Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

SEHRENE ETES Integration to the Kızıldere-2 Geothermal Power Plant

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Keywords: ETES, Carnot Battery, Geothermal Energy Storage, Flexible Geothermal Power Generation

ABSTRACT

The Electro-Thermal-Energy-Storage (ETES) concept is proposed by the Horizon Europe SEHRENE Project as a potential alternative to conventional energy storage systems. The ETES system is designed to store electricity in the form of heat during periods of renewable overproduction, and then reconvert the stored thermal energy into electricity during periods of high power demand. SEHRENE explores the potential application of this system across different context where Waste Heat (WH) is available. This study specifically investigates the potential application of the ETES system to the Kızıldere-2 geothermal power plant in Turkey, operated by Zorlu Enerji. The plant currently operates at an average power output of approximately 50 MW. The on-design analysis shows that integrating the "FULL ETES" configuration significantly enhances operational flexibility, allowing the power output to be modulated between 70% and 145% of the nominal capacity. The off-design analysis examines the influence of ambient air temperature — which varies significantly throughout the year in the Kızıldere region — on ETES performance. Results indicate a substantial deviation in power output, with an average increase of approximately +14% during the coldest month and a decrease of about 15% during the hottest month. Ambient air temperature affects only the discharging phase via the Organic Rankine Cycle (ORC), while the heat pump (HP) performance remains unchanged. Several key design choices are discussed and supported by a sensitivity analysis.

1 INTRODUCTION

Because geothermal energy is continuously available, it has traditionally been used to provide baseload power. This approach made economic sense given the high upfront costs of geothermal plants — running them at full capacity helped maximize returns on investment. However, the growing adoption of renewable energy, especially solar and wind, is transforming the power generation landscape. The intermittency of these resources requires pairing them with flexible, dispatchable generation and effective energy storage to maintain grid stability and support Transmission System Operators (TSOs), ultimately improving both reliability and profitability.

Consequently, flexible and dispatchable power generation has become increasingly important — and in many cases, more profitable — than traditional baseload operation.

Several strategies can be used to achieve flexible power generation from geothermal resources, including:

1. Operating geothermal plants in a flexible mode to provide dispatchable power when needed.

2. Maintaining baseload operation while incorporating an energy storage system, allowing the plant to deliver a flexible and adjustable power output.

This paper focuses on the second option, investigating the integration of an innovative Electro-Thermal Energy Storage (ETES) system in a geothermal plant. The Electro-Thermal-Energy-Storage (ETES) concept is proposed as a potential alternative to conventional energy storage systems by the Horizon Europe SEHRENE Project. This system is designed to store electricity in the form of thermal energy during periods of renewable overproduction, and then reconvert the stored thermal energy into electricity during high power demand periods. Within the SEHRENE project, the applicability of ETES is explored across various scenarios where waste heat is available. In this study, the ETES system is specifically assessed for integration into the Kızıldere-2 geothermal power plant in Turkey, operated by Zorlu Enerji, which currently has an average power generation capacity of approximately 50 MW.

The coupling of the ETES system to Kızıldere-2 power plant is analyzed through a tailor-made numerical model [1], taking into account two different design options:

1. The first case-study reflects the demonstrative system included in the SEHRENE Grant Agreement (GA), which considers a well defined size of the ETES (indicated in the following discussion as “SEHRENE”).
2. The second case-study investigates the ETES maximum size that could potentially be installed in Kızıldere-2 power plant to exploit the whole available WH (indicated in the following discussion as “FULL ETES”).

The first case represents a demonstrative ETES system with an electrical power output of about 10% of the average power of the base-load geothermal plant. The second case, instead, explores the maximum feasible ETES size that can utilize all available waste heat before brine reinjection at the Kızıldere-2 plant. The reinjection temperature is set to 90°C, considering 5°C safety margin with respect to scaling risk [2].

Moreover, each of these two options is evaluated under different operating conditions:

i) at design ambient temperature
ii) at extreme ambient conditions, i.e. considering the coldest and hottest ambient temperature conditions throughout the year, taking into account the off-design behavior of the heat exchangers of the system. The variation of ambient conditions only affects the ETES discharging phase.

Simulation results demonstrate the strong potential of this technology as a sustainable green storage solution. The ETES system shows promising economic and environmental performance, relying on non-critical raw materials for its storage unit. Moreover, this unit employs a thermally enhanced Phase Change Material (PCM), offering both the cost and supply-chain advantages of a widely available material and the technical benefit of quasi-isothermal heat transfer during charging and discharging.

A simplified layout of the Kızıldere-2 geothermal power plant is reported in **Figure 1** for the sake of clarity. This power plant is made by a triple-flash section and a binary ORC unit supplied by the exhaust heat at the high pressure steam turbine outlet. Waste heat for the ETES is extracted from the geothermal fluid prior to reinjection: the figure highlights the coupling point where the ETES system would be integrated.

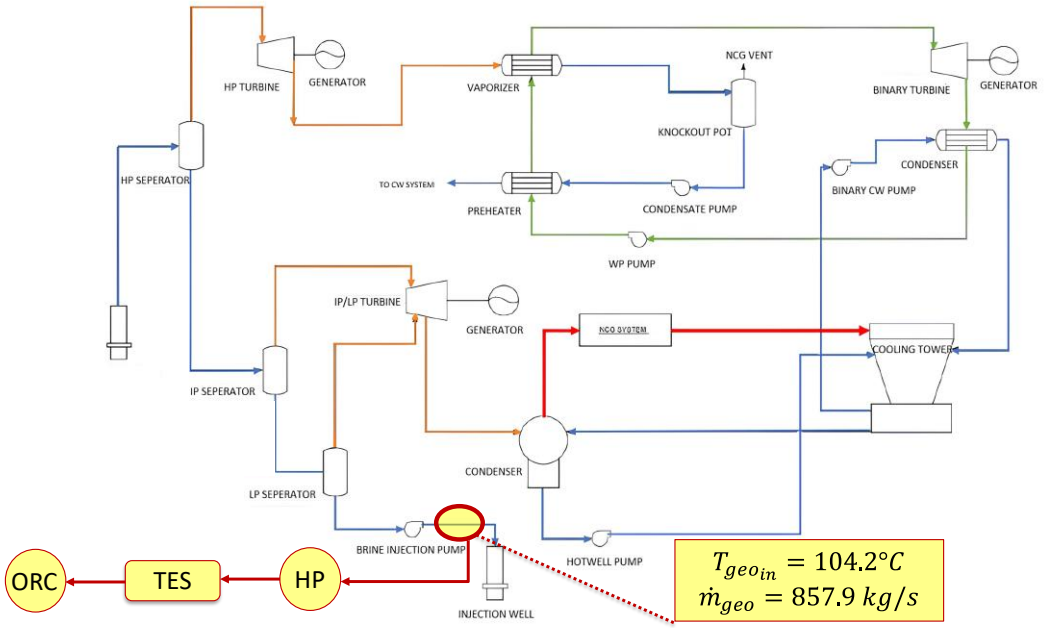


Figure 1. Kızıldere-2 triple flash and binary cycle integrated in the current plant design. The point of coupling of the ETES is here highlighted: the brine stream prior to re-injection is the waste heat source.

2 METHODOLOGY AND RESULTS

The ETES system [1] is made by two main sub-systems:

1. A charging section, featuring a High Temperature Heat Pump (HTHP)
2. A discharging section, consisting of an Organic Rankine Cycle (ORC) unit

These two sub-systems are coupled by a Phase Change Material Thermal Energy Storage (PCM-TES) unit, which is the most innovative component of the overall system. The geothermal brine at the coupling point is always

available and can therefore be used both in the charging cycle, to supply the HTHP evaporator, and in the discharging cycle, to preheat the working fluid before entering the PCM-TES.

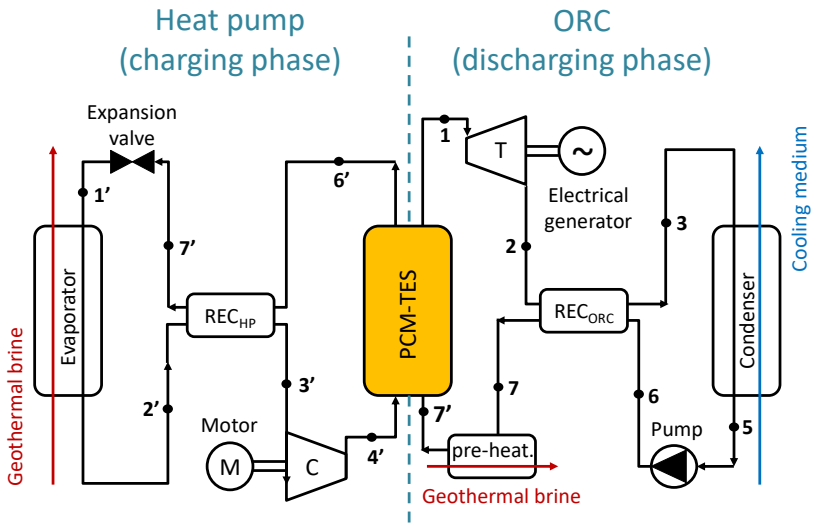


Figure 2. ETES simplified model representation: process flow diagram for charging and discharging cycles.

2.1 Modelling assumptions

Table 1 summarizes the modelling assumptions, in terms of components sizing. Table 2 summarizes the modelling assumptions in terms of boundary conditions.

mode	Stage	Component	Δp [kPa]	ΔT_{pp} [°C]	η_{is} [-] ; η_{th} [-] ; η_{hyd} [-]
HP/ORC		PCM-TES	50	8	η_{th} = 0.95
HP	high pressure	REC$_{HP}$	50	8	
HP	low pressure	REC$_{HP}$	10	-	
HP		EVA	10	8	
ORC		COND	8	8	
ORC	high pressure	REC$_{ORC}$	50	8	
ORC	low pressure	REC$_{ORC}$	8	-	
ORC		Pre-heater	50	8	
HP		Compressor			0.8
HP/ORC		Pump			0.75
ORC		Turbine			0.85
HP/ORC		Generator/Motor			0.95
HP/ORC		Gearbox			0.97
HP	Cond	HP_Brine_Pump	30		η_{hyd} = 0.8

Table 1. Modelling assumptions: components sizing and selection.

		SEHRENE	FULL ETES	SEHRENE	FULL ETES	SEHRENE	FULL ETES
Fluid	**T_{in} [°C]**	**T_{out} [°C]**		$\dot{m}$ [kg/s] (**HP EVA**)		$\dot{m}$ [kg/s] (**ORC Pre-heater**)	
brine	104.2	101.2	90	857.9	857.9	171.58	857.9
PCM	134.8	134.8	134.8			$\dot{m}$ [kg/s] (**ORC Condenser**)	
air	19.91	23.91	23.91			6779	34274
	7.57	11.57	11.57			6675	33675
	32.45	36.45	36.45			6566	33050

Table 2. Modelling assumptions: boundary conditions. The assumptions which are not consistent between the demonstrative "SEHRENE" use-case (ETES size for about 10% increase of the base-load plant power) and the full potential extrapolation "FULL ETES" (full exploitation of the waste heat available) are reported in different colors for the sake of clarity.

Air temperatures are evaluated considering the mean value during the coldest month (January), the mean value during the warmest month (August), and the overall annual mean averaged over the decade 2010–2020 [9]. The design of the system is carried out considering the average temperature along the year which is roughly 20°C. The performance of the system under off-design ORC cooling temperature conditions is assessed by accounting for the off-design behavior of the heat exchangers. A dedicated routine preserves, for each heat exchanger, the same overall heat transfer conductance (given by the product of the overall heat transfer coefficient and the heat exchange area) by varying the pinch points as independent variables. This approach provides approximate

results, as the heat transfer coefficient is assumed constant. The variation of the heat transfer coefficient will be introduced in the model to refine the approximations presented here.

This system is designed for a 4-hour charging period, coinciding with the central hours of the day when renewable electricity production is high and prices are low, and a 2-hour discharging period, covering the peak demand typically occurring in the evening. Cyclopentane is used as the working fluid in both the HTHP and ORC cycles. It was selected in the preliminary analysis based on a comparison of low-GWP fluids suitable for this temperature range [1].

2.2 Simulation results and discussion

Simulation results are reported in Table 3 for design and off-design conditions applied to both the demonstrative "SEHRENE ETES" and the "FULL ETES".

The round trip efficiency (RTE) is defined as: $round\ trip\ efficiency\ (RTE) = \frac{Output\ net\ electrical\ energy\ (ORC)}{Input\ net\ electrical\ energy\ (HTHP)}$

Case	Condition	T_{air} [°C]	η_{ORC} [-]	COP_{HP} [-]	RTE [-]	PR_{COMR} [-]	$P_{el_in(net)}$ [MW]	E_{el_in} [MWh]	$P_{el_out(net)}$ [MW]	E_{el_out} [MWh]
SEHRENE	Off-d COLD	7.57	0.154	5.25	1.01	3.14	2.51	10.04	5.09	10.18
	Design	**19.91**	**0.140**	**5.25**	**0.89**	**3.14**	**2.51**	**10.04**	**4.48**	**8.95**
	Off-d HOT	32.45	0.123	5.25	0.76	3.14	2.51	10.04	3.81	7.62
FULL ETES	Off-d COLD	7.57	0.154	4.30	0.85	4.23	15.20	60.80	25.74	51.49
	Design	**19.91**	**0.140**	**4.30**	**0.74**	**4.23**	**15.20**	**60.80**	**22.58**	**45.16**
	Off-d HOT	32.45	0.123	4.30	0.63	4.23	15.20	60.80	19.18	38.36

Table 3. Simulation results: Round Trip Efficiency (RTE) and ETES electrical net power output are highlighted as they synthetically represent the performance of the ETES system. Moreover, the system performance under design operating conditions is in bold text. SEHRENE (ETES size for about 10% increase of the base-load plant power) and FULL ETES (full exploitation of the waste heat available).

Figure 3 shows the thermodynamic cycle in all the analyzed conditions reported in Table 3 on a Temperature-specific entropy diagram. The same indexing used for the system layout reported in Figure 1 is used to identify the points of interest along the thermodynamic process. Figure 4 shows the difference in the thermal waste heat source exploitation between the demonstrative use-case and the full-potential exploitation case.

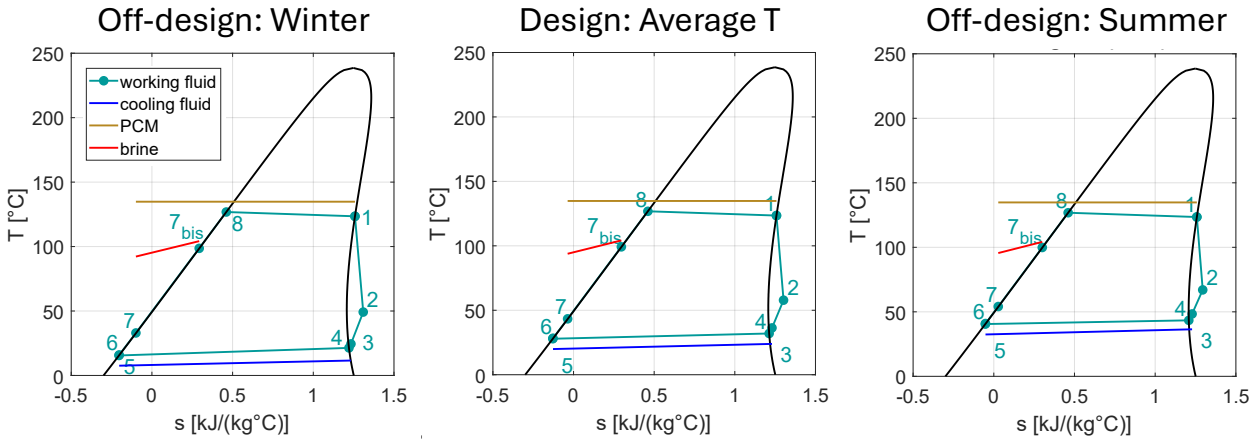


Figure 3. Discharging thermodynamic cycle through ORC recuperative unit represented on Temperature-specific entropy diagram for nominal operation and two off-design conditions.

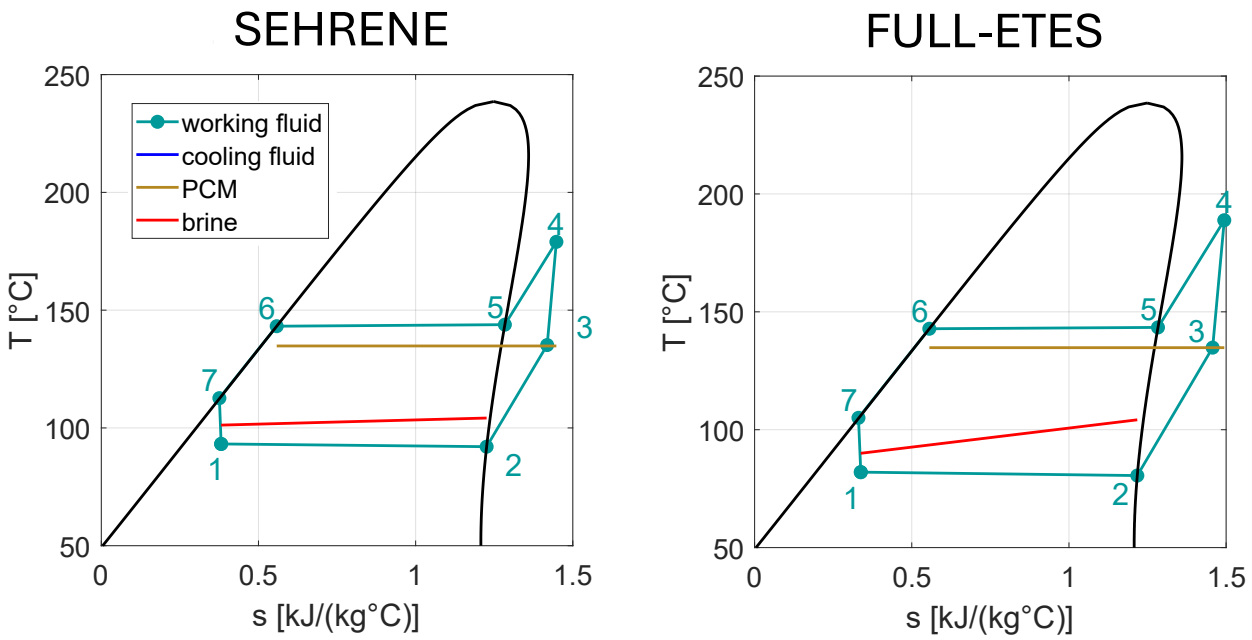


Figure 4. Charging thermodynamic cycle through HTHP recuperative unit represented on Temperature-specific entropy diagram for demonstrative "SEHRENE" case and full WH exploitation "FULL-ETES" case.

Both solutions are studied under the assumption of building a dedicated Air Cooled Condenser (ACC) for the ETES system. A water-cooled ORC would offer higher performance; however, given the limited availability of water from the existing cooling tower, an air-cooled condenser (ACC) is the preferred solution, as it does not impact the performance of the existing power plant. Moreover, both solutions are designed for a charging time of 4 hours and a discharging time of 2 hours. The system is designed to be charged when the electricity prices are at their lowest, typically during the central hours of the day (i.e., around noon) that are usually affected by high renewable energy production and low demand. On the other hand, the discharging time needs to cover typical power demand peak hours, which usually occur in the early evening.

It is worth to mention that the first case "SEHRENE", targets a high round trip efficiency value.

The goal of this case, studied under the SEHRENE EU Project, is to prove the high potential of this technology in comparison with conventional commercial energy storage technologies. In this specific application, thanks to the possibility of using the WH during both the charging and the discharging phases, the achievable RTE ranges between 76% and 101% depending on the ambient air temperature. This system is able to provide a net power output of 4.48 MW with a RTE of 89% under nominal operating conditions. The high round-trip efficiency is achieved by minimizing heat transfer irreversibilities caused by finite temperature differences between the ORC cycle's evaporation and condensation temperatures and the corresponding heat source and heat sink temperatures. Additionally, in the high-temperature heat pump charging cycle, a smaller temperature drop of the heat source allows for a higher evaporation temperature, reducing the temperature lift required by the heat pump (HP), and consequently increasing its coefficient of performance (COP). For this reason, in the charging cycle, the entire geothermal brine mass flow rate is utilized, resulting in a temperature drop of only 3 °C, as reported in Table 2. It is worth noting that the round-trip efficiency can reach very high values, even exceeding 100% under the most favourable conditions (i.e. at the lowest ambient temperatures), due to the integration of waste heat (being the waste heat temperature higher than ambient temperature) in the specific process considered. Specifically, the HTHP stores electricity in the form of heat with a notably high COP, as the temperature lift is limited. During discharge, the ORC benefits from a significantly larger temperature drop across the turbine, which increases as the ambient temperature approaches its seasonal minimum. Moreover, the continuous availability of waste heat from the geothermal power plant enables additional thermal input during the discharging phase, further enhancing the ORC power output. The combined effect of waste heat availability and favourable climatic conditions therefore leads to a round-trip efficiency of the Carnot battery exceeding 100%.

The second case-study, referred to as "FULL ETES", simulates the largest possible system to ensure full exploitation of the thermal source, namely the WH carried by the brine at the reinjection point. The main

objective of this case study is to assess the power modulation achievable through ETES integration in this specific application. The analysis demonstrates the potential to operate the currently base-load plant as a dispatchable power unit. As a matter of fact, simulation results show that integrating the "FULL ETES" allows modulation of the power output between 70% and 145% of the nominal power of 50 MW with a RTE of roughly 74% under design operating conditions.

2.3 Sensitivity analysis

A sensitivity analysis is presented to investigate the impact of two design parameters: the selected PCM temperature (T_{PCM}) and the brine reinjection temperature ($T_{brine\text{-}reinj}$).

The first analysis examines the variation of ETES input and output net electrical power, the total thermal energy available for ORC discharge, and key performance indicators (KPIs), namely ORC efficiency, heat pump (HP) coefficient of performance (COP), and round-trip efficiency (RTE), as a function of T_{PCM}. All other assumptions are kept unchanged, including brine mass flow rate, temperature profile and temperature decay, ambient temperature conditions, and charging and discharging time intervals.

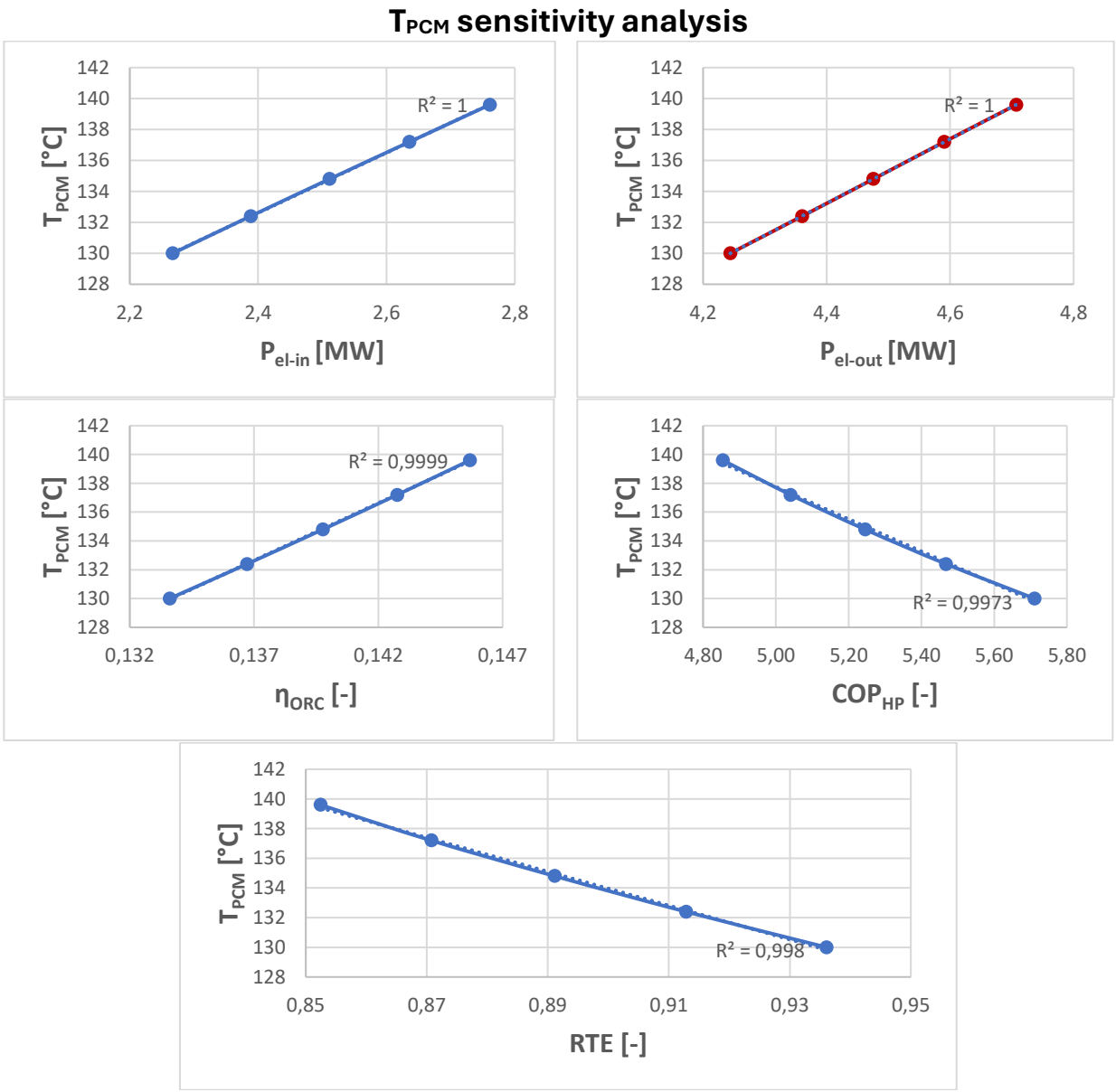


Figure 5. Sensitivity analysis results as a function of PCM temperature. $P_{el\text{-}in}$: net input electrical power; $P_{el\text{-}out}$: net output electrical power; η_{ORC}: ORC efficiency; COP_{HP}: HP COP; RTE: Round-Trip Efficiency.

The results show that both ETES input and output net electrical power increase linearly with increasing T_{PCM}. However, the relative increase of the output power is lower than that of the input power, leading to a decrease in RTE with increasing T_{PCM}. A PCM temperature of 134.8 °C is identified as a reasonable trade-off between

satisfactory power output and high RTE, while the amount of thermal energy stored in the TES and available for ORC discharge remains nearly constant over the investigated T_{PCM} range.

T_{PCM} [°C]	Q_{TES} [MWh]	$P_{el\text{-}in}$ [MW]	$P_{el\text{-}out}$ [MW]	η_{ORC} [-]	COP_{HP} [-]	RTE [-]
130.0	49.19	2.27	4.24	0.134	5.71	0.936
132.4	49.62	2.39	4.36	0.137	5.47	0.913
134.8	50.05	2.51	4.48	0.140	5.25	0.891
137.2	50.49	2.64	4.59	0.143	5.04	0.871
139.6	50.96	2.76	4.71	0.146	4.85	0.852

Table 4. Sensitivity analysis results as a function of PCM temperature.

The second analysis investigates the response of the same parameters to variations in the brine reinjection temperature, while keeping all other assumptions unchanged, including PCM temperature, ambient conditions, and operational time intervals.

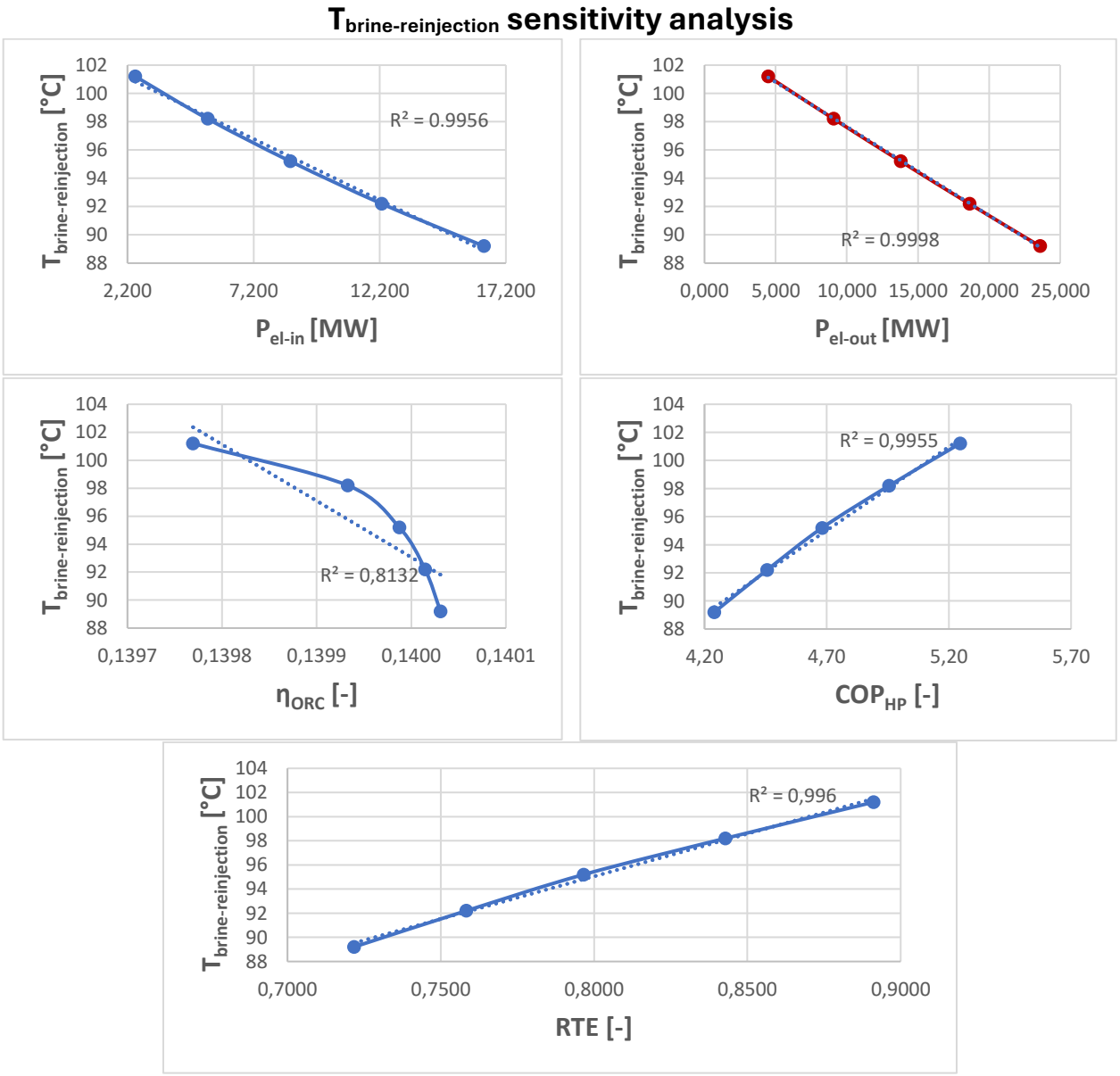


Figure 6. Sensitivity analysis results as a function of reinjection temperature. $P_{el\text{-}in}$: net input electrical power; $P_{el\text{-}out}$: net output electrical power; η_{ORC}: ORC efficiency; COP_{HP}: HP COP; RTE: Round-Trip Efficiency.

The results indicate that both ETES input and output net electrical power increase almost linearly with decreasing $T_{brine\text{-}reinj}$. The input power exhibits a relative increase higher than the output power, resulting in a substantial decrease in RTE as $T_{brine\text{-}reinj}$ decreases. It is worth noting that $T_{brine\text{-}reinj}$ has a strong influence on both ETES performance and system size. Owing to the high waste heat mass flow rate—equal to the brine reinjection

mass flow—the thermal energy stored in the TES and available for ORC discharge increases on average by 53.3 MWh for each 3 °C decrease in reinjection temperature.

$T_{brine-reinj}$ [°C]	Q_{TES} [MWh]	P_{el-in} [MW]	P_{el-out} [MW]	η_{ORC} [-]	COP_{HP} [-]	RTE [-]
101.2	50.05	2.51	4.48	0.1398	5.25	0.891
98.2	101.32	5.38	9.07	0.1399	4.95	0.843
95.2	153.99	8.66	13.79	0.1400	4.68	0.797
92.2	207.79	12.27	18.62	0.1400	4.46	0.758
89.2	263.13	16.33	23.58	0.1400	4.24	0.722

Table 5. Sensitivity analysis results as a function of brine reinjection temperature.

This finding motivated an additional analysis focused on the full exploitation of the available heat source. For this specific application with waste heat integration, the achievable output power is more relevant than RTE. As discussed in the concluding section, the full-potential ETES configuration enables significant advantages in power output modulation, effectively allowing the Kızıldere power plant to transition from base-load operation to flexible dispatch.

3 CONCLUSIONS

First of all, the analysis carried out in this study targets the design of an ETES system for integration in the Kızıldere-2 geothermal power plant for two different case-studies. The first one is a demonstrative use-case targeting a storage system electrical power output of around 10% of the average power output of the base-load geothermal plant, whereas the second case-study represents the maximum ETES size that could be installed at Kızıldere-2 to exploit the full amount of waste heat available at the coupling point before brine reinjection into the reservoir.

The on-design analysis shows that ETES adoption delivers a net power output of 4.48 MW with a round-trip efficiency (RTE) of 89% under nominal operating conditions in the “SEHRENE” case. Integrating the “FULL ETES” configuration further enables flexible operation, allowing the power output to be modulated between 70% and 145% of the 50 MW nominal capacity. The off-design analysis highlights the quite large deviation in power output (approximately +14% in the coldest day and -15% in the hottest day, for both cases) and RTE depending on the ambient air temperature, which exhibits a significant variation along the year in the Kızıldere region. The ambient air temperature affects only the discharging operation through the ORC, leaving unaltered the HTHP performance.

This numerical model, coupled with the data obtained from Turkish market scenarios, will allow to assess the potential economical benefit of ETES integration in Kızıldere-2 geothermal power plant. Moreover, the optimal size of the ETES system for this application will be the result of a techno-economic trade-off, taking into account the average hourly electricity prices combined with the cost of the equipment in terms of capital and operational expenses (CAPEX and OPEX). It is worth to mention that the follow-up of this preliminary study will also take into account the dynamic behavior of the ETES system, which will be essential to assess the actual performance of the ETES system in terms of flexibility and dispatchability when responding to rapid fluctuations of the electricity demand.

Beyond technical feasibility, this study is the first milestone to build a digital twin of the ETES system integrated with an Energy Management System (EMS). This valuable digital instrument that will result from SEHRENE project work will enable the users to assess the financial viability of ETES integration, including investment costs, operational benefits and constraints, as well as projected return on the investment with regards to market clearing price (MCP) and system marginal prices (SMP). The analysis will also consider revenue streams from enhanced power output, improved flexibility for grid services, and potential participation in electricity markets with variable pricing. By combining the technical and financial evaluations, the final aim of this project is to provide a comprehensive outlook on the potential of the ETES to improve geothermal power plant performance while ensuring economic sustainability.

The ETES system enables a temporary decoupling between geothermal heat extraction and electricity generation, allowing energy to be stored during periods of renewable surplus and released during demand peaks.

ETES operation is particularly well suited to supporting daily load ramps, renewable energy integration, and system balancing requirements. Unlike electrochemical batteries, thermal storage integrated with geothermal systems provides predictable and weather-independent flexibility while leveraging existing subsurface

resources. In addition, the participation of ETES-equipped geothermal plants in reserve markets may attract further investment, as the utilization of traditionally baseload renewable resources for reserve provision has been limited to date, thereby expanding future market opportunities.

From a system operator perspective, flexible geothermal plants equipped with ETES can contribute to peak load support, reserve provision, and the reduction of renewable curtailment, ultimately enhancing overall grid stability in future low-carbon electricity systems.

Acknowledgements

The authors would like to thank the colleagues from University of Liege, CEA, ZORLU Energy for their valuable insights and support during this research.

This work was supported by European Union's Horizon Europe Research and Innovation Action, Grant Agreement° 101135763.

This study was carried out within the NEST - Network 4 Energy Sustainable Transition (D.D. 1243 02/08/2022, PE00000021) and received funding under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3, funded from the European Union - NextGenerationEU. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

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