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Analysis and Simulation of CSP and Hybridized Systems

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Simulation and Sensitivity Analysis of a Solar Driven Trigeneration System With Thermal Energy Storage

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Abstract. In the joint European project Thermal Energy Storage for On-demand Solar Trigeneration (TES4Trig), an innovative solar driven CCHP (Combined Cycle Heat and Power) system was investigated. The main components of the CCHP system are an Organic Rankine Cycle (ORC) coupled with an Ejector Cooling Cycle (ECC), a solid-state thermal energy storage (TES) syfstem as well as a parabolic trough collector (PTC) field. The system will be demonstrated on-site at the Lavrio Technological and Cultural Park (LTCP) in Attica, Greece [1]. Simulation results of the system for supplying energy to the administrative building of the LTCP are presented. Furthermore, a simulation for a scaled-up system was carried out for a hospital in Heraklion. The results show that the scaled-up system can deliver 10 % of the electricity demand and 39 % of the heat demand with the ORC cycle. The ECC cycle covers 15 % of the cooling requirement. By that, a load factor of 81.4 % over a year is achieved. This can be further optimized by considering other PTC field variables and TES capacities. From an energy perspective, it can be concluded from the results that a TES4Trig system for large electricity, heating and cooling consumers such as a hospital has great potential for the future. It is preferable that the consumer has a continuous energy consumption to maximize system utilization.

Keywords: Trigeneration, Parabolic Trough Collector, PTC, Thermal Energy Storage, TES, Scale-Up

1. Introduction

In the current European project Thermal Energy Storage for On-demand Solar Trigeneration (TES4Trig), a solar combined cooling, heating, and power (CCHP) system will be built on the site of the Lavrion Technological and Cultural Park (LTCP) in Attica, Greece, in the near future. The solar CCHP system will comprise a parabolic trough collector (PTC) field with a nominal thermal power of 150 kW_{th}, a solid-state thermal energy storage (TES) with a capacity of 400 kWh as well as an Organic Rankine Cycle (ORC) coupled with an Ejector Cooling Cycle (ECC). In this study, the focus is set on results that were achieved for a simulation of the trigeneration system to be built at the LTCP as well as a scale-up simulation of a system for a hospital in Heraklion, Greece.

2. Simulation of solar trigeneration system at the LTCP

In order to investigate the behaviour of the CCHP system for the different seasons over the course of the year, a simulation model was created with the energy system optimization software TOP-Energy® [2]. Regarding the reference system, the PTC has a nominal thermal power of 150 kW_{th} and the TES has a thermal capacity of 400 kWh, whereby the thermal power for charging and discharging is 75 kW_{th}. The reference CCHP plant can deliver a nominal electric power of 10 kW_e. The focus on this work is on parallel electricity and heat production while cooling was neglected as only the electricity production was prioritized in summer (therefore the ECC part, which is normally used for cooling, is not considered in the simulation model). The simulation model is shown in Figure 1 and comprises the solar field, the TES, the ORC unit and the input data table of the building's heat demand. An extra implemented priority block enables the priority setting of different operation strategies. A backup district heating supplier block is required for the times when the ORC cannot deliver heating. The component electricity supplier is the national grid, which is needed to compensate the electricity demand of the building at times when the ORC unit produces too little. The electricity demand block is the building's demand given as a data table. Regarding the energy demand of the administrative building, energy is needed only on work days from Monday to Friday between 10:00 and 17:00. The average heat demand of the administration building is 3.2 kW_{th}. This heat demand varies depending on how cold the weather is, while from June through to October there is no demand for heat, as shown in Figure 2. The total heat demand of the administration building is approximately 28 MWh_{th} per year. The average electricity demand of the administration building is about 1.2 kW_e to power the offices. Unlike the heat demand, the electricity demand is relatively constant regardless of the weather.

The simulation for the reference plant resulted that 86 % of the annual electricity demand of the administrative building can be covered by the ORC, i.e. 8.8 MWh_e of 10.2 MWh_e. Regarding the heat demand, 80 % of the annual heat demand of the administrative building can be covered by the ORC, i.e. 24.2 MWh_{th} of 28 MWh_{th}. [3] The simulations were carried out for the LTCP building in Lavrion using TMY weather data and the electricity and heat demand curves provided by the partner MESE with time intervals of one hour. Figure 2 (left) shows the typical heat and cooling demand curve of the LTCP office building for one year. As can be seen, there is no heating requirement in the summer period, only a cooling requirement (room cooling by means of cold air supply). Figure 2 (right) shows the typical electricity demand curve of the LTCP office building for one day. There is no electrical power demand outside office hours. The daily electrical power demand curve is used for all days of the year. A sensitivity analysis was carried out to investigate the implemented configuration of the CCHP system in Lavrion (reference system) and to compare it with different layouts of the storage and ORC-ECC. Table 1 shows nine cases of ORC and TES capacity sizing which were simulated. Simulation case 5 (SIM 5) is the reference plant. The ORC generator size (for electricity generation and heating via a condenser in the ORC) was varied between 50 and 100 kWh_{th} and the TES capacity was varied between 200 and 800 kWh_{th}. [3] In all cases, the ORC has an efficiency of 13.3 %. The PTC field is identical for all simulation series with a rated thermal output of 150 kW_{th}. It is considered that electricity and thermal energy can be provided in the winter period and only cooling energy in the summer period (corresponding to the TES4Trig system at the Lavrion site).

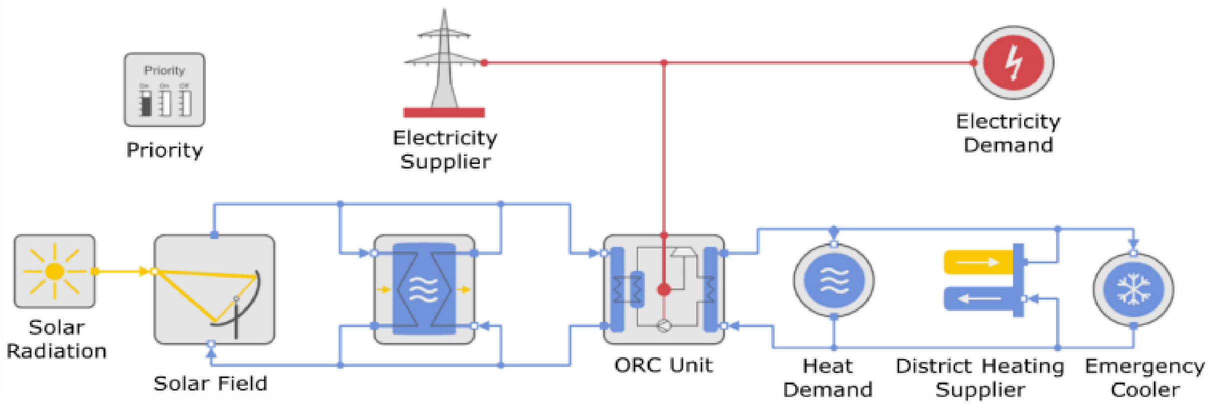

Figure 1. *Simulation model showing the TES4Trig system in TOP-Energy® [3]*

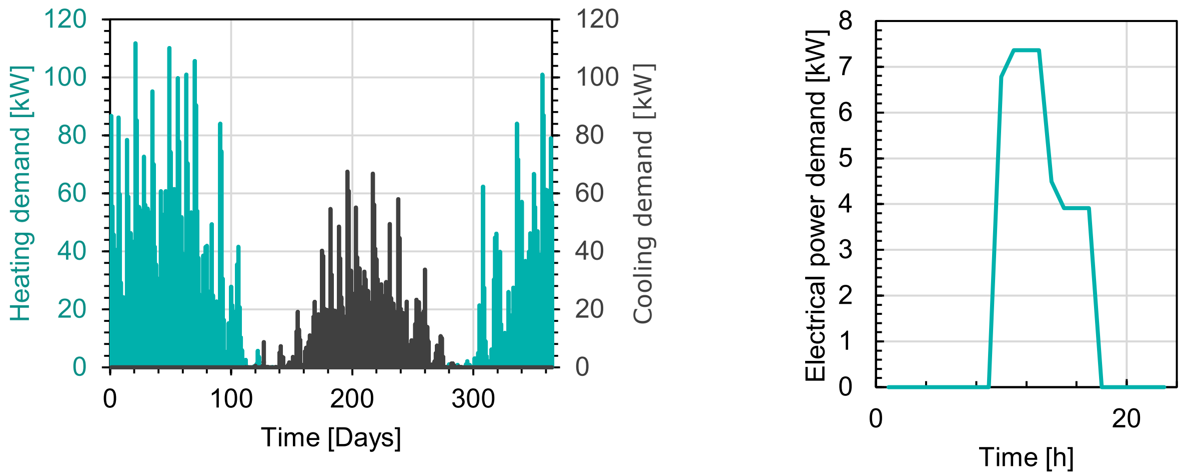

Figure 2. *LTCP heating and cooling demand curve for a typical year (left), LTCP electricity demand curve for a typical day (right) (Source: MESE)*

Table 1. *Simulation cases for various ORC generator sizes and TES capacities [3]*

Simulation case	ORC generator size (kW_{th})	TES capacity (kWh_{th})
SIM 1 / SIM 2 / SIM 3	50 / 50 / 50	200 / 400 / 800
SIM 4 / SIM 5 / SIM 6	75 / 75 / 75	200 / 400 / 800
SIM 7 / SIM 8 / SIM 9	100 / 100 / 100	200 / 400 / 800

The simulation results are shown in the following diagrams. Figure 3 (left) shows the proportion of electricity generated by the ORC and used for the building as well as the proportion of electricity fed into the grid. It can be seen here that the TES4Trig system is oversized for electricity generation in the winter period for the LTCP building. Figure 3 (right) shows how much thermal energy can be used by the ORC and ECC over the entire year. It can be seen that the TES4Trig system has a high proportion of unusable heat throughout the year. Some of the unusable heat is generated in the winter months, as the parabolic trough collector field provides more thermal energy than it needs according to the space heating demand curve. The excess heat generated is therefore not used and can be used for other means e.g. district heating. In the summer months, at weekends when the LTCP is closed, only a very small proportion of the heat energy generated by the parabolic trough collector system can be stored in the heat storage tank. This means that the parabolic trough collector system either does not generate heat energy at the weekend or does not produce any at all.

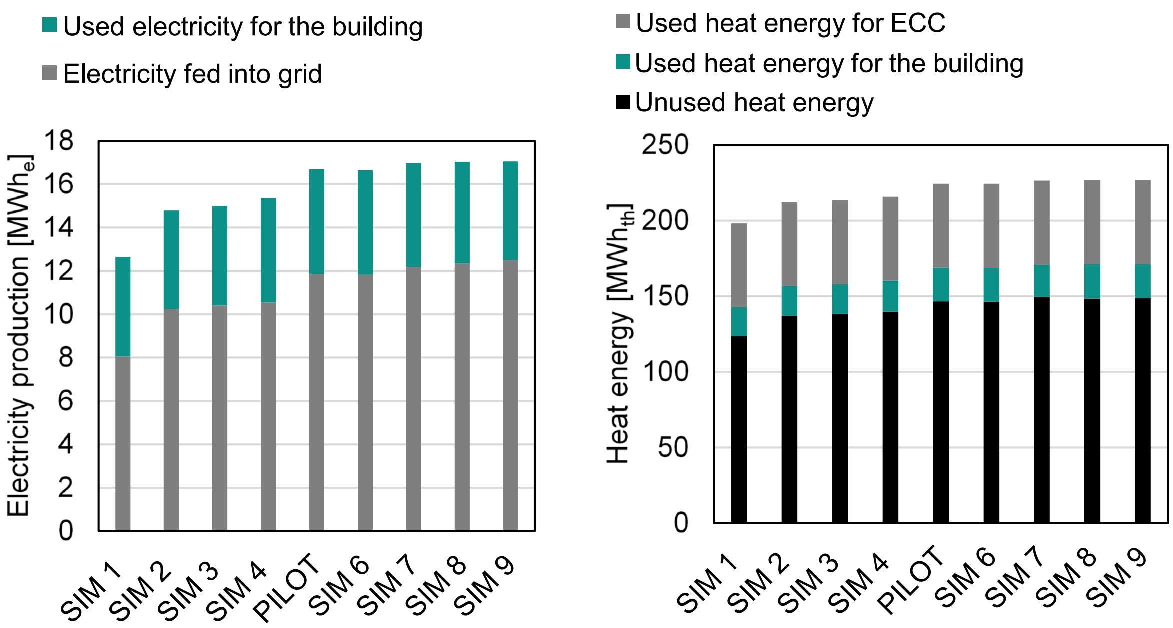

Figure 3. *Breakdown of electricity production (left) and thermal energy (right) generated by the ORC system*

Figure 4 in the left and right diagrams shows the distribution of sources from which the electricity and heat requirements of the LTCP building are covered for the entire year. According to the defined priority, the demand is covered first by the ORC and then by the electricity or heating network as support. Here, too, it can be seen that the pilot system supplies the highest proportions of both electricity and heat for the building. On days with low direct solar radiation, electricity must be supplied from the grid and heat from the heating network.

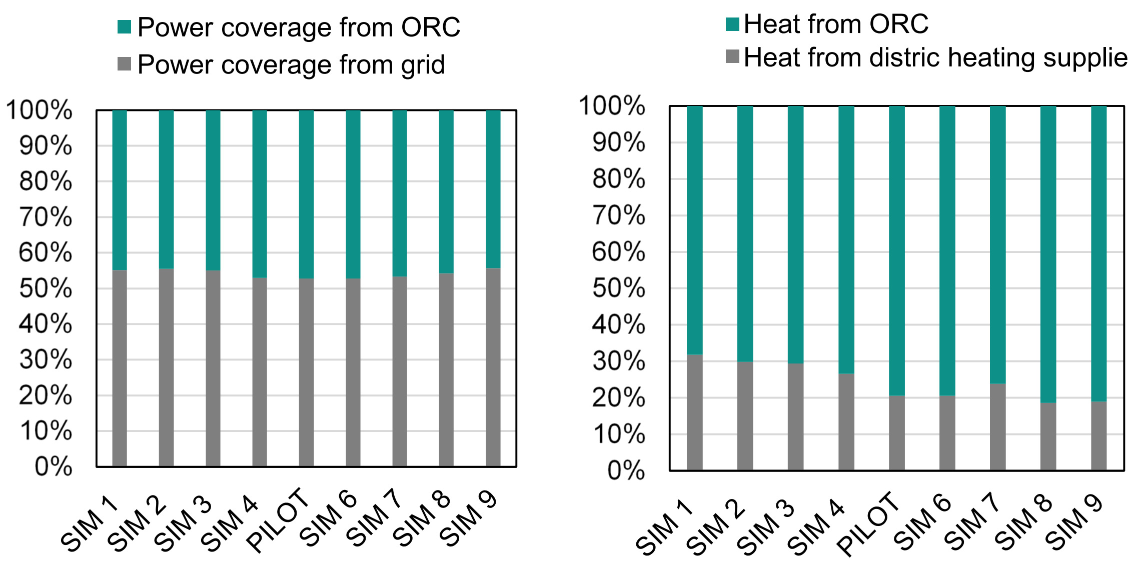

Figure 4. *ORC share in covering the electricity demand (left) and heat demand (right) for the LTCP*

In conclusion, the following summary can be made for the TES4Trig system for the provision of electricity, heating and cooling for the LTCP building: The TES4Trig system is likely to be more suitable for buildings that have a continuous demand for electricity, heating and cooling.

3. Simulation of trigeneration system for a hospital in Heraklion

In the following, scale-up simulations for a hospital in Heraklion are discussed in more detail. The output of the PTC field, the capacity of the heat accumulator and the parameters of the ORC were defined by a project partner and are as shown in Table 2.

Table 2. *Defined component parameters for the scaled-up system*

Component	Variable	Assumption
Parabolic trough collector field	Aperture	5,184 m^2
	Concentration factor	75
	Optical efficiency	81 %
TES	Storage capacity	21.2 MWh_{th}
	Charge and discharge power	4.2 MW_{th}
ORC	Electrical nominal power	1.7 MW_e
	Thermal input power	10.9 MW_{th}
	Nominal electrical efficiency	16 %

The electricity, heat and cooling demand curves of the hospital in Heraklion, shown in Figure 5, were used as input in the simulation model.

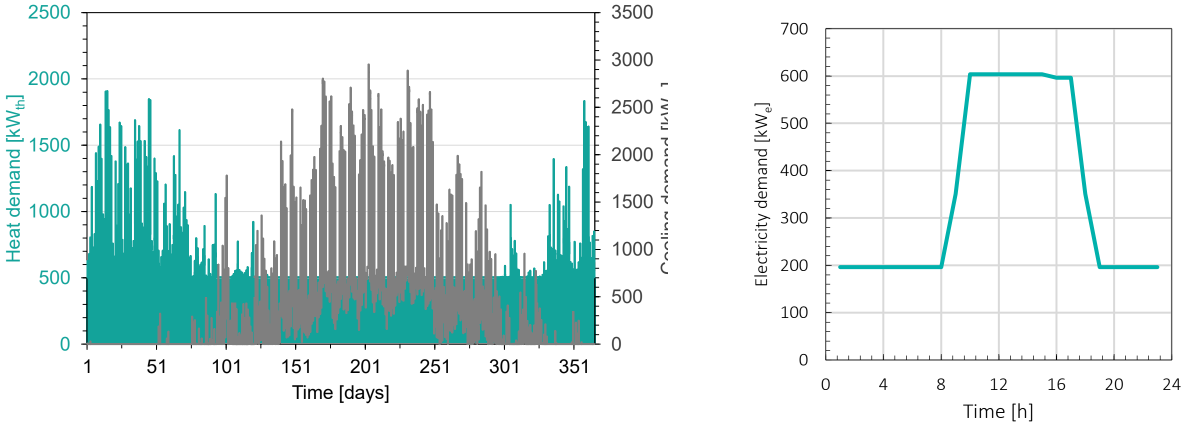

Figure 5. *Heating demand (minimum continuous demand is approx. 504 kW, green data) and cooling demand (grey data) for a typical year (left) and electricity demand for a typical day (right) from the hospital in Heraklion. In the summer period, there is also a minimum demand for heat output (approx. 504 kW)*

As shown in Figure 6, the scaled-up TES4Trig system for supplying electricity, heat and cooling production for the hospital can deliver 10 % of the electricity demand and 39 % of the heat demand with the ORC cycle. The ECC cycle covers 15 % of the cooling requirement. The hospital's annual electricity requirement is 2.65 GWh_e, the heating requirement is 4.89 GWh_{th} and the cooling requirement is 3.22 GWh_{th}. It should also be noted here that the TES4Trig system generates cooling from heat supplied from the parabolic trough collector field and this is done with an efficiency of approx. 10 % from the heat supplied from the solar field. The scaled-up TES4Trig system achieves a load factor of 81.4 % over a year.

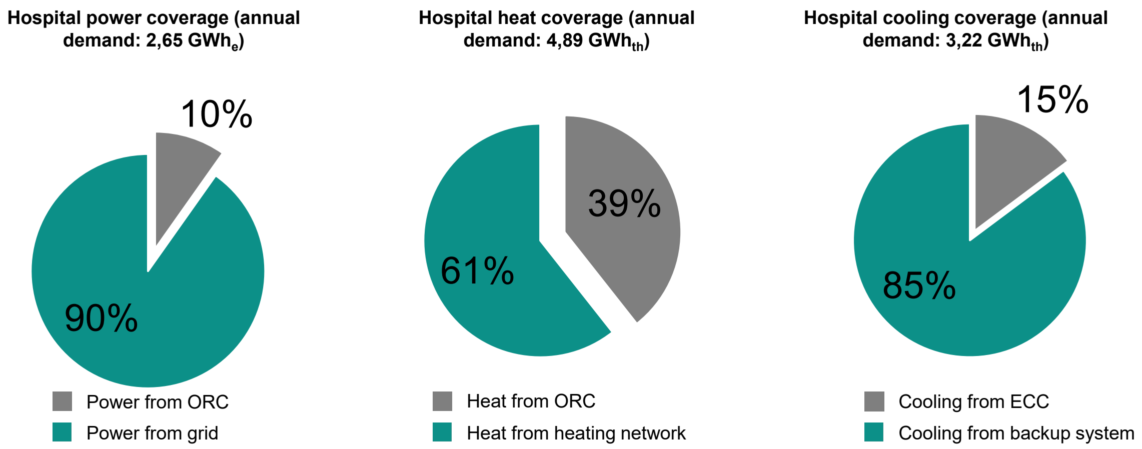

Figure 6. *Simulation results for TES4Trig system scale-up for supplying power, heat and cooling a hospital in Heraklion, Greece*

In conclusion, the scaled-up TES4Trig system achieve high load factor over the year. This can be further optimized by considering other PTC field variables and TES capacities. From an energy perspective, it can be concluded from the results that a TES4Trig system for large electricity, heating and cooling consumers such as the hospital has great potential for the future. It is preferable that the consumer has a continuous consumption of electricity, heating and cooling in order to maximize system utilization.

Outlook

A validation of the simulations was not possible as measurement data was not available. Once the TES4Trig solar trigeneration system is operational, the validation can be included as a task in a follow-up project.

Data availability statement

The detailed and extensive amount of data supporting the results of this work 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 work is limited.

Author contributions

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

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

J. C. Sattler: Conceptualization, Investigation, Methodology, Project administration, Validation, Writing – review & editing;

M. Elbadawi: Writing – original draft, Writing – review & editing;

K. Braimakis: Writing – review & editing;

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D. Tziritas: Data curation, Writing – review & editing;

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

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

Competing interests

The authors declare no competing interests.

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