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Newcline

Advanced thermocline concepts for thermal energy storage for CSP

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Contents

List of Acronyms

CR	central receiver
CSP	concentrated solar power
GUI	graphical user interface
HTF	heat transfer fluid
LCOE	levelized cost of energy
LF	linear Fresnel
PCM	phase change material
PD	parabolic dish
PT	parabolic trough
PV	photovoltaics
TES	thermal energy storage
TESM	thermal energy storage medium
TRL	technological readiness level

1 Motivation

While concentrated solar power (CSP) plants are promising candidates for systems converting solar power to electricity, the resulting levelized cost of energy (LCOE) when employing them still is comparably high (IRENA, 2012) respect to photovoltaics (PV). The main potential advantage of CSP compared to PV is the possibility to provide electricity in the evening hours after sunset efficiently by the use of a thermal energy storage.

Although a thermal storage equips the CSP plant with a decisive advantage, it contributes significantly to its capital cost. A typical molten-salt two-tank storage makes up around 20 % of the investment cost for a parabolic trough (PT) plant and around 10 % for a central receiver (CR) (IRENA, 2012). Around half the cost for such a storage system is caused by the salt itself, and the majority of the remaining cost is for the storage tanks (Kolb et al., 2011). Hence, using one tank instead of two and reducing the amount of salt needed for the thermal storage by replacing it with a cheaper alternative material are direct levers to reduce the LCOE of CSP plants.

Beyond CSP power plants, storing thermal energy at temperatures above 300 °C is also relevant in industrial processes. Furthermore, potential applications are the second life of steam turbines of power plants formerly fed by fossil fuels, where high temperature energy storages could be used to store excess electrical energy to be used to drive the turbine for times of high electricity demand later. Hence, the topic of molten salt storages is also interesting for regions outside geographic areas facilitating the use of CSP.

2 Project objectives

Newcline project, which consortium is formed by Universitat Politècnica de Catalunya-BarcelonaTech (UPC), the Deutsches Zentrum für Luft- und Raumfahrt e. V. / German Aerospace Center (DLR), the University of Applied Sciences Rapperswil (SPF), Kraftblock GmbH (KB) and Empresarios Agrupados Internacional, S.A. (EAI), is supported by the European Commission within the EU Framework Programme for Research and Innovation HORIZON 2020 (Cofund ERA-NET Action, N° 838311).

The overall objective of the European *ERA-NET Newcline* (`http://www.newcline.eu/`) is to develop new thermocline concepts, able to reduce capital costs up to 40 %, that can be applied to different CSP plants (parabolic trough, central receiver, linear Fresnel). Two concepts will be explored. The first concept involves the use of innovative structured ceramic filler refractories. The other one is an innovative combination of solid filler material (the ceramic one is the preferred option) with specially selected encapsulated PCM located at the top and bottom regions of the tank.

Both concepts will be tested in a lab-scale setup, and their TRL will be increased from TRL 4 to TRL 6 through demonstrations at a relevant pilot scale of 4 MWh with at least 50 charge/discharge cycles. Finally, both concepts will be evaluated and optimized in terms of system integration and LCOE savings on a CSP system level and up-scaling for CSP target applications. This last step is where *SPF* is involved. The specific objectives of our contribution are:

- Extend the existing *TRNSYS* simulation framework *pytrnsys* to feature a CSP system including its components
- Develop/extend *TRNSYS TYPES* to simulate a total of six cases: parabolic trough and central receiver plants, each with two tank solutions and both single tank thermocline concepts
- Implement and validate a thermocline storage tank in TRNSYS
- Optimize the integration of the thermocline solutions through system simulation studies
- Do a techno-economic analysis of the simulation results to assess the LCOE reduction potential of the thermocline single-tank solution with the two approaches. The target value for this is at least 10 % LCOE reduction compared to the two-tank solution.

This report deals with the developments and works carried out only by SPF, in the framework of *Newcline* project.

3 Status and work carried out

The *TRNSYS* (Klein et al., 2010) system simulations for this project will be done through the framework *pytrnsys*[1], an open source python framework for *TRNSYS* which has been developed at *SPF*. *Pytrnsys* allows for a user-friendly way to set up, execute and process *TRNSYS* simulations. A GUI coupled with a flow solver supports the creation of hydraulic schemes and allows visualizing the mass flow rates and temperatures determined by the simulations. In 2021 this simulation framework was adapted to support the simulation of CSP plants.

In 2022 the focus moved from the framework to the individual components simulated in such systems and finally, the simulation of references systems featuring conventional two-tank energy storages. Since the core of this project is the thermal storage employed in CSP plants, we tried to decrease the complexity of models of other components as much as possible. In particular, we aimed at representing the CR and the power block of both CSP plants investigated through simple linear an quadratic functions (see section 4.1). These functions were fit to simulation data provided by *Empresarios Agrupados* (*EAI*) (Spain). More components needed were built based on already existing standard *TRNSYS TYPES* or such from the *TESS* library[2]. An overview over the various components can be found in Tab. 1.

component	model
CR	fitting functions
PT field	*TESS TYPE* 1257
power block	fitting functions
heat exchanger	self-created *TRNSYS TYPE*
tank (two-tank)	self-created *TRNSYS TYPE*
tank (thermocline)	to be done

Table 1: Status of the different components that will be used for the simulations within the current project.

Besides optimizing the control scheme, the comparison between the state-of-the-art two-tank CSP plants and systems featuring the thermocline storage solutions explored in this project is the main target of the system simulations within Newcline. Hence, setting up a reliable simulation of a CR and a PT system with two-tank storages is a vital part of this task. These reference simulations are in turn compared to simulation data provided by *EAI*. This analysis has been completed for the CR case (see section 4.2), and is currently in progress for the PT case.

[1] https://pytrnsys.readthedocs.io
[2] http://www.trnsys.com/tess-libraries/index.html

4 Simulations of two-tank reference systems

To be able to compare the results of system simulations with *TRNSYS*, *EAI* provided us with hourly simulation data over a whole year for both reference plants, which were generated with *SAM*[3].

4.1 Component models

4.1.1 Central receiver

The central receiver operates at a fixed output temperature $T_{\text{rec, out}} = 565\,°\text{C}$. To achieve this output temperature for varying solar irradiance levels impinging on the mirror field, the mass flow rate through the central receiver is varied. Analyzing the data from the *SAM* simulation, it can be seen in Fig. 1 that the response of the receiver mass flow rate to the normal irradiance falls into two regimes. The regime marked in yellow is the regime of normal operation, while the one in blue is composed of points during the startup process. The few remaining points are shown in grey. Each regime is represented through a linear function of the form.

$$\dot{m}_{\text{rec}} = c \cdot (I - I_0) \tag{1}$$

Here $\dot{m}_{\text{rec}}$ is the mass flow rate through the receiver, c the linear coefficient, I the beam normal irradiance and I_0 the respective beam radiance offset.

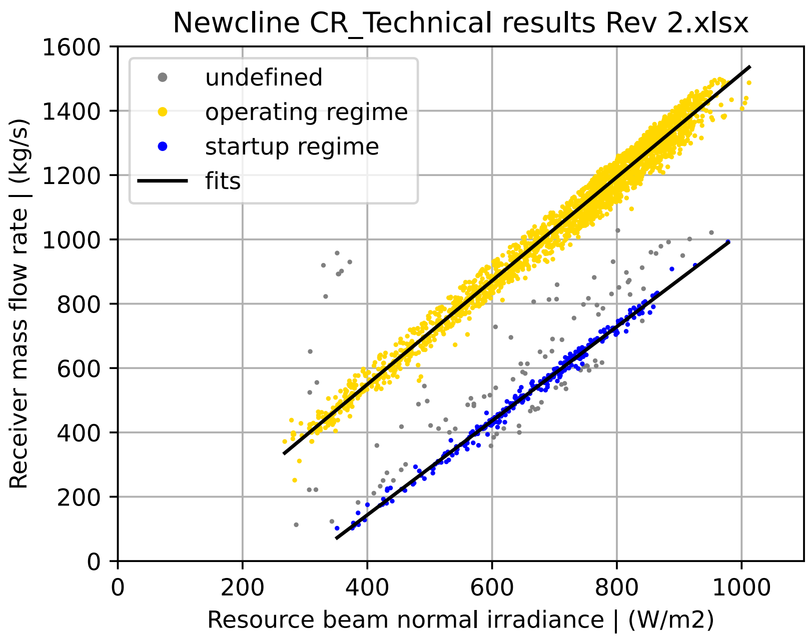

Figure 1: Fitting the mass flow rate through the central receiver in dependence of the normal irradiance. Two separate regimes were fitted with a linear function, as described in the text.

4.1.2 Power block

The power block is a component of both the CR as well as the PT system. For each of these two systems it operates, however, in quite different regimes. Hence, the power block is modeled separately for each system. Two types of functions are used to represent the power block. A linear one

$$y = a \cdot x + y_0 \tag{2}$$

[3]https://sam.nrel.gov/concentrating-solar-power.html

and a quadratic one

$$y = a_0 + a_1 \cdot x + a_2 \cdot x^2 \tag{3}$$

Here, x is the argument of the function, y its value, a the slope of the linear function and y_0 the offset at $x = 0$. In the quadratic function a_0 denotes the constant, a_1 the linear and a_2 the quadratic coefficient.

The power block receives a certain mass flow rate $\dot{m}_{\text{PB}}$ of a heat transfer fluid at a certain temperature $T_{\text{PB, in}}$. Depending on these two variables the electrical power output to the grid $P_{\text{el, grid}}$ and the output temperature $T_{\text{PB, out}}$ vary. To fit equations 2 and 3 over the two input dimensions the fitting process was split into two steps. First, $\dot{m}_{\text{PB}}$ was fixed and the fits for $P_{\text{el, grid}}$ and $T_{\text{PB, out}}$ were done over $T_{\text{PB, in}}$. Then, another round of fits for the resulting coefficients a and y_0 or a_0 to a_2 respectively were done over $\dot{m}_{\text{PB}}$. All fits were done with the python *curve_fit*[4] routine.

Power block for CR system

For the power block of the CR system, *EAI* provided steady state simulation data generated through the software *THERMOFLEX*[5] at three values for $\dot{m}_{\text{PB}}$ at four values of $T_{\text{PB, in}}$ each. First, each set for a fixed $\dot{m}_{\text{PB}}$ was treated separately. The electric power to the grid was fitted with:

$$P_{\text{el, grid}} = a \cdot T_{\text{PB, in}} + P_{\text{el, 0}} \tag{4}$$

and the outlet temperature with:

$$T_{\text{PB, out}} = a_0 + a_1 \cdot T_{\text{PB, in}} + a_2 \cdot T^2_{\text{PB, in}} \tag{5}$$

The resulting fitted coefficients are shown in Figs 2 and 3. The evolution over different mass flow rates $\dot{m}_{\text{PB}}$ is shown in Fig. 2 a) for a, in Fig. 2 b) for $P_{\text{el, 0}}$ and in Fig. 3 a) to c) for a_0 to a_2. The error bars indicate the confidence intervals resulting from the fits. These coefficients were then again fitted with equation 2 over $\dot{m}_{\text{PB}}$, as shown by the black lines in the respective plots. This leads to the following equations mapping $P_{\text{el, grid}}$ and $T_{\text{PB, out}}$ over $\dot{m}_{\text{PB}}$ and $T_{\text{PB, in}}$:

$$P_{\text{el, grid}}\left(\dot{m}_{\text{PB}}, T_{\text{PB, in}}\right) = a\left(\dot{m}_{\text{PB}}\right) \cdot T_{\text{PB, in}} + P_{\text{el, 0}}\left(\dot{m}_{\text{PB}}\right) \tag{6}$$

$$T_{\text{PB, out}}\left(\dot{m}_{\text{PB}}, T_{\text{PB, in}}\right) = a_0\left(\dot{m}_{\text{PB}}\right) + a_1\left(\dot{m}_{\text{PB}}\right) \cdot T_{\text{PB, in}} + a_2\left(\dot{m}_{\text{PB}}\right) \cdot T^2_{\text{PB, in}} \tag{7}$$

Figs. 2 c) and 3 d) show the *THERMOFLEX* data (stars), *SAM* data (dots) and the results of the fitted functions for $P_{\text{el, grid}}$ and $T_{\text{PB, out}}$ respectively. For $P_{\text{el, grid}}$ shown in Fig. 2 the multilinear function corresponds well to both the *THERMOFLEX* and the *SAM* data. Deviations with respect to the *THERMOFLEX* data, which are significant but still below 10 %, can only be seen for points at which $\dot{m}_{\text{PB}}$ and $T_{\text{PB, in}}$ are low simultaneously. For $T_{\text{PB, out}}$ shown in Fig. 3, the fitted function deviates from the *THERMOFLEX* data by 1.3 % in the worst case. The deviation of the fitted function is worse for the comparison to the *SAM* data, especially for the lowest $\dot{m}_{\text{PB}} = 175\,\text{kg/s}$. But even there, the deviation is less than 3 %.

[4] https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html

[5] https://www.thermoflow.com/products_generalpurpose.html

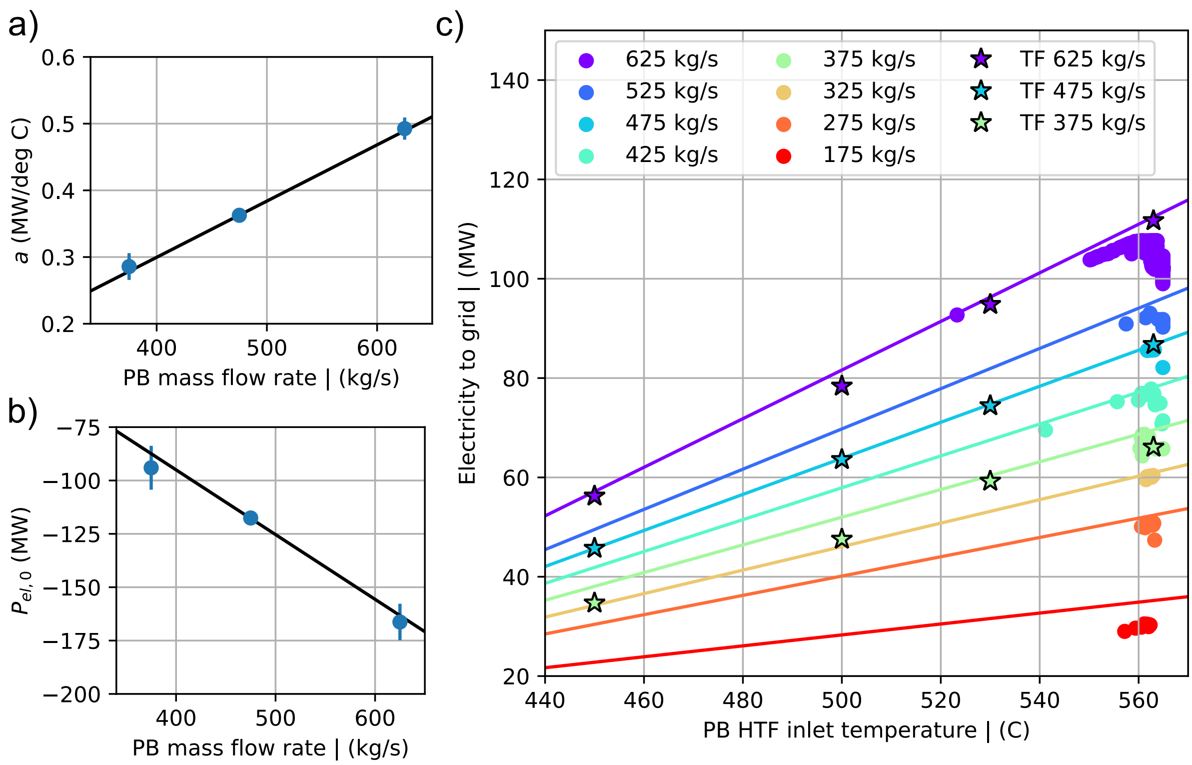

Figure 2: Fitting of the electric power-to-grid output of the power block of the CR system. Scaling factor a for various mass flow rates in a) and offset values in b). The results of the multilinear function (solid lines) are shown in comparison to the *THERMOFLEX* (TF) data (stars) over which the fits were done and in comparison to the *SAM* data (dots) in c). The mass flow rates are color coded.

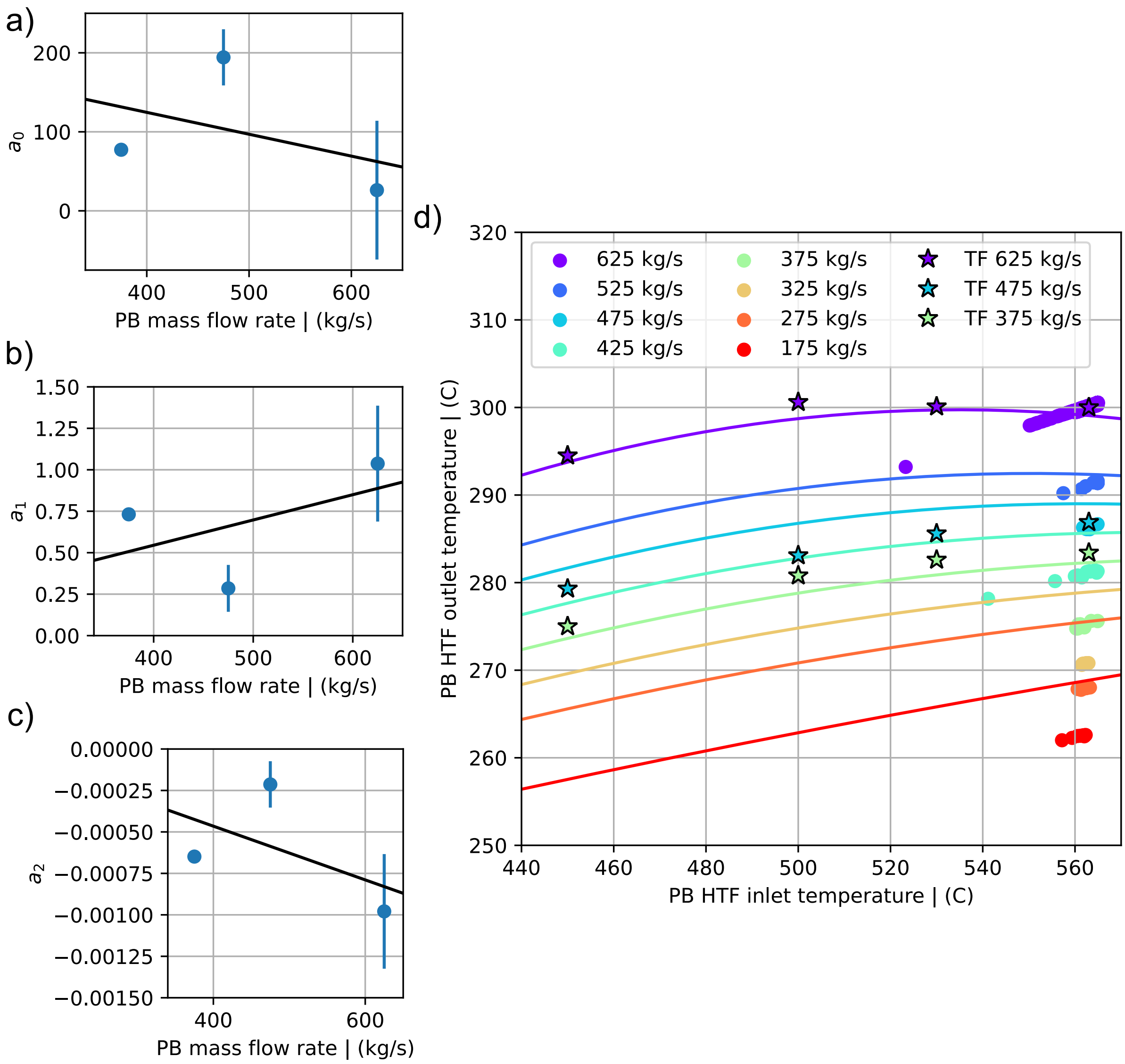

Figure 3: Fitting of the output temperature of the power block of the CR system. Coefficients of the quadratic function in a), b) and c). The results of the functions (solid lines), which are quadratic in $T_{\mathrm{PB,\,in}}$ and linear in $\dot{m}_{\mathrm{PB}}$, are shown in comparison to the *THERMOFLEX* (TF) data (stars) over which the fits were done and in comparison to the *SAM* data (dots) in d). The mass flow rates are color coded.

Power block for PT system

Since it was not possible to attain *THERMOFLEX* simulation data for the power block of the PT system, the *SAM* data were used to fit equation 2 for $P_{\text{el, grid}}$ and $T_{\text{PB, out}}$. In a first step the *SAM* data was separated into several bins in $\dot{m}_{\text{PB}}$ with a width of 50 t/h. The the electric power to the grid was fitted with:

$$P_{\text{el, grid}} = a \cdot T_{\text{PB, in}} + P_{\text{el, 0}} \tag{8}$$

and the outlet temperature with:

$$T_{\text{PB, out}} = a \cdot T_{\text{PB, in}} + T_{\text{out, 0}} \tag{9}$$

The fitted scaling factors a for different $\dot{m}_{\text{PB}}$ are shown in panels a) and the offset values in panels b) of Figs. 4 and 5 respectively. The error bars indicate the confidence intervals resulting from the fits. These coefficients were then again fitted with equation 2 over $\dot{m}_{\text{PB}}$, as shown by the black lines in the respective plots. This leads to the following equations mapping $P_{\text{el, grid}}$ and $T_{\text{PB, out}}$ over $\dot{m}_{\text{PB}}$ and $T_{\text{PB, in}}$:

$$P_{\text{el, grid}}\left(\dot{m}_{\text{PB}}, T_{\text{PB, in}}\right) = a\left(\dot{m}_{\text{PB}}\right) \cdot T_{\text{PB, in}} + P_{\text{el, 0}}\left(\dot{m}_{\text{PB}}\right) \tag{10}$$

$$T_{\text{PB, out}}\left(\dot{m}_{\text{PB}}, T_{\text{PB, in}}\right) = a\left(\dot{m}_{\text{PB}}\right) \cdot T_{\text{PB, in}} + T_{\text{out, 0}} \tag{11}$$

The results of these fitted functions are compared to the *SAM* data in panels c) of Figs. 4 and 5. The largest deviation of the function from a data point for $P_{\text{el, grid}}$ is less than 3 %. Furthermore, the multilinear function corresponds well to the *SAM* data for $T_{\text{PB, out}}$.

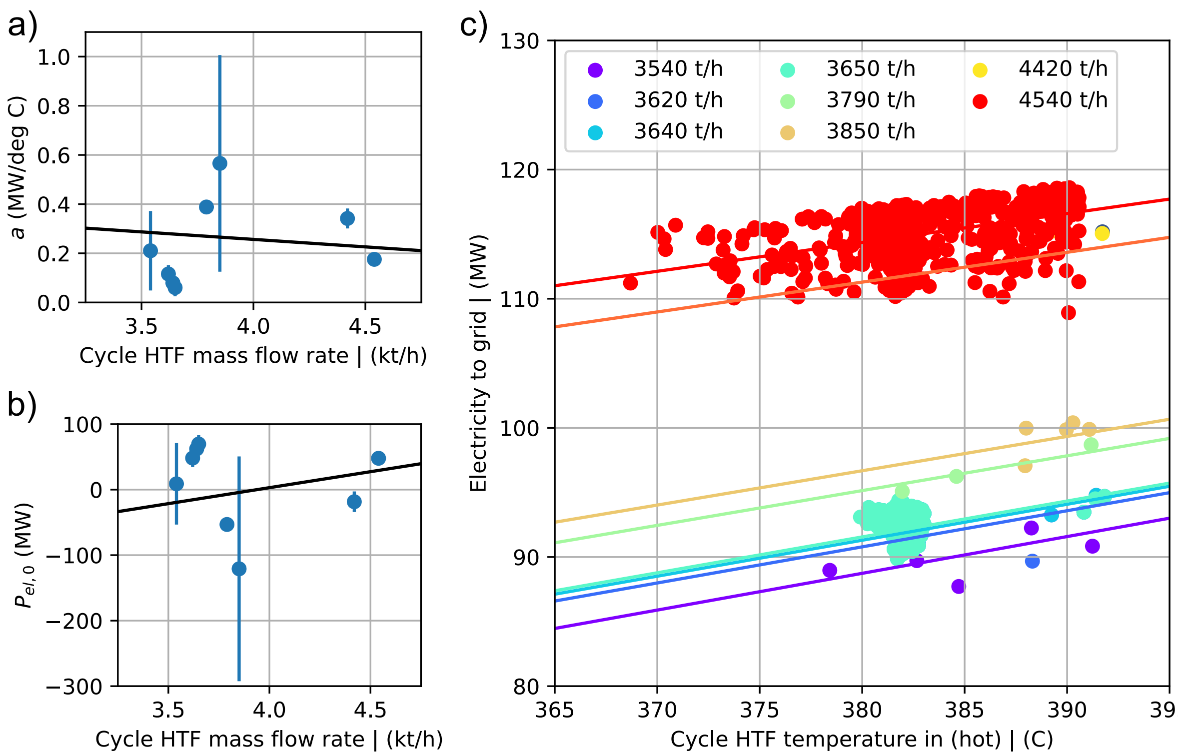

Figure 4: Fitting the electric power-to-grid output of the power block of the PT system. Scaling factor a for various mass flow rates in a) and offset values in b). The multilinear fit (solid lines) is shown in comparison to the data (dots) in c), where the respective mass flow rates are color coded.

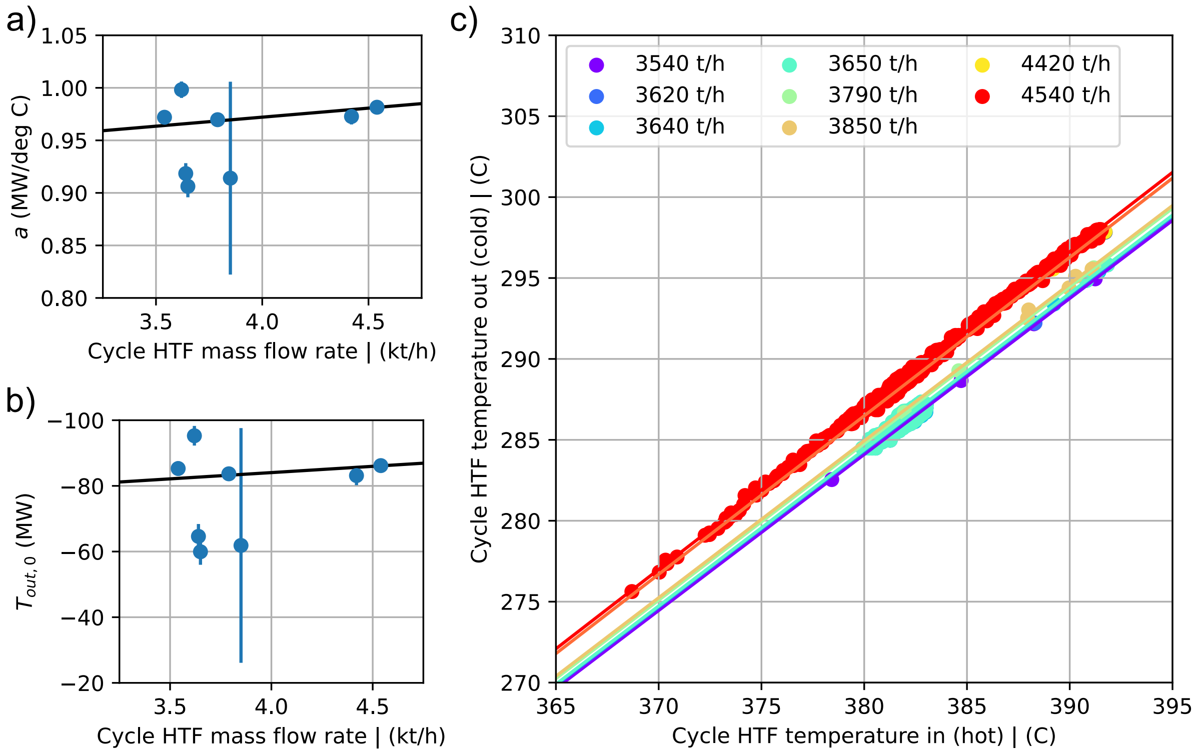

Figure 5: Fitting the output temperature of the power block of the PT system. Scaling factor a for various mass flow rates in a) and offset values in b). The multilinear fit (solid lines) are shown in comparison to the data (dots) in c), where the respective mass flow rates are color coded.

4.2 Central receiver two-tank plant

The hydraulic scheme of the CR plant used in the system simulations with *pytrnsys* is shown in Fig.6. There are mainly two operation modes and loops:

- the charging operational mode, where the solar central receiver generation loop, which collects energy from the sun and, or stores it in the molten salt storage tanks, or delivers it directly to the power block,
- the discharging operational mode, where the power block, either from the molten salt storage tanks and/or directly from the central receiver, consumes thermal energy to generate electricity.

The central receiver is enabled when there is enough normal irradiance and enough cold salt volume to be heated. The power block is activated when there is enough energy in the storage tank, which implies that regardless of the instantaneous irradiance, it can operate in the evening or at night.

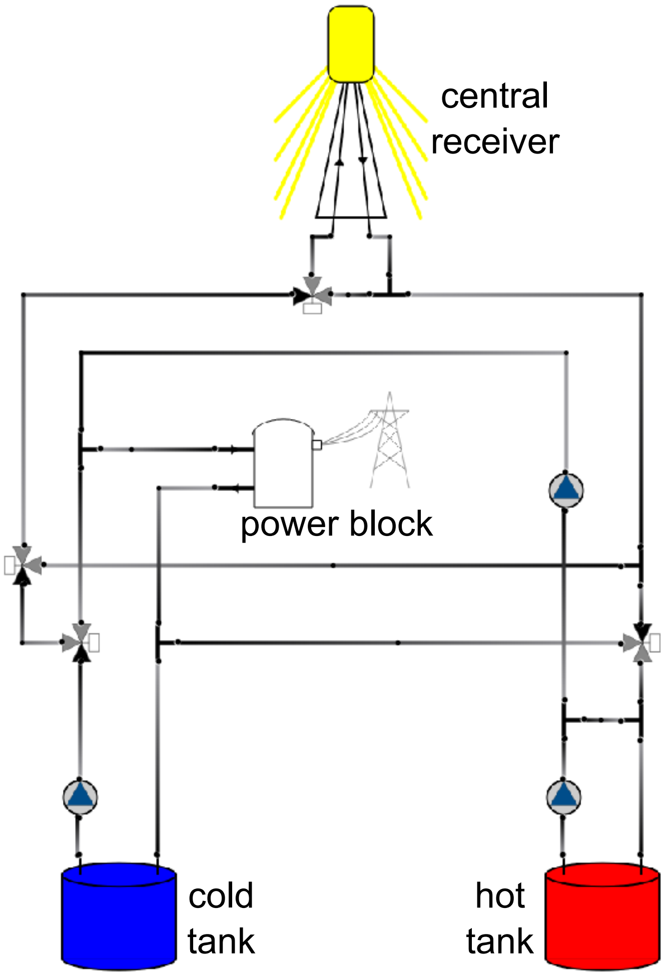

Figure 6: Hydraulic scheme of the CR plant simulated with *pytrnsys*.

The results used to compare between simulations with *SAM* and *TRNSYS* for three different power values over a three-day period in February are sown in Fig. 7. The power values compared are the thermal output power of the CR, the thermal input power to the power block and the electrical power fed to the grid by the power block. While the central receiver power is well reproduced by *TRNSYS* as compared to *SAM*, there is some shift visible for the other two powers. This is related to how startup processes are handled in both simulation environments.

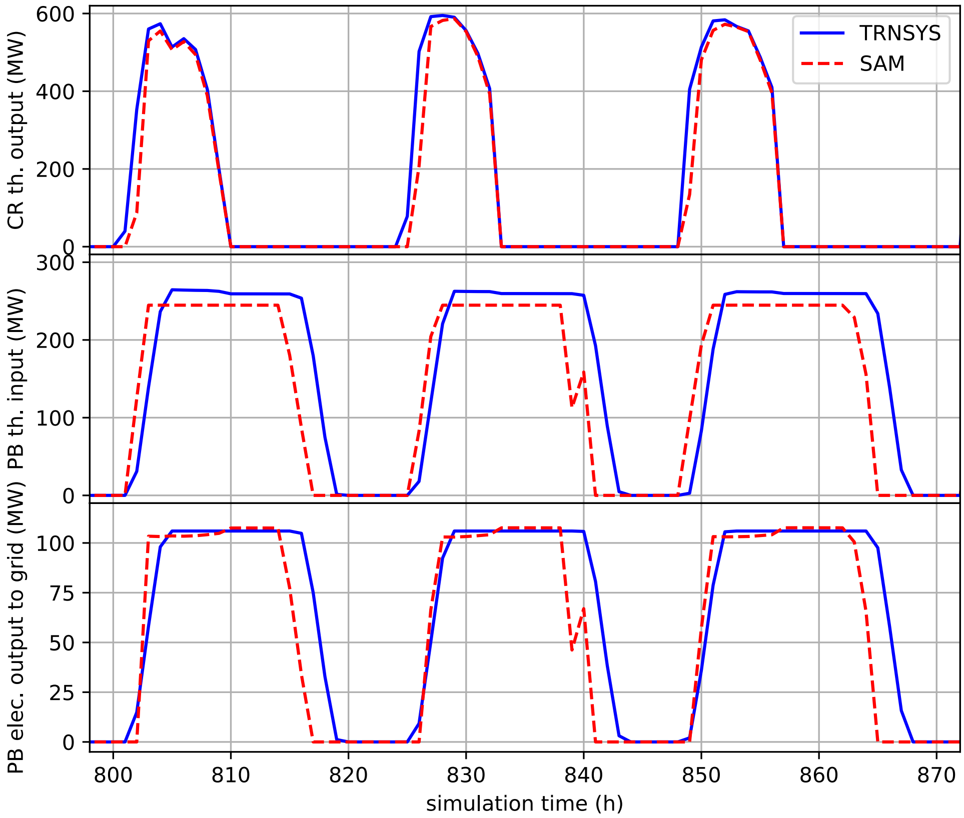

Figure 7: Comparison between the *SAM* and the *TRNSYS* simulations for a selected time window of the simulation over a year. The upper panel shows the thermal output power of the central receiver, the central one the thermal input power to the power block and the bottom panel the electric output power to the grid.

The monthly energy balances for both *SAM* and TRNSYS simulations are shown in Fig. 8. The positive side of the energy balance is composed by the thermal output energy of the CR only, while on the negative side there are three components. The first is the electricity provided to the grid, the second are the losses and consumption of the power block, which is the difference between the energy provided to the power block and its electrical output, and the third is the thermal energy lost in the storage tanks.

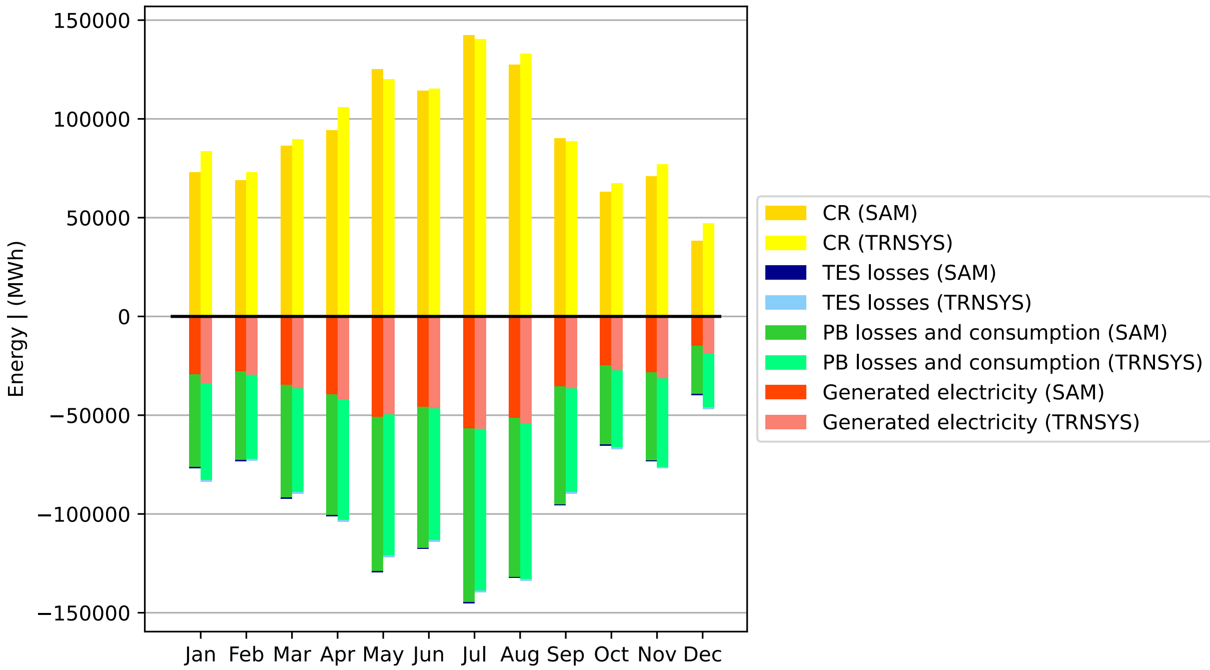

Figure 8: Comparison between the monthly energy balances of the *SAM* and the *TRNSYS* simulations.

Results of both simulation programs are compared: the thermal output of the CR obtained with *TRNSYS* is 4.3 % higher than the obtained with SAM. The power block losses and consumption obtained with *TRNSYS* is 5.6 % higher than SAM. And the TES losses calculated with *TRNSYS* are 0.4 % lower than those calculated with SAM. All this concludes in the generated electricity obtained with *TRNSYS* is 0.2 % lower than the generated electricity obtained with SAM.

4.3 Parabolic trough two-tank plant

Fig. 9 shows the hydraulic scheme of the PT plant used in the system simulations with *pytrnsys*. These simulations are currently in progress.

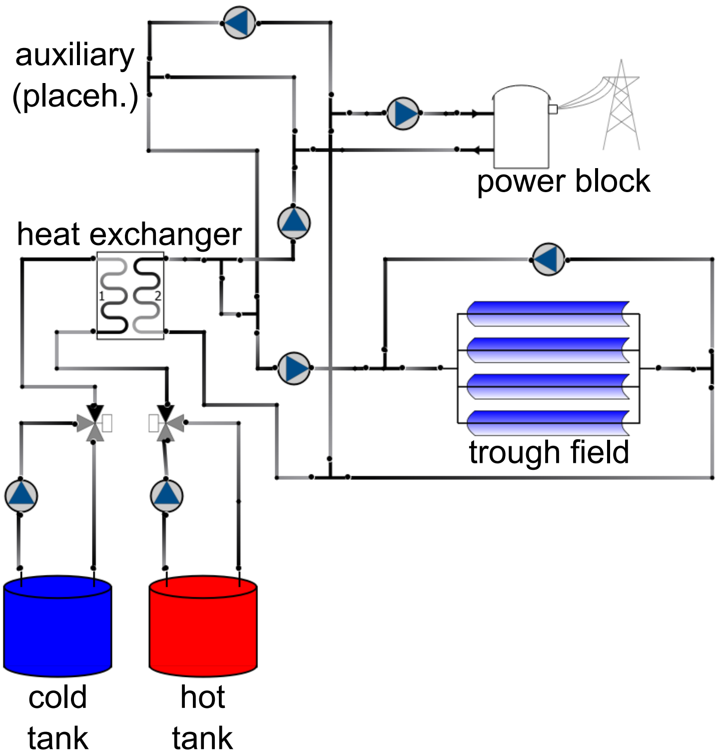

Figure 9: Hydraulic scheme of the PT plant simulated with *pytrnsys*.

5 International cooperation

Newcline is a project of the European consortium *CSP ERANET*. Besides *SPF* there are four European partners involved:

- *Universitat Politècnica de Catalunya (UPC)* is a Catalan university located in Terrassa (Barcelona). Within the UPC, the technological center of heat and mass transfer (CTTC) is leading the whole project. Their main expertise is on computational fluid dynamics in the relevant field.
- *Empresarios Agrupados (EAI)* is a Spanish engineering firm with a strong experience in thermal storage systems for CSP plants and provides support in the engineering and design aspects of the project.
- The *Thermal Process Technology* department of the *German Aerospace Center DLR* has been involved in the development of high-temperature thermal energy storage over decades. *Newcline* will employ the institution's testing facility *TESIS* in Cologne to demonstrate its two filler concepts on a pilot scale.
- *Kraftblock* is a German company founded in 2014 that develops and sells high-temperature (up to 1300 °C) energy storage systems. It follows a sustainable approach using 85 % recycled raw materials. *Kraftblock's* task within *Newcline* is the material development.

Online meetings between the partners are conducted on a three-week basis and a first in-person meeting at *DLR* in Cologne took place in June 2022. The next in-person meeting is planned for January 2023 at *EAI* in Madrid.

6 Publications and conference contributions

So far, neither publications nor conference contributions were generated.

7 Evaluation 2022 and outlook 2023

In the second year of the project *Newcline* the base for the system simulations was laid by creating models for the different components needed to represent a CSP plant. This was achieved through a close collaboration between *SPF* and *EAI*. The strong experience of *EAI* in designing and building CSP power plants enabled *SPF* to employ their know-how on *TRNSYS* simulations to extend the existing simulation framework to support the simulation of such systems.

The next step after the creation of component models is the simulation of the reference CR and PT systems. While this was completed for the former, it is underway for the latter and will be finished soon. The results reported here and the final outcome of the simulation of the PT system will be reported in deliverable 8.1 of the project, wrapping up this task within the system simulation efforts of *Newcline*.

In 2023 the work on system simulations will reach the core of the project: the thermocline tank. Based on previous work by *DLR* a thermocline energy storage model will be developed and validated with data from pilot experiments. The integration of thermocline concepts into the system simulations will be reported in deliverable 8.2.

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