THERMODYNAMIC MODEL OF A CARNOT BATTERY FOR THE EXPLOITATION OF WASTE HEAT ENERGY

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Abstract - The rapid increase in the installed capacity of RES power plants is leading to a significant overproduction of electricity in several European countries, for long periods. The conventional solutions to use the excess of renewable electricity produced by photovoltaic plants and, therefore, achieve the goal of the energy transition are energy storage by using electric batteries. A technology that would allow the recovery of excess electrical energy produced by photovoltaic systems and, at the same time, exploit the availability of waste heat are Carnot batteries (also called Pumped Thermal Energy Storage – PTES) which is particularly attractive, because for example they do not require a huge amount of critical materials, such as lithium-ion batteries. By using this technology, the thermal waste produced in energy-intensive companies should be reused to increase the energy efficiency of the storage plants. The issue of the exploitation of waste heat is regarded as very important in the European Industrial Countries. In this sense, the CE-HEAT project (Interreg Central Europe) of the European Union aims to improve the governance of energy efficiency by focusing on the field of waste heat use in the Central European space; waste heat exploitation is recognized as a major issue in the latest Energy Efficiency Directive (2012/27/EU).

In general, the efficiency of Carnot batteries is poor but can increase if they are thermally integrated, reaching efficiencies close to the best mechanical energy storage technologies (Pumped Hydro Energy Storage – PHES). The paper, using data from the waste heat of the European project CE-HEAT and the excess electrical energy produced by photovoltaic systems in the Friuli Venezia Giulia region, aims to estimate the energy that can be recovered by producing a Carnot battery.

Keywords - Carnot Battery, Waste Heat, Power-To-Power Efficiency, Organic Rankine Cycle, Pumped Thermal Energy Storage.

I. INTRODUCTION

In consequence of the rapid increase in the installed capacity of RES power plants, an important over-production of electric energy is expected in various European Countries, for long periods [1, 2, 3, 4]. This fact asks for big investments in the energy storage sector, in order to exploit efficiently the RES, and to achieves the target of the energy transition.

For this purpose, the Carnot Battery technology (also named Pumped Thermal Energy Storage – PTES) seems particularly attractive,

because it is easily scalable and it does not require a huge amount of critical materials [5], like Li-ions batteries.

Unfortunately, the irreversibility in the fluid machinery and in the heat exchangers make the round-trip efficiency of standalone (or symmetric) Carnot Batteries quite poor. On the contrary, thermally-integrated (or asymmetric) Carnot Batteries may have efficiencies comparable with the best mechanical energy storage technologies, like Pumped Hydro Energy Storage – PHES[6, 7,8].In this context, an interesting option appears for the exploitation of industrial waste heat, in the temperature range 40° - 80°C.

In fact, this temperature level is generally regarded to be too low to be the input of a power cycle, like ORC, as well as for an absorption chiller.

II. METHODOLOGY

In the industrial areas of the developed Countries there is a lot of heat of this kind potentially available, but it is not extensively used.

In the paper, the idea of thermally integrated Carnot Battery is summarizing and a thermodynamic model is presented for a Carnot Battery made up with a heat pump, an ORC engine, and two thermal storages. The lower temperature thermal storage is fed by industrial waste heat, in the temperature range 40° - 80°C (Figure 1).

The model has been presented in a previous work [9] and allows to study the effect of the thermal integration, and of different kind of fluid in the two cycles, on the round-trip efficiency of the storage system.

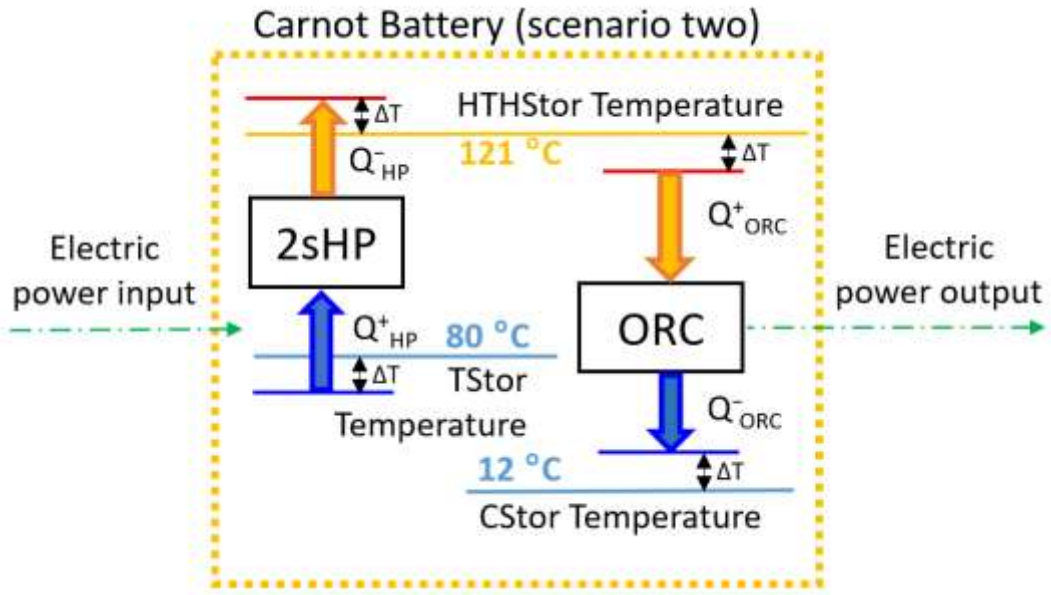


Figure 1: The asymmetric Carnot Battery operation scheme: the devices work between two storages at different temperature.

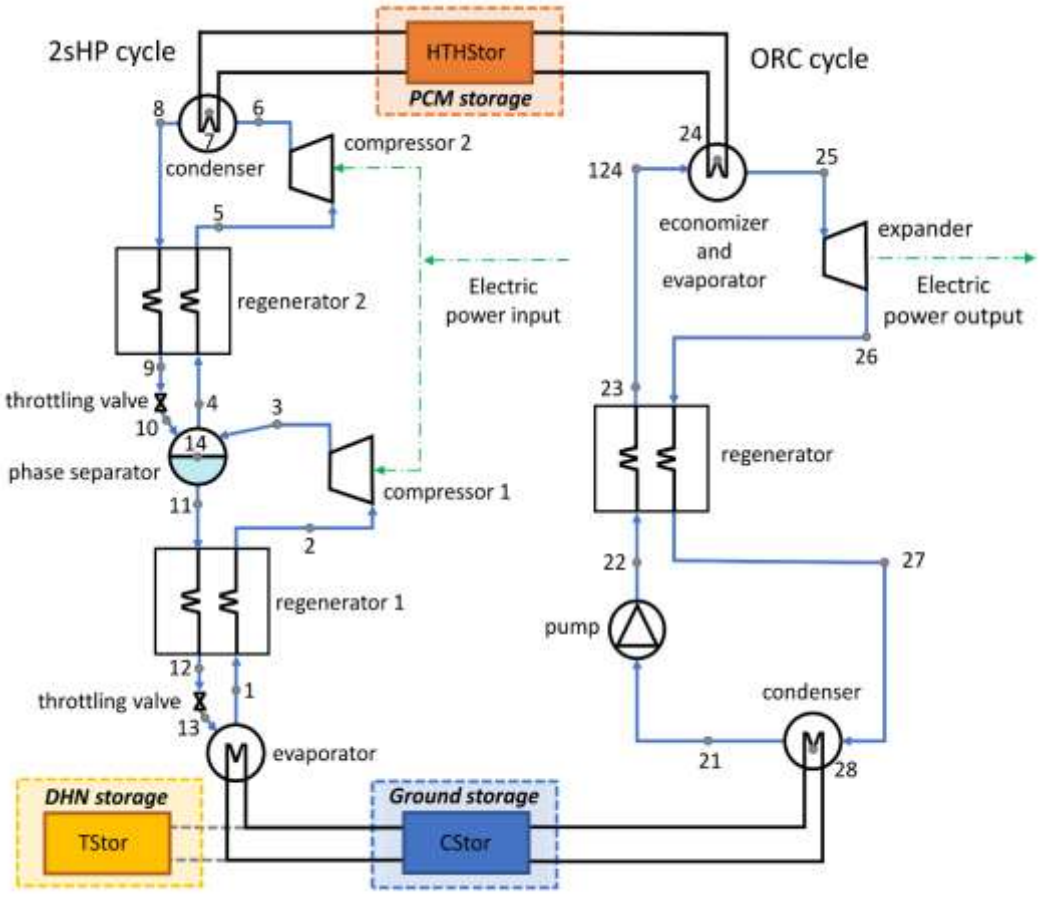


Figure 2. The operation diagram of the cycles of the CB for both scenarios.

The diagram of the Carnot Battery is shown in Figure 2. The T-s diagram of the Two stage HP considered for the charging phase of the CB is shown in Figure 3. The 2sHP uses renewable electric energy (PVps) to charge the HTHStor. Starting from point 1, the working fluid enters the first regenerator, where it is superheated. Then, it enters the first compressor (point 2) and its pressure raises the intermediate value (point 3) just before entering the phase separator. The vapor exits the phase separator (point 4) to pass through the second regenerator to get superheated again (point 5). The second compressor raises the

working fluid pressure to the condensation pressure. Then, the hot vapor enters the condenser (point 6), where it exchanges heat with the water coming from the HTHStor, becoming saturated vapor (point 7). The further heat released by the working fluids into the condenser makes the fluid condense, becoming saturated liquid (point 8). The HTHStor is charged at a temperature of about 120-135°C.

The fluid enters the second regenerator to exchange heat and reach the sub-cooled condition (point 9). It passes through a lamination valve to adiabatically expand and lower its pressure (point 10).

Entering the phase separator again, the fluid liquid fraction is splitted and leaves the separator to enter into the first regenerator (point 11). Once it has exchanged some heat, the fluid passes through another lamination valve (from point 12 to 13) to reduce its pressure to the evaporation pressure.

The fluid enters the evaporator, where it absorbs heat from the water coming from the DHN -or waste heat - storage (TStor). At the exit of the evaporator, the fluid reaches the condition of point 1 and the cycle starts again. Therefore, the 2sHP uses an electric energy source (PVps) to charge the HTHStor.

The ORC does the opposite (Figure 4): it discharges the HTHStor to produce electric energy (Figure 3).

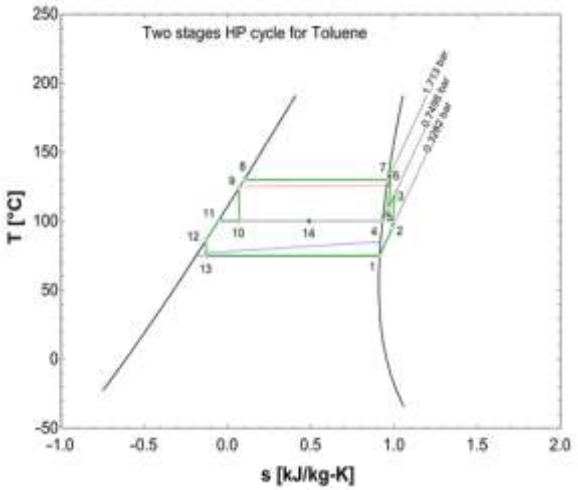


Figure 3. The HP cycle

Starting from point 21, a pump raises the pressure of the liquid working fluid (point 22) through a regenerator, where the fluid gets heated (point 23). The fluid, successively, enters the economizer (point 124), where it starts absorbing heat from the water coming from the HTHStor.

The fluid absorbs heat into the evaporator (point 24), becoming saturated vapor (point 25). Then, the vapor drives the expander, which, connected to a generator, produces electric energy.

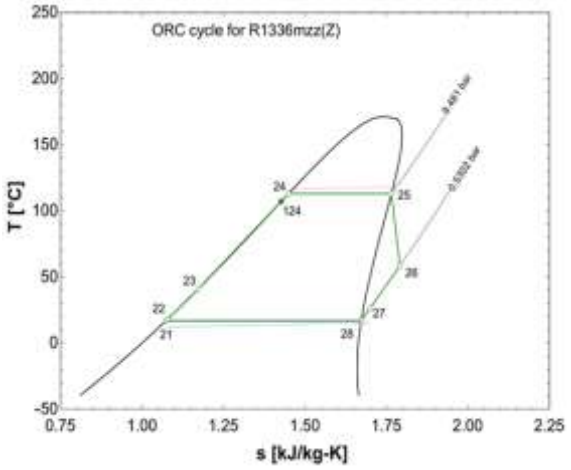


Figure 4. The ORC cycle.

The exhaust vapor at the expander exit (point 26) is hot enough to enter the regenerator and heat the fluid coming out the pump. Once the fluid comes out of the regenerator (point 27), it enters the condenser, where it releases heat to the water coming from the ground storage (CStor), firstly de-superheating to saturated vapor (point 28), and successively condensing into saturated liquid that flows out of the condenser (point 21).

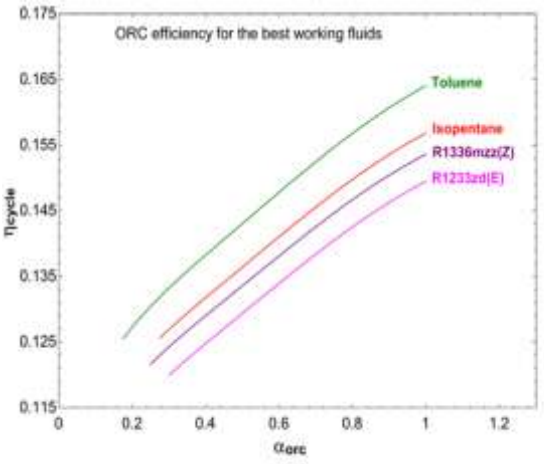


Figure 5. The ORC efficiency

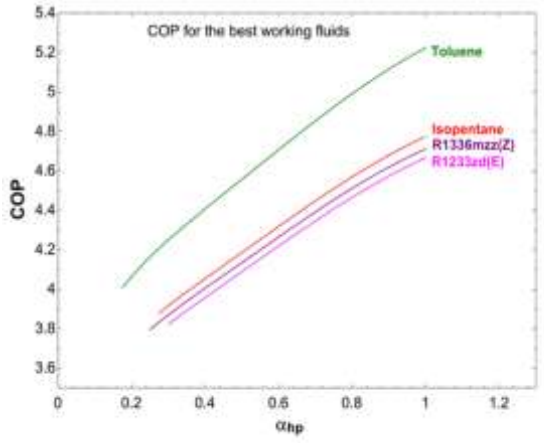


Figure 6. The HP COP

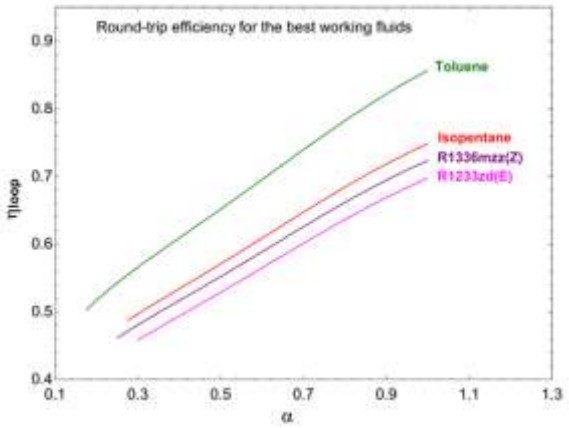


Figure 7. The ROUND-TRIP efficiency

Further details about the model can be found in [9]

Fluid	α	HP COP	ORC η_{cycle}	η_{loop}
Toluene	1	5.223	0.164	0.857
	0.175 *	4.008	0.125	0.503
Isopentane	1	4.774	0.157	0.748
	0.275 *	3.879	0.126	0.487
R1336mzz(Z)	1	4.712	0.154	0.724
	0.25 *	3.795	0.122	0.462
R1233zd(E)	1	4.666	0.149	0.697
	0.3 *	3.822	0.120	0.459

Table 1. Round-trip efficiency values obtained for maximum and minimum values of the part-load factor *α*.

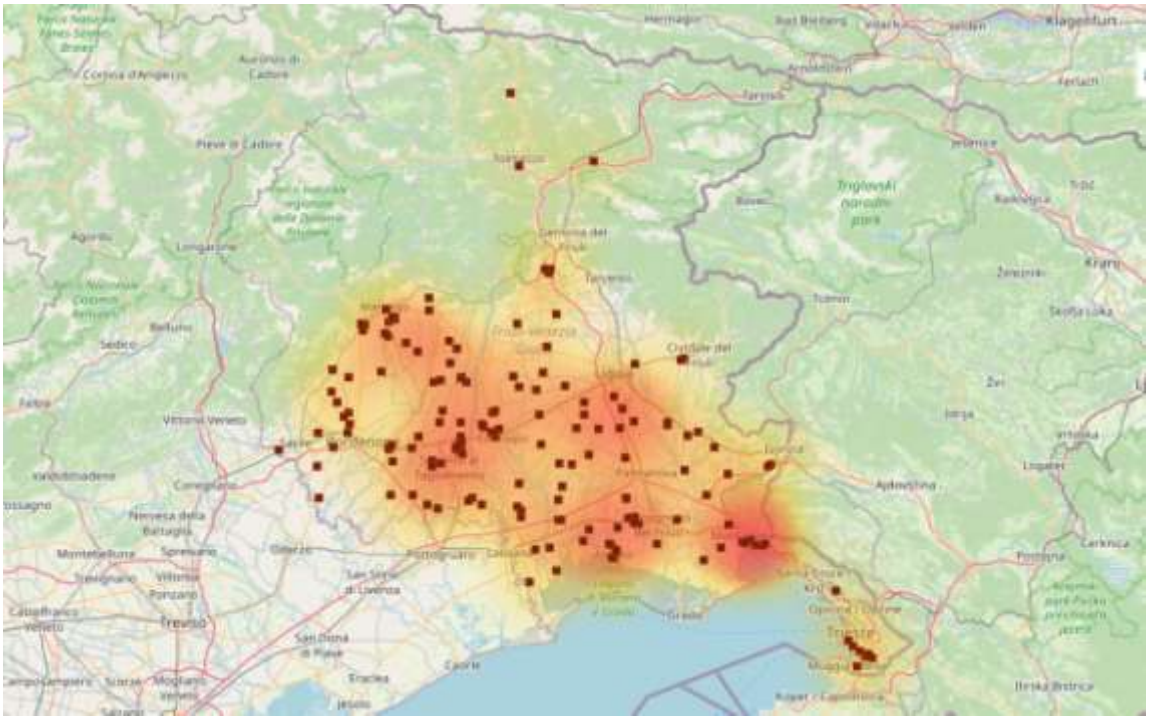


Figure 8. The atlas of the European project CE-HEAT

On this basis, the ORC efficiency during the discharge phase, the COP of the HP during the charging phase and the round rip efficiency are obtained and shown in Figures 5, 6 and 7, respectively, as a function of the of a part-load factor α, which can vary from the full-load conditions (α = 1) to the inactive machine (α = 0). The same performance parameters are shown in Table 1, for the maximum and the minimum values of the part-load factor allowed by the model.

The overall results indicate Toluene as the best candidate, while the other three fluids have similar performance parameters. The adoption of Toluene is quite problematic, because of its very hight specific volume and low saturation pressure at the considered condensation temperature of the ORC.

Therefore, taking also into account the need of using fluids with low flammability and as low as possible GWP, the R1233zd(E) is considered in the following.
To evaluate the storage potential of this solution, the data of the industrial waste heat potentially available in the region Friuli Venezia Giulia (North-East of Italy) are considered in the paper. The data have been obtained from the European project CE-HEAT [10]. The CE-HEAT project, which began in June 2016, is funded by the European Regional Development Fund under the Interreg program and involves eight partners from Italy, Austria, Croatia, Germany, Poland, the Czech Republic and Slovenia.

The aim of the project is to promote the recovery of waste heat, particularly in industrial and electricity production plants. In many sectors, in fact, the

processes used have a low efficiency that leads to dissipating a large part of the energy produced.
The European Directive 2012/27/EU underlines the importance and opportunity of using this energy source.

The atlas contains the most relevant data to evaluate the amount of energy recoverable from emissions from production facilities in the Friuli Venezia Giulia region.
A heatmap immediately identifies the sites with the greatest amount of dissipated energy.

By clicking on the icons of the different companies, you can obtain the energy and power currently dissipated by the plant; by zooming in, the icons of the individual waste heat emission point will be visible and, by clicking on the icon, the main data are available to understand which technologies are suitable for recovering this heat.
Numerous filters, search tools and data export are also available to help potential investors find the waste heat best suited to their business.

The data were obtained from the annual reports required by the AIA, from the GSE website or collected directly from the companies, and are therefore to be considered as reliable estimates, suitable for an initial assessment of the situation.

An important amount of available waste heat can be inferred from the data base (Figure 8), suggesting the interesting option of exploit this waste heat for defining a set of energy storage systems, in form of asymmetric CBs. In Figure 9, it is shown an example of possible excess of photovoltaic energy production during the central hours of the day. Notice that the increment of the size of the photovoltaic plant is expected to have a small effect on the time period where power integration would be required, while the excess of power production would be very important, so that it would not be possible to obtain a complete exploitation of the renewable energy production.

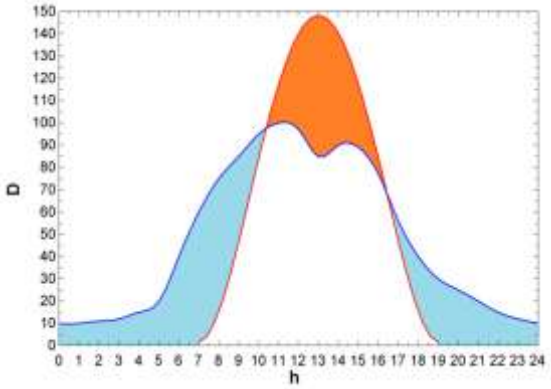


Figure 9. An example of mismatch between the power demand of an hypothetical industrial area and the power production of a 150 MWp solar plant.

III. RESULTS

By using the results shown in Table 1,the average COP of Heat pump can be estimated at about 4,2 and the average round-trip efficiency of the whole operation (charging and discharging Phases) at about 0,61, taking into account that all CBs will be operated preferably at a hight value of the part-load factor.
A storage temperature fed by the thermal waste of 80 °C has been considered, by filtering the data base of the waste heat in order of eliminating all potential thermal recovery at a temperature level below this value.
A hot storage temperature of the Carnot battery of 130 °C has beenchosen and the working fluid considered for both machines, HP and ORC, is R1233zd(E). In this hypothesis, for each MWh of actually recovered heat, it is possible to store 310 kWh of excess of renewable energy, in form ofhigh temperature heat. During the discharge phase, 190 kWh of electrical energy are obtained by Carnot battery, consistently with the average round trip efficiency of about 0,61.

IV. CONCLUSION

Taking into account the Friuli-Venezia-Giulia region alone, there are 5.362.000 MWh of waste heat with a temperature higher than 80 °C and a 70% use equal to 3.754.022 MWh of waste heat available at the companies in the area considered in the study, it isconcluded that the same area would be able to receive 1.160.000 MWh which corresponds approximately to the annual production of an 880 MWp photovoltaic system positioned centrally in the FVG region.

REFERENCES

[1] International Energy Agency (IEA). How to Avoid Gas Shortages in the European Union in 2023. Available online: https://www.iea.org/reports/how-to-avoid-gas-shortages-in-the-european-union-in-2023 (accessed on 17 February 2023).
[2] R. De Souza,M. Casisi,D. Micheli,M. Reini,“A Review of Small–Medium Combined Heat and Power (CHP)Technologies and Their Role within the 100% Renewable Energy Systems Scenario”,Energies, 2021,vol. 14,issue 17, 5338.
[3] International Energy Agency (IEA). Grid-Scale Storage, Paris. Available online: https://www.iea.org/reports/grid-scale-storage, (accessed on 4 April 2023).
[4] R. De Souza, E. Nadalon,M. Casisi,M. Reini,“Optimal Sharing Electricity and Thermal Energy Integration for an Energy Community in the Perspective of 100% RES Scenario”,Sustainability, 2022,vol. 14, issue 16, 10125.
[5] A. Vecchi, A. Sciacovelli, “Thermo-mechanical energy storage options for long-duration storage—A techno-economic com-parative assessment of established and novel concepts,”in Proc. ECOS, 2022.
[6] G.F.Frate, L. Ferrari, U. Desideri,“Rankine Carnot Batteries with the Integration of Thermal Energy Sources: A Review,” Energies 2020, vol.13, 4766.
[7] G. F. Frate, M. Antonelli,U. Desideri,“A novel Pumped Thermal Electricity Storage (PTES) system with thermal integration”Applied Thermal Engineering, 2017, vol. 121, pp. 1051–1058.

[8] G. F. Frate, L. Ferrari,U. Desideri,"Multi-criteria investigation of a pumped thermal electricity storage (PTES) system with thermal integration and sensible heat storage,"Energy Conversion Management, 2020, vol. 208, 112530.

[9] E.Nadalon, R. De Souza, M. Casisi, M. Reini, "Part-load Energy Performance Assessment of a Pumped Thermal Energy Storage System for an Energy Community," Energies, 2023, vol. 16, issue 15, 5720.

[10] ProgrammeInterreg 2014-20, "CE-HEATWaste heat - Freeenergy," start date 2016- end date 2019,https://programme2014-20.interreg-central.eu/Content.Node/CE-HEAT.html

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