization coefficients of the linear system is solved through a TDMA algorithm under an iteration pattern.

Model Validation

The model has been cross-validated by comparing the results against the experimental campaigns available in literature. In order to validate the tank response, the model has been compared with the experimental work by Pacheco et al. [2]. In the work the authors studied the temperature profiles of a thermocline tank filled with quartzite sand and silica sand sensible fillers. Secondly the results of the PCM behavior were validated against the results of the experimental campaign of Nallussamy and Velraj [7] who studied the thermal response of paraffin wax filled capsules in a small water storage. Both works have been frequently used by different authors to validate their models for latent filled thermocline storage [8-9]. **Figure 1** shows the results for the validation in both cases.

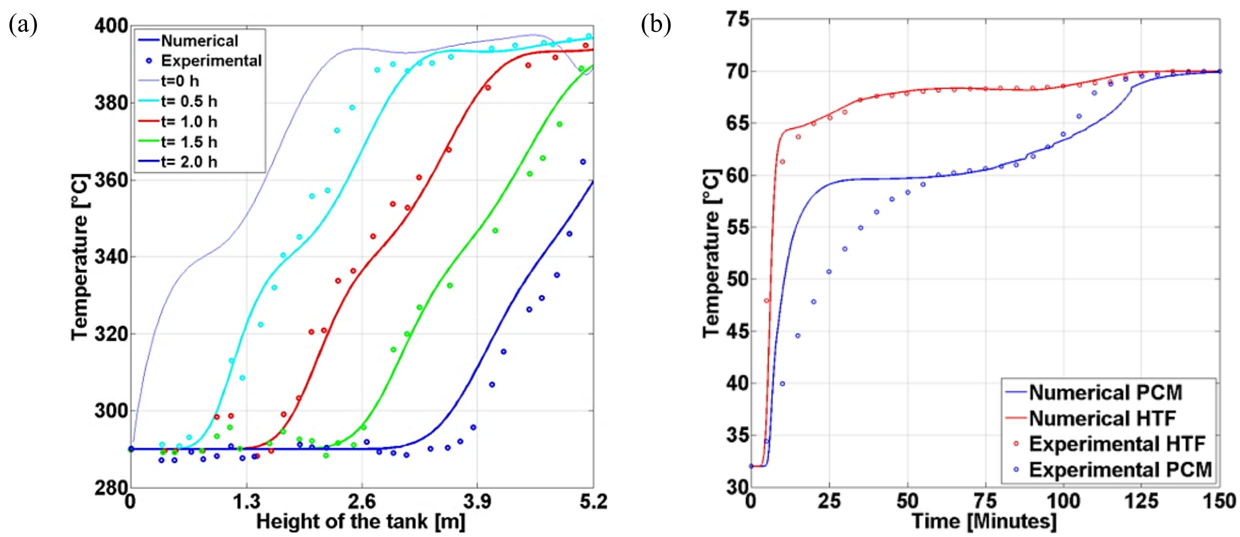

FIGURE 1. a) Thermocline profile validation [2] - b) PCM and HTF temperature evolution validation [7]

Figure 1a shows the temperature profiles along the height of the tank. The thermal gradient is well reproduced and follows a trend similar to the experimental values. The discrepancies that can be observed from the graph can be linked to the following reasons: simplification of the mathematical model, uncertainty on the experimental measurements and unavailability of all the parameters from the work of Pacheco et al. **Figure 1b** illustrates the temperature evolution of both HTF (water) and PCM capsules (paraffin wax) at the axial position of x/L=0.5 and radial position of r/R=0.8 (the position of the sensor was not specified and the position considered was the radial position at which the volume is split in half [3]).The temperature evolution for both HTF and PCM follows a similar trend as the experimental values. The overall discrepancies are linked to simplification of the model and uncertainty on the actual position of the sensor inside the capsules. The temperature discrepancies for the PCM in the first 50 minutes can be linked to difference with the real properties of the paraffin as well as not accounting for contact melting. Paraffins have been observed to have high temperature range for melting process and thus the phase change starts at lower temperatures than assumed. However, if salts are considered as PCM, the phase change is not characterized by high melting ranges and the model is considered viable for such applications.

Lastly the model was validated in a multi layered configuration by comparing against the results from the model developed by Galione et al. [3]. This was done both by matching the design parameters such as mass of the HTF and PCM and the dynamic performance such as discharging time. The results are presented in **Table 1**. The case study was performed for two layers of PCM of 7% of the total height of the tank. The tank stops to operate when the outlet temperature reaches a cut-off limit temperature and therefore not all the energy in the tank can be used [3]. Overall the model showed good agreement with results in [3] with a maximum error of 1.18% for the mass of PCMs.

TABLE 1. Validation of the MLSPCM model against the numerical model by Galione et al [3]

	Size = 3.42 h	*Energy = 3.02 MWh*	
	Reference case	**Model results**	**Percentual difference**
Mass of PCM (ton)	17.0	16.8	1.18%
Mass of solid filler (ton)	42.7	43.0	0.70%
Operation Time (h)	2.86	2.86	0.00%
Energy ratio (%)	76.9	76.4	0.65%

Tank Design and Cost Estimation

In the case of the design of MLSPCM tank an iterative process is required for sizing the volume of storage. In a thermocline storage the outlet temperature decreases with time as the thermal gradient region starts to be withdrawn [8]. This can cause the depletion of the thermocline region and therefore an outlet temperature limit must be set. In this sense, firstly the tank is designed for certain requirements (such as size and energy) and secondly tested according to its dynamic performance. The MLSPCM tank cannot release all the energy that stores and therefore an oversize is necessary. Consequently as this depends on the dynamic performance of the tank an iteration algorithm is required [8]. Furthermore the geometrical parameters such as porosity and width of the different fillers must be optimized. This can be done by employing a genetic algorithm to maximize the energetic effectiveness of the tank (defined as the energy released over the total energy stored). **Table 2** summarizes the geometrical parameters varied during the optimization process and their optimal values in a particular case, while **Fig. 2** illustrates the final configuration for the tank. It is interesting to notice the different values of porosities between the latent and sensible filler layers. This is because the system tends to store more HTF in sensible part and less in the latent side which, by storing more energy and having an isothermal energy transfer, can better stabilize the temperature of the incoming fluid from the lower part of the tank. The latent materials for the two layers of fillers have to be chosen mainly according to their melting temperature. Indeed as already suggested by Galione et al. [3], the phase change temperature of the encapsulated PCM (E-PCM) needs to lie between the hot temperature and the cut-off temperature for the top layer, to achieve higher efficiencies. The same reasoning can be applied for the bottom layer.

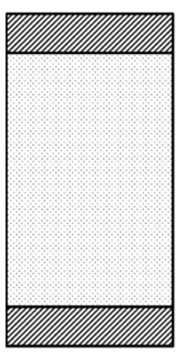

FIGURE 2. MLSPCM tank configuration

TABLE 2. Optimization details for the MLSPCM design

Optimization details			
Decision Variables:	**Limits**	**Results**	**Unit**
Porosity 1st layer (ϵ_{pcm_1})	10:50	22	%
Porosity 2nd layer (ϵ_{pcm_2})	10:50	37	%
Porosity 3rd layer (ϵ_3)	10:50	22	%
Width 1st layer	5:10	7	%
Width 3rd layer	5:10	7	%
Diameter of the fillers	5:20	9.1	mm

The methodology to calculate the costs of the TES is similar to the one suggested by Nithyanandam et al [9]. The capital expenditure (CAPEX) of the TES can be expressed as the sum of TES material, container and overhead costs. This last term accounts for the miscellaneous costs such as electrical, piping, instrumental, valves and it is assumed as the 10% of the TES material. Moreover when considering the costs, first the masses of PCM, sensible fillers and HTF are calculated and then multiplied by the specific costs. Lastly, tank costs are calculated by considering the costs for the steel, the insulation and foundation. The CAPEX accounts for the costs listed below.

$$\text{PCM cost} = \left(C_{pcm_1}\rho_{pcm_1}\left(1-\epsilon_{pcm_1}\right) width_1 + C_{pcm_2}\,\rho_{pcm_2}\left(1-\epsilon_{pcm_2}\right) width_2\right)\pi R_t^2\left(\frac{R_{int}}{R_{ext}}\right)^3 \quad (9)$$

$$\text{HTF cost} = (\epsilon_1\, width_1 + \epsilon_2 width_2 + \epsilon_3 width_3)\,\pi R_t^2\, C_{HTF} \quad (10)$$

Sensible filler cost = $$(1-\epsilon_3) width_3\, \pi R_t^2\, C_{FM} \tag{11}$$

Tank material costs = $$\rho_{SS} H_T\, (\pi(R_t + w_t)^2 - R_t^2) C_{SS} + \pi R_t^2 C_F + 2\pi R_t H_t C_{INS} \tag{12}$$

For the specific cost of the EPCM, the cost reference values are extracted from [10] in which a detailed breakdown of all the costs for the PCM, encapsulation materials and process are given. **Table 3** presents the details of the cost for the main storage materials used in a STPP application. **Table 4** presents then a cost comparison with a two tank application. The tank design parameters are taken from previous work of the authors [1]. Two different configuration of MLSPCM tank have been tested depending on the width of the PCM layers. It can be seen that both thermocline configurations were able to deliver the same TES capacity (9 hours) for less volume, and that such volume was found to decrease as a function of the width of the PCM layers. This was expected as PCMs are characterized by having a larger storage capacity than molten salts. This variation resulted from the specific TES cost estimation for the thermocline TES system, calculated to be 16.7$/MWh$_{th}$, 30.1% less than the specific costs of the two-tank TES system (23.9$/MWh$_{th}$). Lastly, it is shown that an optimum width of PCM layer can be determined as despite PCM integration decreases the volume, it increases the specific cost of the TES system.

TABLE 3. Cost breakdown for storage materials [10]

Material		Cost
Sensible solid filler	Quarzite and Silica sand	72 $/ton
PCM 1	Li_2CO_3/Na_2CO_3 / K_2CO_3	8.51 $/kg
PCM 2	NaNO3	7.27 $/kg
HTF	Molten Salt	0.75 $/kg

TABLE 4. Cost comparison between MLSPCM tanks and two tank TES

TES Configuration	SM	Power [MW]	TES size [h]	TES Volume [m3]	TES Cost [$/kWh$_{th}$]
2-Tank	2	110	9	24330	23.9
1-Tank (2x7% PCM)	2	110	9	15200	16.7
1-Tank (2x15% PCM)	2	110	9	14400	25.9

TES Model Dynamic Response and Integration in STPP Model

During charging and discharging the hot zone increases or decreases respectively while the thermocline region travels throughout the height of the tank. When discharging, the hot salts are firstly displaced and subsequently the lower regions. Therefore the outlet temperature is not constant but starts to drop after a certain time. The same reasoning can be applied to a charging cycle, with a cut-off limit for the cold outlet temperature. In addition the tank cannot be discharged completely in order not to compromise its functionality. Hence to cope with these problems the MLSPCM tank stops to operate when the outlet temperature drops to a certain threshold defined as cut-off temperature [13-15]. **Figure 3** illustrates a discharge cycle of a MLSPCM tank for a size of 9 hours.

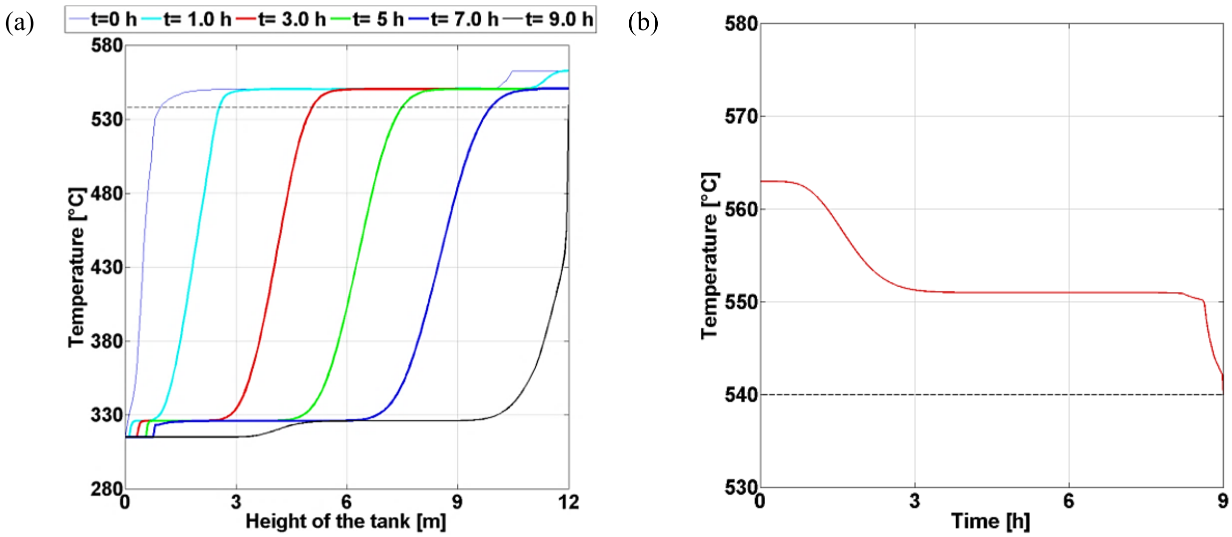

FIGURE 3. MLSPCM dynamic response – a): Temperature profile evolution – b): Outlet temperature evolution

Figure 3a illustrates the thermal gradient evolution until the cut-off temperature is reached. In **Figure 3b** the outlet temperature is shown. In this case there is a first drop of temperature to the melting point of the top layer of PCM. The temperature of the PCM is therefore stabilized and when the latent heat of the PCMs cannot be exploited anymore the outlet temperature starts to drop up to reaching the cut-off temperature. This profile of outlet temperature is different from a two tank solution in which the HTF is always provided at the nominal temperature.

The model developed in Matlab of the MLSPCM is highly demanding from a computational time perspective. The time steps required to solve it with proper accuracy are in the order of seconds while when simulating a power plant performance for the whole year higher time steps are used. To keep a proper accuracy, while at the same time allowing higher time steps in the tool, the solution chosen was an interpolant function with correlations according to the varying working conditions of the thermocline tank (i.e. inlet mass flows temperatures). This method proved to be efficient from a dynamic perspective as the RMSD error with the simulations was ranging between 0.5% and 1.5% depending on the different working conditions. The approach followed was to simulate one cycle in Matlab and create interpolant functions to be input in TRNSYS, thus requiring only one accurate simulation for the storage. Secondly, after having developed the component a pre-defined dispatch strategy (PDS) was developed for a typical STPP operation [1]. The PDS sets the operation of the STPP according to the price of electricity for a peak strategy while it allows the STPP to always operate for a baseload operation. When the STPP is set to run (PDS=1) the incoming power from the solar field is compared with the nominal value (SM=1), which is the one required by the power block (PB). If this is higher, the exceeding power can be used to charge the storage if this is not full (state of charge (SOC) lower than 1). In case of a fully charged storage a buffer is filled with the incoming molten salt (this in opposite with a two tank system in which the volume of the tanks is variable and therefore no buffers are required). In case the solar energy is not high enough the TES discharges unless empty in order to compensate the difference between the nominal power and the incoming one. If in a particular case the TES is empty the power plant is shut down. In optimal configurations the TES size is enough to accommodate the energy requirement during the dispatching operation. The operational implementation of a thermocline tank is a parallel scheme to the receiver and the Steam Generation Train, oppositely to a two tank system where the hot and cold tanks are placed in series. **Figure 4** illustrates a diagram of a STPP integrating a thermocline (TC) tank.

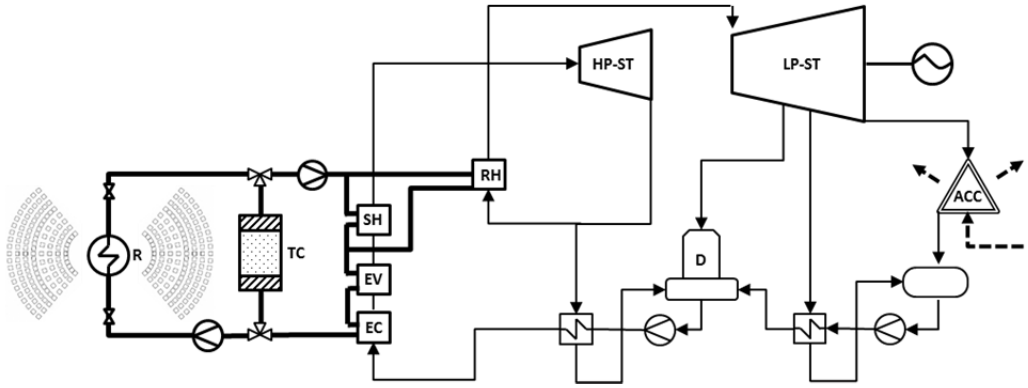

FIGURE 4: STPP Layout integrating a thermocline multi-layered tank (TC-MLSPCM)

POWER PLANT TECHNO-ECONOMIC OPTIMIZATION

The analysis of the STPP was performed using DYESOPT [1]. The performance of STPPs and of the MLSPCM integrated in such systems can be evaluated with different performance indicators [1]. However when optimizing for different design objectives, these can be conflicting and therefore optimal trade-offs can be identified. For instance when minimizing the Levelized Cost of Electricity (LCOE) of a power plant, higher investments (CAPEX) are typically required (e.g. due to larger power blocks). However, especially in case of new technologies a high CAPEX can represent a high risk desired to be minimized. The same reasoning can be applied when it is intended to maximize the plant profits in terms of Internal Rate of Return (IRR). In order to examine the trade-offs, a multi-objective optimization was carried out in DYESOPT. In particular the study was carried by optimizing the design of a STPPs located in South Africa [1], showing the trade-offs between IRR vs. CAPEX and LCOE vs. CAPEX while varying all critical design parameters summarized below in **Table 5**.

TABLE 5. Main decision variables for STPP design optimization

Decision Variables	*Limits*	*Unit*
Solar Multiple	1:3	[-]
Electrical Power	50:130	MWe
TES size (hours)	3:20	h
Tank cut off	538:550	°C
Power blocks design specifications		

The price scheme taken into account was the same as the one previously presented by the authors [1], with a two-tier price with 270% peak price during 5 hours of peak demand. The results of the optimization identified two different optimum approaches for the integration of the tank, one for each of the two design objectives considered. In the case of the IRR, for which the hourly electricity price is relevant, the optimizer converged to configurations with small solar fields (SM equal to 1 in most of the simulated points) and 5h of TES, just enough to shift production to peaking hours, even in presence of bad-radiation days. Oppositely, for minimum LCOE the optimizer converged to large solar fields and TES units in order to sell as much electricity as possible without considering the hourly price. This means that an optimal TES size can be found according to the desired design objective.

COMPARISON WITH TWO TANK APPLICATION

In the optimizations presented in the previous section, the MLSPCM proved to be a valid solution in order to replace the typical two tank solution. However the outlet temperature of the MLSPCM is not constant in opposition with the two tank solution. This means that, when the tank is almost fully discharged, a drop in the power production is observed as the turbine inlet temperature (TIT) decreases. In order to check the viability of the MLSPCM tank in comparison with the two tank solution, two similar power plant configurations obtained from the optimization study (110 MWe) and integrated with the two different TES technologies were analyzed. A sensitivity analysis is presented in terms of different SM and TES size. The power plants were compared in terms of techno-economic indicators (LEC and IRR) for the South African market with results presented in **Fig. 5a** and **Fig. 5b** respectively.

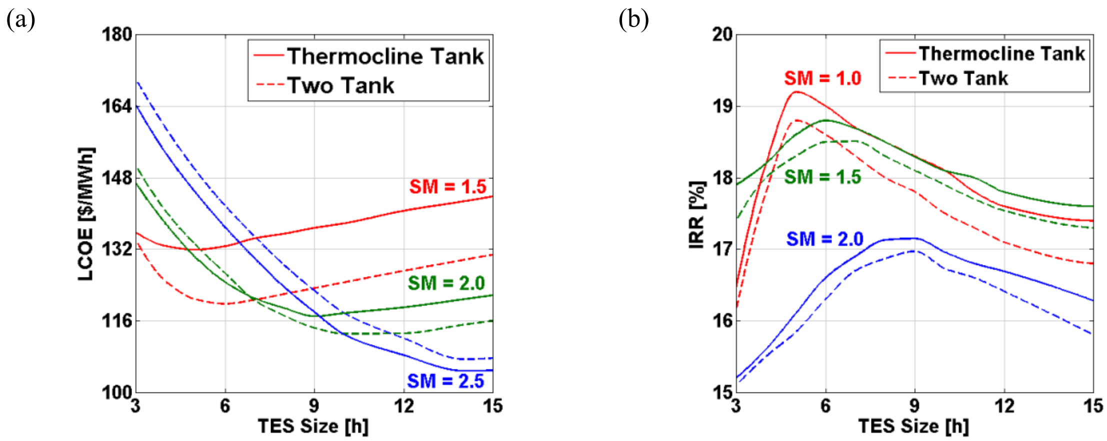

FIGURE 5. Sensitivity analysis between a two tank and a single tank MLSPCM – a) LEC comparison – b) IRR comparison

The main difference between the two power plants is the operation strategy as, when minimizing the LEC, a baseload strategy is preferred. In opposition to this, when maximizing the IRR, the actual price tariff scheme is taken into consideration, hence switching towards a peaking strategy [1]. With the current cost estimates, as shown in **Fig.5**, there is not a single better option but one technology is preferable over the other depending on the design and operation strategy of the power plant. In fact in the case of the LEC minimization a baseload operation is preferred, therefore the thermocline tank is almost fully discharged daily. This means that if the SM is not high enough to allow the SOC to be brought back at high values the two tank storage is a more economical solution. This can be explained by referring to **Fig. 3b.** If the SOC is constantly kept below 30%, the outlet temperature of the tank would always be lower than the hot temperature of the HTF cycle, affecting the overall electricity production. This concept explains why for a SM of 1.5 only small tanks (3 hours size) can have a comparable performance with the two tank systems. However when increasing the SM, the tank can be brought back to higher state of charge more consistently improving the performance. Therefore for a SM equal to 2.5 the MLSPCM tank is more economical viable decreasing the LEC by 1.61%, while for a SM of 2.0 the single tank is a better solution only for sizes up to 6 hours. However, when considering a peaking strategy to maximize profits under the South African tariff scheme, different trends are observed. In fact, in these cases even for lower SMs the storage can be fully charged during low prices hours and discharged during peak hours without reaching minimum tank levels, thus keeping higher outlet temperatures and therefore not affecting significantly the PB. **Fig. 5b** summarizes this last concept, highlighting that, within a peaking strategy, the single tank is a more economically viable solution, increasing the IRR by 2.1% and that a clear optimum size of 5 h is found able to accommodate the 5 h peak price hours of the South African market.

CONCLUSIONS

A detailed methodology has been presented to show the thermodynamic and economic performance of single tank MLSPCM storage systems when integrated into molten salt STPPs. For such, a thermodynamic model has been developed and validated and then integrated in an existing optimization tool for techno-economic performance evaluation of STPPs (DYESOPT). It was shown that a storage system based on a MLSPCM tank can provide the required energy to the PB at the expense of a decrease in production output due to a drop in temperature at the outlet of the tank during discharge. Amidst this drop, when compared to the more acquainted two-tank alternative, the study shows that the MLSCPM is able to improve the economic performance of a STPP especially during peaking strategies, increasing the resulting IRR by up to 2.1%. If a baseload operation is considered, the MLSPCM tank improves the techno-economic performance only under particular design conditions especially with high solar multiple decreasing the LCOE by up to 1.61%. However, it is acknowledged that a second analysis including the impact of cycling and degradation is needed in order to enhance the comparative analysis among storage concepts.

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