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Analysis and Simulation of CSP and Hybridized Systems

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Modeling and Evaluation of a Solar Trigeneration System With Thermal Energy Storage

A Study

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Abstract. In the present study, an on-demand solar combined cooling, heating, and power (CCHP) system with parabolic trough collector (PTC) and solid-state thermal energy storage (TES) is investigated, which will be demonstrated on-site in 2024 at the Administration Building of the Lavrio Technological and Cultural Park (LTCP) in Attica, Greece, covering the energy needs of the building in form of heating and electricity in winter and cooling during summer. The system is based on a combined Organic Rankine Cycle and an Ejector Cooling Cycle (ORC-ECC), which is modeled and simulated in a steady-state manner while the PTC and TES systems are modeled dynamically, i.e., they are influenced by the thermal inertia of the components, the variable weather conditions of the location, and the defined operating strategies. The ORC-ECC simulation results show an efficiency of up to 14.20 % for the ORC system and a Coefficient of Performance (COP) of 0.10 for the ECC system under defined conditions. The dynamic simulations for the specified operating strategies indicate that on typical sunny days up to 100 % of the consumers' electricity consumption can be covered by the system.

Keywords: Solar Trigeneration System, Parabolic Trough Collector (PTC), Thermal Energy Storage (TES), Organic Rankine Cycle (ORC), Ejector Cooling Cycle (ECC), Simulation

1. Introduction

The EU SET plan for CSP aims to achieve significant cost reductions of existing technologies (in the short term) and to work towards developing the next generation of technologies (in the longer term). According to IRENA, in 2021, the levelized cost of electricity (LCOE) from CSP was 0.114 €/kWh$_e$, while only 110 MW$_e$ of new CSP plants were commissioned globally [1]. To further reduce costs, the implementation of highly efficient, flexible CSP technologies equipped with thermal energy storage (TES) is necessary. Furthermore, higher overall system efficiencies can be attained by combined cooling, heating, and power (CCHP) schemes that can receive additional revenue by covering the heating and cooling demands of utility, commercial, or residential consumers.

The joint European project Thermal Energy Storage for On-demand Solar Trigeneration (TES4Trig) aims at unifying the above strategies into a single innovative CCHP system (TES4Trig system) driven by a PTC field. The TES4Trig system comprises an Organic Rankine Cycle (ORC) coupled with an Ejector Cooling Cycle (ECC), a cost-effective solid-state TES system, as well as the PTC field. The TES4Trig system will be demonstrated on-site at the Administration Building of the Lavrio Technological and Cultural Park (LTCP) in Attica, Greece, and cover its energy needs. By that, the system's feasibility shall be proven, and its performance evaluated in a real operating environment. On sunny days, solar power from the PTC field can be used directly for driving the ORC-ECC system. To enhance operational flexibility, the TES can be charged with surplus solar thermal power from the PTC field, allowing on-demand electricity generation throughout the whole year as well as space heating and cooling production in winter and summer, respectively.

The demonstration phase is planned to take place in 2024. The Solar-Institut Jülich has the main focus on simulation work, which includes simulations of the whole TES4Trig system and its performance, as well as validation with available measurement data. Within the project, a first version of the simulation model of the TES4Trig system (combining the PTC, TES, and ORC-ECC systems) has been designed. The PTC and TES simulation models are based on [2] and have been modified, enhanced, and customized for the present study. The PTC field and TES modeling and validation have been discussed in detail in [2-4]. In the present study, the development of the ORC-ECC simulation model as well as the results of the first simulations of the complete TES4Trig system, are presented and discussed.

2. Description of Simulation Models and Analysis

As it is shown in Figure 1, the TES4Trig system has been divided into two parts. The left part comprises a PTC field, a TES, and a heat exchanger (HEX), which are interconnected through a heat transfer fluid (HTF) loop. The HEX transfers the energy from the PTC system and TES to the ORC-ECC system, which is shown on the right part of the overall system in Figure 1. The ORC-ECC system can produce either electricity and space heating through the ORC or cooling through the ECC.

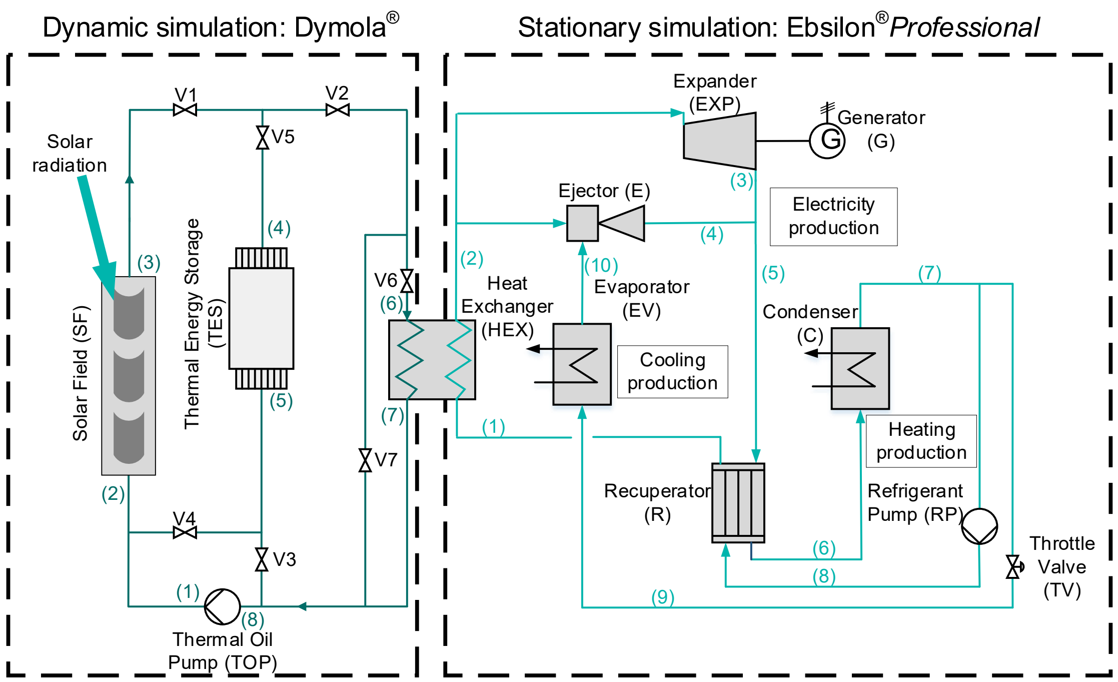

Figure 1. *The TES4Trig system is divided into two parts: dynamic modeling (left) and steady-state simulation (right).*

The PTC and TES systems have been dynamically modeled and simulated in Dymola® (based on Modelica language) to investigate the influence of weather-dependent variations on system performance. The ORC-ECC system is modeled and simulated in a steady-state manner since its functionality primarily depends on user demand rather than the weather conditions due to the application of the integrated TES. More details about the individual components are given in the following sections 2.1 and 2.2.

2.1. Stationary simulation of ORC-ECC

The modeling of the ORC-ECC system was carried out using Ebsilon®*Professional*. The ORC-ECC system has four different operating modes, as shown in Table 1. Heating and electricity are generated by the ORC components, while cooling is provided by the ECC system. Since space heating and cooling are usually not required at the same time, the ORC and ECC do not operate simultaneously. The system uses a recuperator for both ORC and ECC operations. R1233zd(E) was chosen as the working fluid owing to its safety (non-toxic and non-flammable) and environmentally favorable properties (zero Ozone Depletion Potential (ODP), ultra-low Global Warming Potential (GWP)). [5]

Table 1. *Application of the individual operating modes.*

Operation	Electricity	Heating	Cooling
1) Summer operation with cooling (cooling only)			x
2) Summer operation without cooling (electricity only)	x		
3) Winter operation with heating (combined heat and power (CHP))	x	x	
4) Winter operation without heating (electricity only)	x		

Figure 2 shows the T-s diagram for the ORC system on the left and the T-s diagram for the ECC system on the right. The ORC system as a thermal cycle basically consists of a condenser (C) for heat generation, a pump, the heat exchanger (HEX) connected to the solar field, and an expander for power generation. The ECC system also as a thermal cycle consists of the shared heat exchanger (HEX), the shared condenser (C), an ejector (E), and, ultimately, an evaporator (EV) for cooling. There are only two different design pressure levels in the ORC system, while the ECC system requires three different design pressure levels. The highest temperature level for ORC and ECC systems is 135 °C and 140 °C, respectively. A superheating of the organic fluid by 20 K is specified for both systems in HEX.

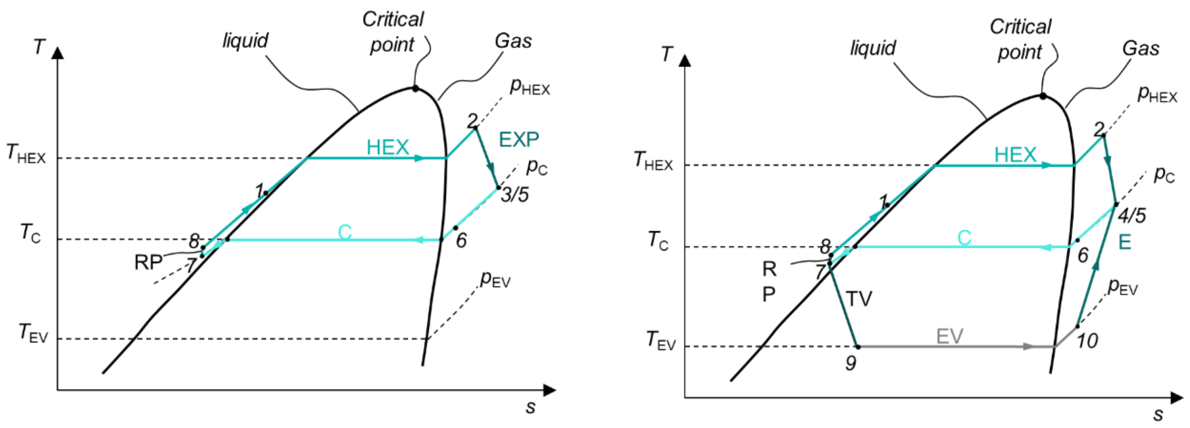

Figure 2. *T-s diagram for the ORC system (left), T-s diagram for the ECC system (right).*

The design temperatures and pressures are shown in

Table ***2*** for the ORC and the ECC mode. The HEX provides a nominal capacity of 75 kW_{th} in nominal design condition. After the condenser, subcooling of 5 K is provided. An isentropic efficiency of 65 % and a mechanical efficiency of 90 % were assumed for the expander and the pump.

Table 2. *Design temperatures and pressures for the ORC and ECC system with abbreviations according to the T-s diagrams of Figure 2.*

Components	**ORC mode**		**ECC mode**	
	T [°C]	*p* [bar]	*T* [°C]	*p* [bar]
Heat exchanger (HEX)	135.00	17.35	140.00	20.93
Condenser (C) for				
- Operating mode 1:			45.00	2.52
- Operating mode 2:	55.00	3.39		
- Operating mode 3:	21.00	3.39		
- Operating mode 4:	40.00	3.39		
Evaporator (EV)			5.00	0.59

Discussion and results

After determining the required design conditions, the ORC system was modeled and simulated in Ebsilon®*Professional* for full load and various part loads. The expander was modeled as a turbine. The efficiencies of the turbine and pump were assumed to be constant, and the components with heat-exchanging functions were supposed to have no pressure losses. With these assumptions, the gross efficiencies of the system at full and part load remain constant and have values of 11.39 %, 9.72 %, and 14.20 % for operation modes 2, 3, and 4, respectively.

The ejector of the ECC system is a device with two fluid inlets and one fluid outlet, as is shown in Figure 2 of [6]. A high-pressure flow (primary or driving flow) from the HEX enters through a high-pressure inlet and is mixed with a low-pressure flow (secondary or entrainment flow) that enters through a low-pressure inlet (coming from the EV). The mixed flow (entrained flow) is then discharged through the outlet with an intermediate, so-called back pressure. The ejector has the purpose of increasing the pressure of the low-pressure stream by entraining it with the accelerated high-pressure stream [6,7]. For modeling the ECC system, the ejector has been programmed and modeled as a new component in Ebsilon®*Professional*. The algorithm for calculating the ejector parameters was taken from [6]. The newly modeled ejector was implemented in the simulation model of the ECC system. As the cooling demand for the consumer (i.e., the LTCP) is much higher than the cooling generated, it is planned to operate the ECC system only at full load. The ECC system has a COP of 0.10.

The output of the heat exchanger, generator, condenser, and evaporator are listed in Table 3 for all operating modes in full load condition. There is no generator for the summer operation with cooling (mode 1), and no evaporator for all other operating modes is available.

Table 3. *Results of the ECC system for design (full load) mode.*

Component output	Operating mode 1	Operating mode 2	Operating mode 3	Operating mode 4
Heat exchanger capacity [kW_{th}]	75.00	75.00	75.00	75.00
Generator produced power [kW_e]		8.50	7.29	10.65
Condenser power [kW_{th}]	80.97	64.4	65.56	62.33
Evaporator power [kW_{th}]	7.67			

2.2 Dynamic simulation of TES4Trig system

The dynamic simulation of the TES4Trig system was carried out in Dymola®. The components PTC field and TES have been modeled in detail and discretized in one dimension. The concrete TES model used in the current version of the TES4Trig simulation is not the same TES design as shall be installed at LCPT in reality as the data was not available at the time of writing the present paper but was configured to deliver identical design values in the simulation. The technical assumptions for the simulations are shown in Table 4. The simulations were dynamic and, therefore, influenced by the thermal inertia of the components, the variable weather conditions of the location, and the defined operating strategies.

Table 4. *Technical assumptions for the PTC and TES components.*

Technology	Technical Assumptions
PTC	Heat Transfer Fluid: Helisol® XA Nominal field outlet temperature: 380 °C PTC Field size: 150 kW
TES	Storage medium: Concrete Nominal ΔT: 50 °C Charge and discharge power: 75 kW_{th} Storage capacity: 400 kWh

Operating modes

The operating modes at nominal condition are defined for one day for the location Lavrio, Greece. The sequence of the operating modes that are active for defined conditions during a day are shown in Figure 3 and described below.

At the beginning of the day, at sunrise, the SF preheating mode begins, i.e., the oil starts to circulate in the PTC field with the minimum mass flow rate which is defined as 50 % of the nominal rate. The PTC field consists of two rows of collectors with a total of 96 m and, as stated in Table 4, has a nominal thermal power of 150 kW. The SF preheating phase continues up to a temperature of 180 °C for the oil at the PTC field outlet. This temperature is defined as the minimum inlet temperature of oil into the TES.

The charging mode (TES Charge) starts immediately after the SF preheating mode. In this mode, the oil flows through the TES to charge it, and the mass flow rate is maintained at a constant permissible minimum until the PTC outlet temperature of 310 °C is attained.

Following this, the production and TES charge mode starts. For the specified typical day, it is assumed that a constant power of 75 kW_{th} is supplied to the ORC-ECC system (regardless of the demand), which leads to a temperature reduction of 50 °C at the HEX generator in the nominal operating conditions. In case the PTC field yields higher power, the TES is simultaneously charged with the remaining power above the required 75 kW_{th} for the ORC-ECC system.

In the afternoon, when the PTC field no longer provides sufficient power, the TES compensates for the required power difference, i.e., production and TES discharge are performed simultaneously.

After sunset, only the TES discharge mode takes place and continues until energy is no longer required by the consumer, or the TES is empty. The empty state of the TES is when the TES temperature at its hottest point reaches 180 °C.

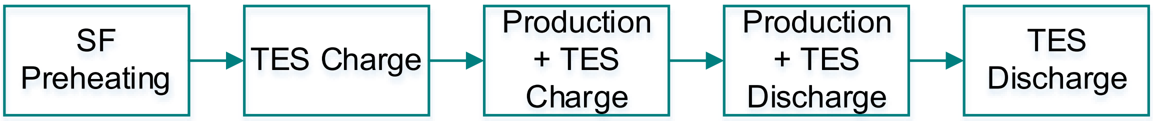

Figure 3. *Sequence of the operating modes for the TES4Trig system.*

Discussion and results

The temperature curves of T2 to T7 are shown in the diagrams of Figure 4 for a chosen day (June 26th) at the location Lavrio. T2 to T7 refer to the oil temperature at positions 2 to 7 of Figure 1, left. T2 and T3 are the oil temperatures at the inlet and outlet of the SF in the top left diagram, while in the bottom left diagram, T6 and T7 show the oil temperature at the inlet and outlet of HEX. T4 in the top right diagram shows the temperature at position 4. For the first three modes of the operation strategy, T4 and T5 in the top right diagram show the oil temperature curves at the inlet and outlet of TES, respectively. For the last two modes, where the oil flow is reversed, T4 and T5 are the oil temperatures at the outlet and inlet of the TES. The vertical lines indicate the time of the beginning of the switching of the operating modes. The turquoise squares in each diagram demonstrate the periods during which the respective component has been bypassed.

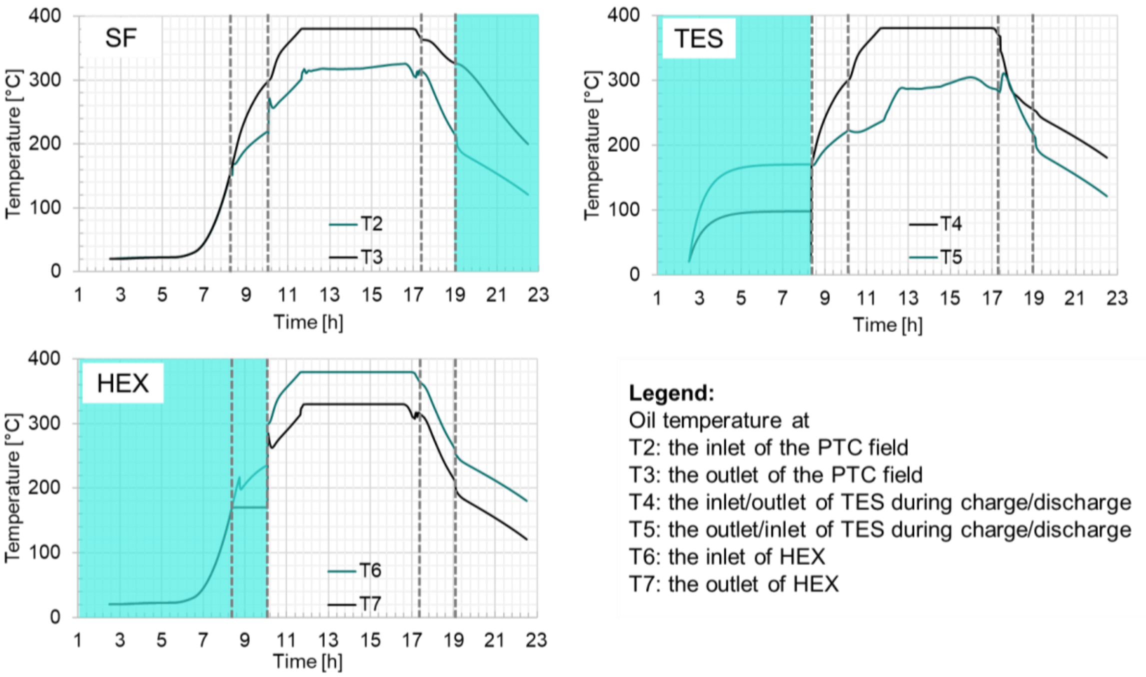

Figure 4. *Temperature curves of the thermal oil at the inlet and outlet of the SF (top left), TES (top right) and HEX (bottom left).*

The most important details are described below. The components are named according to Figure 1, left:

- In SF preheating mode, valves V1, V2, and V7 are open, and the TES and HEX are bypassed.
- In TES charging mode, the HEX is bypassed, and only valves V1, V3, and V5 are open.
- During production and charging mode, the HEX is activated, and except for valves V4 and V7, all the other valves are open. The mass flow through the oil pump is controlled by a PID controller, which ensures that the temperature T3 is maintained at a constant value of 380 °C as long as sufficient direct normal irradiance (DNI) is available. Temperatures T4 and T6 have the identical values as T3 in this mode.

- In production and discharge mode, valves V3 and V7 are closed. Opening valve V4 reverses the flow direction in the TES, i.e., temperatures T2 and T5 equate to T1, and T6 is the mixing temperature of T3 and T4 weighted by the corresponding mass flow rates.
- In TES discharge mode after sunset, the solar field is bypassed, i.e., valves V1, V3, and V7 are closed while temperatures T1 and T5 have the same values, and T4 and T6 are similar as well.

As it can be seen in Figure 4 bottom left, at noon, when the oil temperature of 380 °C is reached, with the nominal mass flow rate of oil through HEX, the nominal temperature difference of 50 °C is also attained. In this scenario, the TES can be charged up to ca. 70 % of its total capacity. This percentage will be different for winter or cloudy days. On the weekend, when no energy for the building is needed, the TES can be fully charged such that on Monday early morning hours, it can be partially discharged and recharged again when the system operates in production + TES charge mode later during the day. This could be repeated in the following days until the TES is empty.

By applying the efficiencies calculated in 2.1, it is now possible to verify how much of the building demand can be supported by the TES4Trig system. On a typical summer day when no heating is required, it is suitable to apply the efficiency of operation mode two from Table 1 to calculate the output of the ORC system. In that case, the TES4Trig system can support the electricity consumption of the office (ca. 33 kWh_e) by up to 88 %. Only in the first hour of the day, it is necessary to have a backup from the grid, in case TES had been fully discharged at the beginning of the day. As the system is working continuously in full load condition, there will be surplus electrical energy of ca. 80 kWh_e that can be fed into the network or saved as thermal energy in TES for the following days. If TES was not fully discharged the previous day, the TES4Trig system has the possibility to support the electricity consumption of the building up to 100 %.

3. Outlook

The TES4Trig system shall be commissioned by March 2024, applying a new generation of TES system that uses aggregates as the storage medium. Until the end of the project, the simulation model of the TES4Trig system will be continuously improved, its functionality extended, and, ideally, validations of components carried out (once measurement data is available). Furthermore, it is planned to perform a simulation of a scaled-up TES4Trig system.

Data availability statement

The detailed and extensive amount of data supporting the results of this paper is only (and even only in parts) accessible to the consortium members of project TES4Trig within legal restrictions bound by a cooperation agreement. For reasons of maintaining intellectual property, the information and data presented in this paper is limited.

Author contributions

Z. Mahdi: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing;

J. C. Sattler: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing;

S. Alexopoulos: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing;

K. Braimakis: Conceptualization, Investigation, Methodology, Project administration, Validation, Writing – review & editing;

C. Teixeira Boura: Supervision, Project administration, Writing – review & editing;

U. Herrmann: Supervision, Writing – review & editing;

S. Karellas: Supervision, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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