INTEGRATION OF PUMPED THERMAL ENERGY STORAGE INTO MULTI-ENERGY URBAN DISTRICTS: COMPARISON BETWEEN BRAYTON AND RANKINE TECHNOLOGIES

Alessandra Ghilardi[1]*, Guido Francesco Frate[1], Lorenzo Ferrari[1]

[1] University of Pisa, Department of Energy, Systems, Territory, and Constructions Engineering (DESTEC), Pisa, Italy

*Corresponding Author: alessandra.ghilardi@phd.unipi.it

ABSTRACT

The transition towards net-zero emissions scenarios implicates installing a large share of power generated from Renewable Energy Sources (RES). Nowadays, relying on energy storage is one of the most effective practices to make the integration of RES possible. In addition, enhancing sector coupling is also promising, as many urban contexts already involve electric and thermal energy carriers. In this framework, Pumped Thermal Energy Storage (PTES) emerges as a suitable technology to address both concepts since it can store the electric surplus produced by the RES in the form of thermal exergy using a heat pump. The stored exergy can then be converted to electricity through a heat engine or utilized directly for heating or cooling. This paper investigates integrating two PTES technologies (Brayton-based and Rankine-based) into an urban district involving generation from photovoltaic modules and electric, heating, and cooling loads. In this context, the choice between one or the other technology depends significantly on the economic and demand scenarios, with the Brayton alternative performing better for power-to-heat-to-power purposes, while the Rankine one is more efficient for power-to-heat usages. To address this question, a Mixed Integer Linear Programming approach is used to solve the optimal energy dispatch within the district to minimize the daily operational cost. By investigating different demand mix and market conditions scenarios, results highlight that the Brayton PTES is the most convenient for medium-low natural gas prices and scenarios with high electricity demand share (hot weather scenarios), where the operational cost reduction is 5% more than the Ra-PTES. Vice versa, the Rankine technology performs better than the Brayton for medium-high natural gas prices and the high thermal demand shares (cold weather scenarios).

1 INTRODUCTION

The power produced by Renewable Energy Sources (RES) is increasing and is expected to cover 60% of gross inland energy consumption by 2050 (European Commission Directorate-General for Climate Action, 2019). Energy Storage Systems (ESS) are then necessary to manage the aleatory production from RES, thus providing safety and flexibility to the power grid (Frate *et al*., 2021). At the same time, integrating a large share of RES must deal with the architecture of existing energy systems, which usually are Multi-Energy Systems (MES) (Mancarella, 2014) that include heating, cooling, transport, and fuel, besides the electric energy. Optimizing the mutual interactions between the energy carriers involved in MES is known as Sector Coupling (SC), an effective strategy for integrating large shares of RES electric production (Ramsebner *et al*., 2021).

Combining ESS and SC concepts discloses potential synergies in RES integration (Victoria *et al*., 2019). Among the ESS technologies, Carnot Batteries (CB) are the most suitable to address the SC necessities of MES since their operation is based on Power-to-Heat (P2H)/Power-to-Cool (P2C) and Heat-to-Power (H2P) conversions. CBs store the RES surplus electricity as thermal exergy into Thermal Energy Storages (TES) by powering a Heat Pump (HP). The stored exergy can be discharged at a later time to run a Heat Engine (HE) and produce back electricity (Dumont *et al*., 2020), acting then overall as a Power-to-Power (P2P) storage capacity. Despite CB working as P2P devices have some positive features, such as independence from geographical restrictions and raw materials, and long operational

https://doi.org/10.52202/077185-0078

life, benchmark ESS technologies, such as Li-ion batteries, are still more cost-effective. However, CBs can be more flexible by providing direct heating and/or direct cooling by directly discharging the thermal exergy stored in the TES. This flexible operation is known in the literature as a multi-energy storage operation, among which Liquid Air Energy Storage (LAES) and Pumped Thermal Energy Storage (PTES) are the most promising technologies. In (Vecchi *et al*., 2021), the authors investigated the application of LAES to fulfil the electric, heating, and cooling demands of a MES, finding that operational cost reduction of up to 12.6% can be achieved when multi-energy flexibility is allowed. However, PTES technologies exhibit higher theoretical round-trip efficiency compared to LAES.

This paper then focuses on PTES, which includes two main configurations: the Rankine-based (Ra-PTES) and the Brayton-based (Br-PTES). The Ra-PTES uses a Vapor Compression Heat Pump (VCHP) for the charging phase and an Organic Rankine Cycle (ORC) for the discharge. The round-trip efficiency of the Ra-PTES can achieve 40-60% according to the layout (Dumont and Lemort, 2020). In general terms, the VCHP, which performs the P2H conversion, gives the most influential contribution to the overall efficiency since the VCHP temperature lift is limited, especially when used for District Heating and Cooling (DHC) applications (Arpagaus *et al*., 2018), considering High Temperature TES (HT-TES) temperatures up to 80 °C and Low Temperature TES (LT-TES) down to 5-7 °C. The ORC performance, which impacts the H2P conversion, is poor, rarely above 10%. Literature concerning Ra-PTES as a multi-energy storage capacity mostly focuses on the thermodynamic assessment (Steinmann *et al*., 2019)(Lykas *et al*., 2023). Operational aspects are instead investigated only by (Frate *et al*., 2023), where the combined electric, heating, and cooling provision brings economic and CO_2 emissions savings up to 20% compared to the traditional P2P operation.

The Br-PTES exhibits some opposite performance. The charging phase is performed by a Br-HP, which works between a LT-TES with temperatures down to -100 °C and a HT-TES working up to 600 °C (Olympios *et al*., 2022). The discharge is realized by a Br-HE that works within the same LT-TES and HT-TES. In this case, the HP achieves a low Coefficient of Performance (COP), while the HE benefits from the vast temperature difference of the thermal reservoirs to achieve efficiencies up to 45%. The overall round-trip efficiency can achieve values up to 50-70%. The Br-PTES used as a multi-energy storage capacity is investigated by (Zhang *et al*., 2020), where a Br-PTES capacity is used to provide combined cooling, heating and power to a domestic building to assess its thermodynamic performance. Concerning operational insights, (Ghilardi *et al*., 2023) investigate the Br-PTES integration into an urban district that includes residential and commercial buildings, proving that the combined provision of cooling, heating and power can bring to 5% of operational cost savings compared to the exclusive P2P operation.

Given this framework, the Rankine layout seems more appropriate to fulfill the thermal requirements of an urban district, since its storage temperatures match the user's temperature profiles and due to the high performance of the P2H conversion. On the other hand, Br-PTES shows a less intuitive integration with the thermal requirements of an urban district due to the substantial temperature differences and low performance of the P2H conversion. However, the Br P2P performance is far superior to the Ra-PTES, so the former could suit better urban districts with high electric demand share. However, the prevalence of one technology over the other cannot be stated a priori. In fact, according to their different performance for P2H and P2P, the cost-effectiveness of using the Br or the Ra alternative can depend on the demand energy mix of the district. In addition, the electricity and Natural Gas (NG) prices could also play a role in selecting one technology over the other since avoiding NG purchasing could be more advantageous when having an efficient P2H conversion, or vice versa.

So far, the literature lacks a proper comparison between these two technologies to understand their cost-effectiveness when integrated into MES. The novel contribution of this paper, then, is filling this gap by comparing for the first time in literature the operational cost reduction when using a Br-PTES or a Ra-PTES capacity to optimize the energy dispatchment within a MES. This investigation aims to identify which of these two technologies is more convenient in different contexts by:

- Evaluating different demand mix scenarios (i.e., different share between electricity, heating, and cooling) related to realistic urban districts with different weather conditions;
- Evaluating different market conditions (i.e., different combinations of electricity and NG prices) related to realistic urban districts with different weather conditions.

https://doi.org/10.52202/077185-0078

2 METHODOLOGY

2.1 Case study

The case study simulates an urban district of 500 residential buildings located in Italy and characterized by electric, heating, and cooling demands that vary seasonally. The district's energy requirements are computed using the software nPro Energy developed by (Wirtz, 2023), where the electric and thermal (heating and cooling) loads are created starting from the outdoor temperature profile – provided by (European Commission Joint Research Center, 2023) – of the selected location. **Figure 1** provides an overview of the system architecture. The case study simulates an Italian residential district, which is typically connected both to the electric and to the natural gas grids that work as backups providing $\dot{W}_{el,pur}$ and $\dot{Q}_{pur}$, respectively. In fact, despite future energy systems are going to be fully electrified, existing districts still rely on natural gas grid. The district is equipped with a District Heating and Cooling network represented by the heating and cooling busses, which are at 75 °C (D. S. Østergaard et al., 2022) and 7 °C (P. A. Østergaard et al., 2022), respectively. Starting from the natural gas grid, then, the heating is produced by using a thermal boiler, since it is a common layout (instead of CHP plants) for medium-small residential districts, while CHP plants are used for plants with at a bigger scale. The backup cooling generation, $\dot{Q}_{chill}$, is instead provided by an electric chiller, which is the most efficient cooling technology available nowadays. From the perspective of decarbonizing existing residential districts, the district relies on the renewable energy produced by photovoltaic (PV) modules, $\dot{W}_{RES}$, which is optimally managed by a PTES storage capacity.

The core element of this study is the PTES storage capacity, which can be a Br-PTES or a Ra-PTES. In both the investigated layouts, the PTES capacity can exploit its unique multi-energy storage feature by being charged by the electric input $\dot{W}_{ch}$, and providing multiple energy carriers during the discharge. Particularly, the storage can provide electric discharges $\dot{W}_{dis}$, direct heating discharges $\dot{Q}_{dis,heat}$ to fulfill the heating demand, or direct cooling discharges $\dot{Q}_{dis,cool}$ to fulfill the cooling demand. Details concerning the Br-PTES layout and Ra-PTES layout are given in Section 2.2 and Section 2.3, respectively.

The PV plant size is designed to cover 50% of the total demand of the district, $\dot{W}_{dem,tot}$, given by the sum of electric, heating and cooling demands. The storage nominal charging rate $\overline{\dot{W}}_{ch}$ is consequently designed by considering the duration curve of the surplus PV production, $\dot{W}_{RES} - \dot{W}_{dem,tot}$, and is

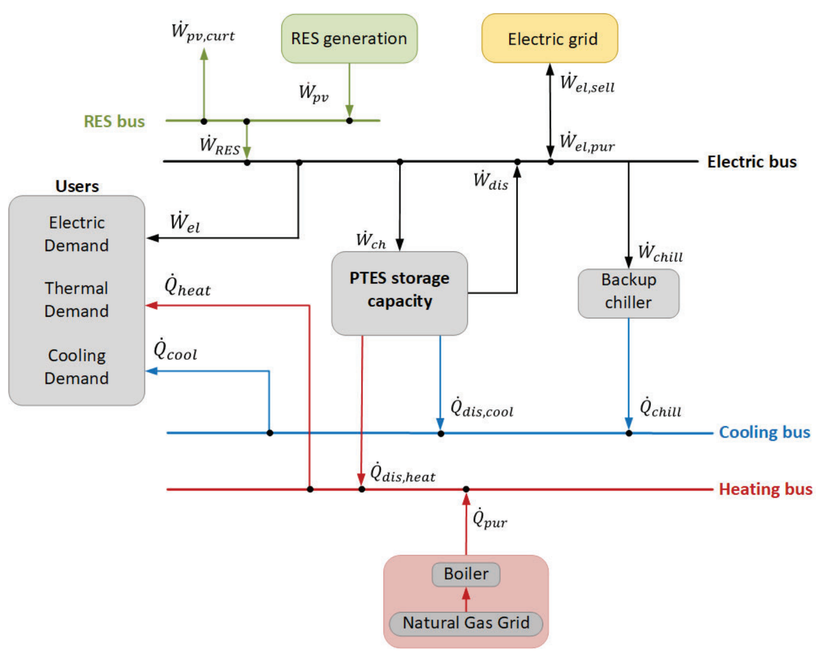

Figure 1. District configuration. Generation, demand, multi-energy PTES storage capacity, and backup grids.

https://doi.org/10.52202/077185-0078

dimensioned to store 80% of the occurrences. The charging time is set equal to 6 hours, a typical value for the integration of PV production.

2.2 Brayton layout and model

The Br-PTES capacity layout is given in **Figure 2**. During the charging phase, the power input $\bar{\dot{W}}_{ch}$ coming from the electric bus powers a Brayton Heat Pump (Br-HP). The latter works using a LT-TES as the cold reservoir and a HT-TES as the hot reservoir. In this way, thermal exergy is stored both in the HT-TES and the LT-TES during the same charging cycle since the LT-TES works below the ambient temperature. The thermal exergy stored in both two tanks can be used later to run a Brayton Heat Engine (Br-HE) and produce back electricity $\bar{\dot{W}}_{dis}$ for the electric bus by using the HT-TES as the hot reservoir and the LT-TES as the cold reservoir. Besides this operational modality, which is the traditional P2P operation, the Br-PTES can also discharge the HT-TES and LT-TES to provide direct heating $\dot{Q}_{dis,heat}$ to the heating bus and direct cooling $\dot{Q}_{dis,cool}$ to the cooling bus and fulfil the district's thermal requirements.

The models of the Br-HP and Br-HE are based on the work by (Frate, Ferrari, et al., 2022). The layout involves solid-based HT-TES and LT-TES made of limestone, working at 590 °C and -100 °C, respectively. The HT-TES and LT-TES are supposed to be adiabatic and iso-thermal during the charging and discharging phases, thanks to peculiar array arrangements that are possible for the solid based layouts (Wang et al., 2021). The cycles' working fluid is Argon, which proved to be the best-performing fluid in terms of round-trip efficiency for solid-based Br-PTES. It is worth noting that the Brayton layout does not work with the environment as a thermal reservoir but directly within HT-TES and LT-TES. For this reason, its performance is not affected by the variations of ambient temperature at each timestep. The performance of the charging and discharging cycles are then modelled by defining electric-to-heat performance parameters as follows in Equation 1 and Equation 2:

$$\alpha_{HT,ch/dis} = \frac{\bar{\dot{Q}}_{ch/dis,HT}}{\bar{\dot{W}}_{ch/dis}} \tag{1}$$

$$\alpha_{LT,ch/dis} = \frac{\bar{\dot{Q}}_{ch/dis,LT}}{\bar{\dot{W}}_{ch/dis}} \tag{2}$$

where $\bar{\dot{Q}}_{HT,ch/dis}$ and $\bar{\dot{Q}}_{LT,ch/dis}$ are the nominal charging/discharging heat flow rates for the HT-TES and LT-TES, respectively; $\bar{\dot{W}}_{ch/dis}$ is the nominal charging/discharging power of the PTES. The performance parameters are synthetically reported in **Table 1**. Part-load performance is not modelled since Br-PTES can benefit from the inventory control to keep turbomachine efficiency unchanged (Frate, Paternostro, et al., 2022).

It is worth noting here that the LT-TES has the possibility of curtailing some energy $\dot{Q}_{curt,LT}$. This is necessary since the HP and the HE use HT-TES and LT-TES simultaneously when charging or discharging the storage, while the tanks can independently work when providing direct heating or

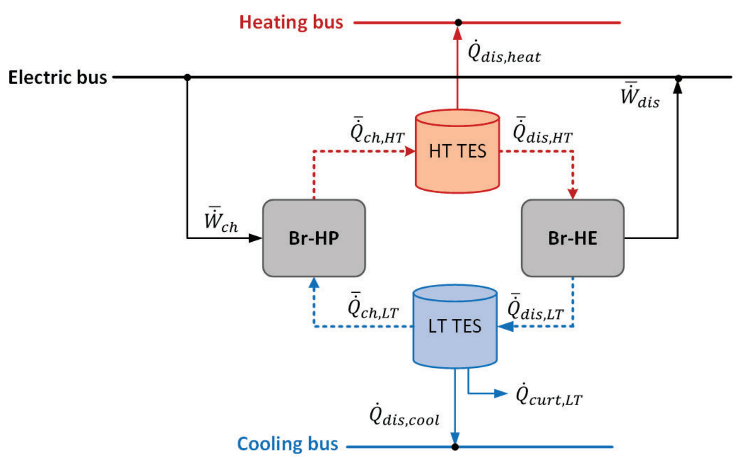

Figure 2. Brayton layout. Model based on (Ghilardi *et al*., 2023).

https://doi.org/10.52202/077185-0078

cooling. This means that if there is a direct heating discharge, it must be an equivalent cooling discharge within the optimization horizon. In case this does not happen, e.g., during wintertime when there is no cooling demand to be fulfilled, the system is forced to curtail some stored exergy to keep the HT-TES and LT-TES balanced.

2.3 Rankine layout and model

In the Rankine layout, the district relies on a Ra-PTES as storage capacity, arranged as in **Figure 3**. Unlike in the Br layout, here, the environment can be used as a thermal reservoir/sink, so the HT-TES and LT-TES work independently since PTES is equipped with separate HP and chiller. The HT-TES and LT-TES are supposed to be adiabatic and iso-thermal during the charging and discharging phase, since are made of phase change materials. During the charging phase, the HP is powered by an electric input $\dot{W}_{hp}$ and pumps heat from the environment up to the HT-TES, where thermal exergy is stored. The chiller, who works independently from the HP, can also contribute to the PTES charging phase by absorbing an electric input $\dot{W}_{chill}$, and storing thermal exergy in the LT-TES while using the environment as a sink. During the discharge, an ORC is used to produce back electricity $\dot{W}_{dis}$. The ORC uses the HT-TES as the hot source for the evaporation phase, while it can choose between the environment or the LT-TES for the condensation phase. In this layout, the chiller itself works as the charging device for the PTES by providing $\dot{Q}_{cool,bus}$ and the backup chiller to provide direct cooling $\dot{Q}_{chill}$ when the storage is not operating. The HP can also provide direct heating when it is not working as the PTES charging device. Also in this case, besides the traditional electric discharge, the HT-TES and LT-TES can provide direct heating and direct cooling, $\dot{Q}_{dis,heat}$ and $\dot{Q}_{dis,cool}$, respectively.

In this layout, the environment plays the role of thermal reservoir for the VCHP, the chiller and the ORC, so the performance of these components is affected by the changes in the outdoor temperature at each timestep. For this reason, the coefficients of performance (EER, COP, and η_{orc}) are computed by multiplying the Carnot efficiency changing with the outdoor temperature (EER^c, COP^c, and η^c), for the second law efficiency, ψ_{hp} and ψ_{orc}, computed at design conditions (yearly average ambient temperature $T_{amb} = 15°C$), while ψ_{chill} is computed considering standard summer reference conditions ($T_{amb} = 35°C$). The operative working fluid of the Rankine PTES is R1234yf, one of the most suitable for this application given the critical temperature < 100 °C and environmentally friendly properties, according to (Arpagaus *et al*., 2018). The formulation of the performance coefficients is based on (Vijayaraghavan and Goswami, 2003), as follows in Equation (3), Equation (4) and Equation (5). According to typical values for District Heating and Cooling (DHC) networks (P. A. Østergaard et al., 2022), the temperatures of HT-TES and LT-TES are T_h = 80 °C and T_c = 2°C, respectively. The performance parameters are synthetically reported in **Table 1**.

$$EER = \psi_{chill} \cdot EER^c; EER^c = \frac{T_c}{T_h - T_c} \quad (3)$$

$$COP = \psi_{hp} \cdot COP^c; COP^c = \frac{T_h}{T_h - T_c} \quad (4)$$

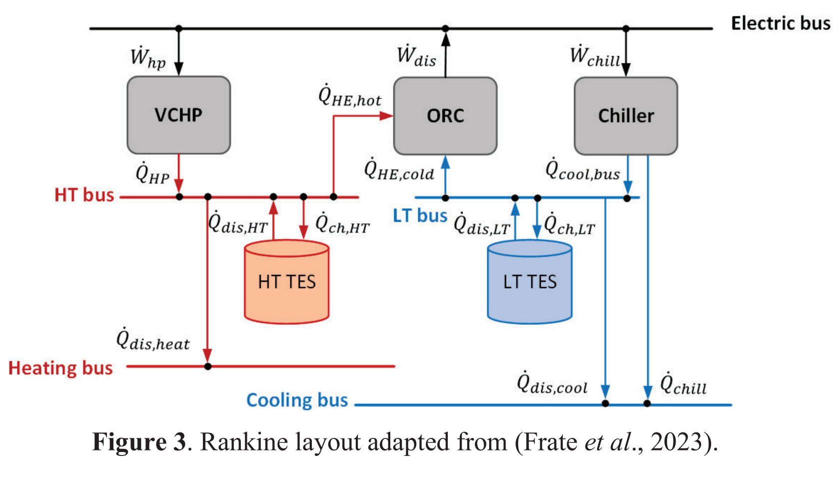

Figure 3. Rankine layout adapted from (Frate *et al*., 2023).

https://doi.org/10.52202/077185-0078

$$\eta_{orc} = \psi_{orc} \cdot \eta^c; \eta^c = 1 - \frac{T_c}{T_h} \quad (5)$$

Table 1. Efficiencies at design conditions for Ra-PTES and Br-PTES for the different operational modalities: Power-to-Heat (P2H); Power-to-Cool (P2C), and Heat-to-Power (H2P).

Operational mode	Performance coeff	Ra-PTES	Performance coeff	Br-PTES
P2C	$\boldsymbol{EER}$	4.68	$\alpha_{LT,ch}$	1.33
P2H	$\boldsymbol{COP}$	2.51	$\alpha_{HT,ch}$	1.86
H2P	$\boldsymbol{\eta_{orc}}$	0.083-0.097	$1/\alpha_{HT,dis}$	0.41

2.4 MILP formulation

The optimization problem is formulated using a Mixed Integer Linear Programming (MILP) approach, a state-of-the-art method to solve energy dispatchment problems (Urbanucci, 2018). The objective function f_{ob} of the optimization problem is defined as the sum of operational costs minus the operational revenues due to the purchasing/selling of electricity and NG from the grids over the optimization horizon $\bar{T}$. According to this formulation, the control region of the problem includes the users, the storage capacity and the PV plant, being the backup grids (i.e., electric grid and NG grid) the only to give positive or negative contributions to the total operational cost. Equation (7) shows f_{ob}, where $\dot{W}_{el,pur}$ is the electricity purchased from the electric grid (kWh); $p_{el,pur}$ the price of the electricity purchased from the electric grid (€/kWh); $\dot{Q}_{pur,ng}$ the equivalent heat flow rate purchased through the natural gas grid (kWh); $p_{ng,pur}$ the price of the heat purchased from the natural gas grid (€/kWh); $\dot{W}_{el,sell}$ the electricity sold to the electric grid (kWh); $p_{el,sell}$ the economic reward for selling electricity to the grid (€/kWh). The optimization problem is solved considering an hourly time-discretization and a rolling optimization horizon of 24 hours to simulate the system over the whole year.

$$f_{ob} = \left(\sum_t^{\bar{T}} \left[\dot{W}_{el,pur}(t) \cdot p_{el,pur}(t) + \dot{Q}_{pur,ng}(t) \cdot p_{ng,pur}(t) - \dot{W}_{el,sell}(t) \cdot p_{el,sell}(t)\right] \cdot \Delta t\right) \quad (7)$$

The optimization problem is subjected to a set of constraints that define the feasible region Ω in which the optimization variables $\boldsymbol{x}$ vary according to their boundaries to find the minimum value of f_{ob}. The first set of constraints is shared by both system layouts (Ra and Br) and guarantees the energy balance to be equal to 0 on electric, heating and cooling busses. Beyond that, specific sets of constraints based on integer variables k are used to control the operational strategy of each layout. Particularly, the Rankine layout is subjected to the following main operational:

- The electrical charge of the VCHP ($k_{ch,HP}$) and electrical discharge of the ORC ($k_{dis,ORC}$) are mutually exclusive: $k_{ch,HP} + k_{dis,ORC} \le 1$ (8)
- Mutual exclusive charge and discharge on the HT and LT-TES (z intended as LT and HT): $k_{ch,zTES} + k_{dis,zTES} \le 1$ (9)
- The electrical charge of the chiller ($k_{ch,chill}$) and discharge of the ORC ($k_{dis,ORC}$) are mutually exclusive: $k_{ch,chill} + k_{dis,ORC} \le 1$; (10)
- Mutual exclusive HT/LT-TES ($k_{dis,zTES}$) discharge for direct heating/cooling ($k_{heat/cool}$) or to produce electricity by running the ORC ($k_{dis,ORC}$): $k_{heat/cool} + k_{dis,ORC} \le k_{dis,zTES}$ (11)
- The ORC can use the environment (k_{env}) or the LT-TES (k_{LT}) as a cold reservoir for the condensation phase: $k_{LT} + k_{env} \le k_{dis,ORC}$

The Brayton layout is instead less flexible in terms of operation, so the only few operative constraints it is subjected to are summarized here as follows:

- Mutual exclusive charge (k_{ch}) or discharge ($k_{dis,HE}$): $k_{ch} + k_{dis,HE} \le 1$ (12)
- Mutual exclusive charge ($k_{ch,zTES}$) and discharge ($k_{dis,zTES}$) on the HT and LT -TES (z intended as LT and HT): $k_{ch,zTES} + k_{dis,zTES} \le 1$ (13)
- Mutual exclusive HT/LT-TES ($k_{dis,zTES}$) discharge for direct heating/cooling ($k_{heat/cool}$) or to run the Br-HE ($k_{dis,HE}$): $k_{heat/cool} + k_{dis,HE} \le k_{dis,zTES}$ (14)

2.5 Simulated scenarios

Three different demand scenarios were selected to provide a comparative analysis between the performance of the Br and Ra layouts. The scenarios are representative of the climate conditions of

https://doi.org/10.52202/077185-0078

three Italian cities located in the North, Center, and South, respectively. The Northern city (Bergamo) has high heating demand due to cold winter weather, low cooling, and electricity demand. The Center city (Pisa) has intermediate conditions, while the Southern one (Catania) is characterized by low heating demand, high cooling demand due to hot summers, and high electricity demand. The yearly share between electricity, heating, and cooling demand of the three scenarios were simulated with the software nPro Energy (Wirtz, 2023) and summarized in **Table 2**. Given the size of the district, the storage charging and discharging power, $\overline{W}_{ch}$ and $\overline{W}_{dis}$, are set equal to 1 MW, while the plant size has variable installed power (~ 3 MW) according to the city scenario.

Table 2*:* Yearly demand share between electricity, heating and cooling for the selected scenarios

	Yearly demand (MWh)			**Yearly share (% on total demand)**		
	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Northern Italy	2800	4120	1480	33	49	17
Central Italy	3200	3600	1600	38	43	19
Southern Italy	3600	2880	1920	43	34	23

Besides the demand share, the energy prices also play a key role in defining the operational patterns and cost-effectiveness of the Br-PTES over the Ra-PTES layout or vice versa. For this reason, different electricity and natural gas price scenarios are evaluated. The baseline scenario refers to historical data for electricity and natural gas prices downloaded from (ARERA, 2023) for the year 2019, equal to 0.2 €/kWh and 0.7 €/Sm^3, respectively. In addition, 25 combinations of prices were evaluated to simulate different market conditions in the period 2019-2023, as summarized in **Table 3**.

Table 3*:* Electricity and natural gas price combinations investigated. The central value in the range refers to the baseline scenario related to electricity and natural gas prices in 2019 for Italy.

Electricity (€/kWh)	**Natural gas (€/Sm^3)**
0.06 – 0.2 – 0.6	0.2 – 0.7 – 2.1

The operational cost saving is used as the primary key performance indicator to prove the cost-effectiveness of one technology over the other. The adimensional parameter OC/OC_0 is then defined, where OC is the Operational Cost, and OC_0 is the operational cost when no storage capacity is installed in the system.

3 RESULTS AND DISCUSSION

3.1 Sensitivity to energy demand mix

Results in **Figure 4** show the OC reduction compared to the baseline scenario with no storage capacity installed in the system (OC_0). Results are related to the three demand mix scenarios (North, Center, South) and the baseline market conditions scenario with historical electricity and NG prices for Italy in 2019. The Br-PTES shows an advantage in terms of overall OC reduction for all the simulated scenarios. However, for the Northern city, the performance of Br and Ra technologies are very similar (OC/OC_0 ~ 27%), while the advantage of using the Brayton alternative is more evident going towards the South. The Northern scenario, indeed, is the one with the highest heating demand, so the Ra-PTES can best exploit its efficient P2H conversion (COP = 2.50), thus avoiding purchasing NG from the grid, which is significantly lower than the NG purchasing by the Br-PTES.

On the other hand, the heating demand is reducing going towards the southern scenario, while the electric and cooling demands are increasing. This is reflected in a better performance of the Br-PTES, which can exploit its efficient P2P conversion (40% efficiency), thus avoiding purchasing electricity from the grid. This trend continues going towards the Southern scenario, where the purchasing of electricity grows for both technologies due to the electricity and cooling higher demand. However, the electricity purchased by the Br-PTES compared to the Ra-PTES still is favorable. In the Southern scenario, the Br-PTES capacity exploits its efficient P2P conversion not only to fulfil the electric demand directly, but also to power the electric chiller to cover the cooling demand, which in the South is significant also when the RES production is absent (the cooling load is nonzero also during night hours). This reflects an overall more pronounced cost-effectiveness of the Br-PTES over the Ra-PTES, with a relative cost reduction of 5% compared to 1% in the Northern scenario.

https://doi.org/10.52202/077185-0078

The Ra layout shows a different trend. In the Center scenarios, the OC is higher than the Northern one since the heating demand is reducing, so the advantage of the efficient P2H conversion is less impacting. However, this trend is reversed going towards the South. In this case, indeed, the heating requirement is reducing, but at the same time, the cooling demand is increasing. The Ra layout exploits its efficient P2C conversion (EER=4.68) and brings an economic advantage. In this case, then, the disadvantage of having a lower heating provision is compensated by supplying a significative share of cooling, which brings to an overall OC reduction similar to the one of the Northern city scenario.

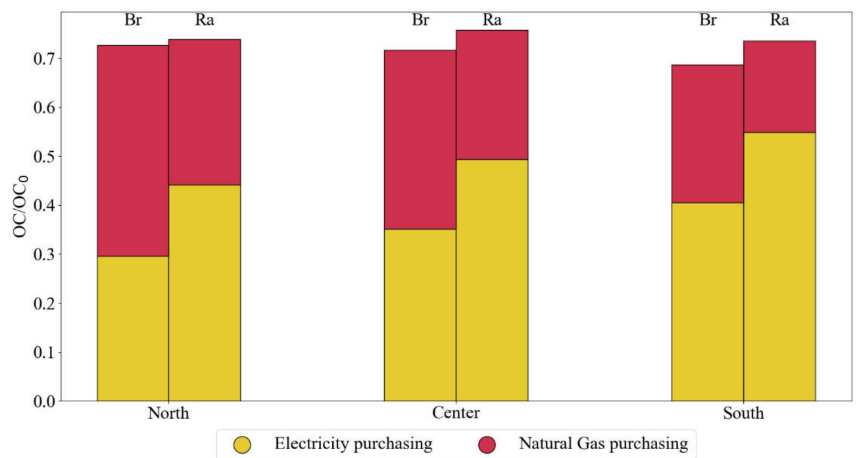

Figure 4. Operational Cost (OC) reduction compared to a baseline scenario without storage capacity installed in the system (OC_0). Baseline market conditions referred to electricity and natural gas price for Italy in 2019.

3.2 Storage fulfilment share

The results shown in the previous section reflect the storage behavior in acting as a multi-energy storage device. **Figure 5** then shows how the entire discharged energy by the storage is distributed over the electric, direct heating, and direct cooling discharges. The Br-PTES and the Ra-PTES show a complementary behavior for all the analyzed scenarios. The Br-PTES works mainly as a P2P device (electric battery behavior), while the Ra-PTES acts as a P2H/P2C device (heat pump/chiller behavior). Concerning the Br-PTES, the electricity provision represents 70% of the electrical charges for all the scenarios. However, going towards the Southern climates, part of the discharges is also used to cover an increasing share of the heating and cooling demand. As described in Section 2.2, the Br-PTES works using the HT-TES and LT-TES simultaneously, causing some unavoidable curtailment losses to keep the storage tanks balanced. When there is simultaneous heating and cooling demand (more evident for the Center and South scenarios), the tanks can easily be balanced without curtailment losses, as the cooling discharges counterbalance the heating ones and vice versa by also receiving an economic reward (demand fulfilment instead of non-rewarded curtailment). Because of this, the Br-PTES uses part of the stored energy to fulfil the increasing cooling demand going towards the South, and at the same time, provides direct heating for domestic hot water to avoid curtailment. However, the P2C performance coefficient of the Br-PTES is poor (1.33) compared to the efficiency of the backup chiller (4.68 at nominal conditions). For this reason, the direct cooling provision is limited to 10%, while the impact of the efficient P2P conversion is used to charge the storage and use electric discharges to run the electric backup chiller directly.

The Ra-PTES, instead, uses only 10% of the discharges to fulfil the electric requirement of the district while devolves all the rest for the direct heating and direct cooling provision. In this case, since the VCHP and the chiller work independently, direct heating and direct cooling discharges are not constrained to work simultaneously. For this reason, the trend follows the demand share, where the Ra-PTES uses almost 50% of the charged energy to fulfil the district heating in the Northern city, while in the Southern scenario, the 53% of the discharges are used to fulfil the cooling demand.

https://doi.org/10.52202/077185-0078

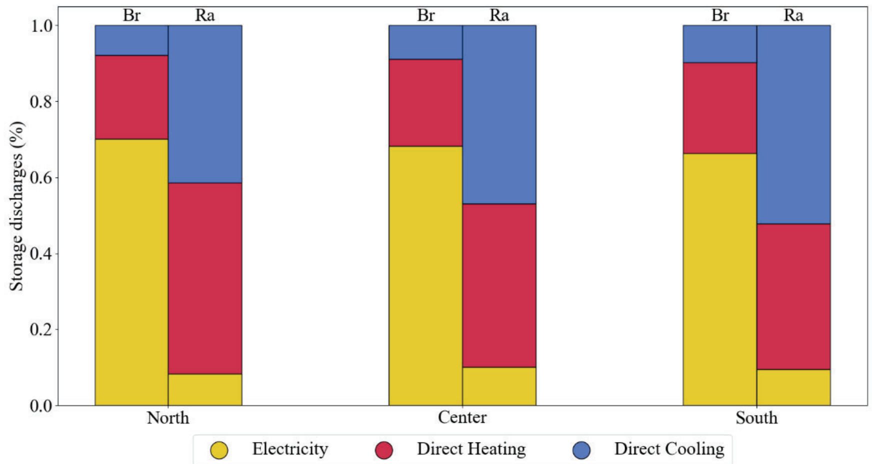

Figure 5. Storage discharge share partitioned by electricity, direct heating, and direct cooling provision for the three demand mix scenarios.

3.3 Sensitivity to market conditions

Market conditions – defined by the ratio between the electricity and the NG prices – strongly impact the results as well. Despite **Figure 4** showing that the Br-PTES is overall more convenient for the three demand scenarios, the situation could profoundly change when the ratio between electricity and NG prices changes. **Figure 6** shows the sensitivity analysis with respect to the electricity and NG prices for the three evaluated scenarios (from Northern to Southern Italy). Red areas in the plot indicate when Ra-layout is more convenient, while blue areas indicate when Br-layout is more convenient. For all the scenarios considered, the Rankine layout outperforms the Brayton one for the cases with low-to-medium electricity prices and high natural gas prices (upper-left corner of each scenario). In these situations, it is more convenient to avoid purchasing NG from the grid, while purchasing cheap electricity is advantageous. By doing so, systems that perform an efficient P2H conversion – as Ra-PTES does, are favored. This phenomenon is even more evident for demand mix scenarios where the heating share is high (i.e., Northern case study), where most of the OC contribution is given by the NG purchasing (see **Figure 4** for reference). The area where Ra-PTES is convenient is more widespread for the Northern scenario, meaning that with high heating demand shares, the Ra convenience is still evident even for lower NG prices.

Concerning the other extreme case, i.e., for low-to-medium NG prices and the high price of electricity, the Brayton technology is instead the best performing one. In this case, avoiding purchasing electricity from the grid is more beneficial than avoiding NG purchasing. Therefore, the Br-PTES, since it operates with higher P2P efficiency than the Ra-PTES, brings evident economic advantages. This behavior is emphasized by going towards the Southern scenario, where most of the OC contribution is given by electricity purchasing (**Figure 4**). The blue area (related to the Br convenience) is more widespread in this case, as the electricity and cooling demands are greater here, and the efficient P2P conversion of the Br is more impactful.

4 CONCLUSIONS

This paper investigated the cost-effectiveness of two different Pumped Thermal Energy Storage (PTES) technologies (Rankine-based and Brayton-based) to support the integration of Renewable Energy Sources (RES) generation into a Multi-Energy urban district characterized by electric, heating, and cooling demand. The study aimed to identify which technology minimizes yearly Operational Cost (OC) across three demand scenarios representing a North, Center, and South city in Italy. Each scenario considered various combinations of electricity and Natural Gas (NG) prices. The energy dispatch was optimized over a year using a Mixed Integer Linear Program (MILP) with a 24-hour rolling horizon.

The findings for baseline market conditions (Italy's 2019 electricity and NG prices) revealed similar performance for Br-PTES and Ra-PTES in the North city (OC reduction of ~27%). However, in Southern cities with higher cooling and electricity demands, Br-PTES performed better due to its higher

https://doi.org/10.52202/077185-0078

Power-to-Power (H2P) conversion efficiency (40% vs. 10%). Conversely, Ra-PTES performs better in the Northern city due to its superior Power-to-Heat (P2H) efficiency (2.50 vs. 1.86).
Sensitivity analysis to market conditions showed Ra-PTES was more advantageous with medium-high NG prices, exploiting P2H to avoid NG costs. Br-PTES was preferable with high electricity prices, leveraging efficient H2P conversion to maximize RES use and minimize grid electricity purchases. Additionally, Br-PTES predominantly works as an electric battery (60% of discharges for P2P), whereas Ra-PTES primarily utilized stored energy for P2H and cooling. In conclusion, the analysis shows that both technologies show a good performance in cutting the Operational Costs. However, the prevalence of one technology over the other could be affected by changes in the turbomachinery efficiency, which could impact on the overall round-trip efficiency Finally, despite PTES storage is a valid alternative to benchmark technologies (since it overcomes some important limitations like raw materials dependency and power-capacity decoupling), still its economic competitiveness with Li-ion batteries is an open question to be addressed during the future developments of this study. Specifically, if we only consider operational costs, a system equipped with Li-ion batteries and electric heat pumps could be more cost-effective given its higher round-trip efficiency. However, PTES systems benefit from a lower cost per kWh, and recent studies testify that Br-PTES shows a lower LCOE compared to Li-on batteries (Smallbone et al., 2017) (Parisi et al., 2024), meaning that a more detailed economic analysis comparison including capital costs could provide additional insights in answering this research question.

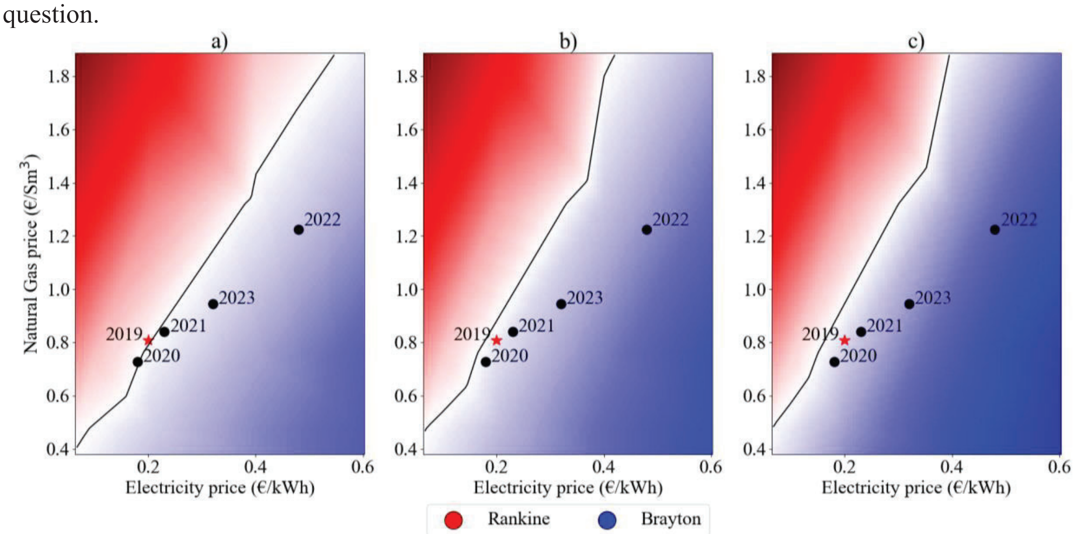

Figure 6. Sensitivity analysis to electricity and natural gas price for: a) Northern Italy; b) Central Italy; c) Southern Italy. Rankine layout is more convenient in red areas, while Brayton layout is more convenient in blue areas. The red marker refers to the baseline market conditions of 2019 in Italy, investigated in **Figure 4**, while red markers relate to years until 2023 as reference.

NOMENCLATURE

Acronyms

Br	Brayton-Joule
CB	Carnot Battery
COP	Coefficient Of Performance
DHC	District Heating and Cooling
ESS	Energy Storage System
HE	Heat Engine
HP	Heat Pump
HT	High Temperature
H2P	Heat-to-Power
LT	Low Temperature
MES	Multi-Energy System
MILP	Mixed Integer Linear Programming
NG	Natural Gas
OC	Operating Costs
ORC	Organic Rankine Cycle
PTES	Pumped Thermal Energy Storage
P2H	Power-to-Heat
P2P	Power-to-Power
P2C	Power-to-Cool
Ra	Rankine
RES	Renewable Energy Source

https://doi.org/10.52202/077185-0078

TES Thermal Energy Storage
VCHP Vapor Compression Heat Pump

Subscripts

ch charge
chill chiller
cool cooling
curt curtailment
dem demand
dir direct
dis discharge
el electric
env environment
heat heating
obj objective
pur purchasing
sell selling
tot total
0 baseline

Symbols

f function
t timestep
$\overline{T}$ optimization horizon
$\dot{W}$ power
$\dot{Q}$ heat flow rate

REFERENCES

ARERA. (2023). *Prezzi e tariffe*. https://www.arera.it/it/prezzi.htm#

Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., & Bertsch, S. S. (2018). High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. *Energy*, *152*, 985–1010. https://doi.org/10.1016/j.energy.2018.03.166

Dumont, O., Frate, G. F., Pillai, A., Lecompte, S., De paepe, M., & Lemort, V. (2020). Carnot battery technology: A state-of-the-art review. *Journal of Energy Storage*, *32*(August). https://doi.org/10.1016/j.est.2020.101756

Dumont, O., & Lemort, V. (2020). Mapping of performance of pumped thermal energy storage (Carnot battery) using waste heat recovery. *Energy*, *211*, 118963. https://doi.org/10.1016/j.energy.2020.118963

European Commission Directorate-General for Climate Action. (2019). *Going climate-neutral by 2050 – A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*. https://doi.org/https://data.europa.eu/doi/10.2834/02074

European Commission Joint Research Center. (2023). *Photovoltaic Geographical Information System (PVGIS)*. https://re.jrc.ec.europa.eu/pvg_tools/en/

Frate, G. F., Ferrari, L., & Desideri, U. (2021). Energy storage for grid-scale applications: Technology review and economic feasibility analysis. *Renewable Energy*, *163*, 1754–1772.

Frate, G. F., Ferrari, L., & Desideri, U. (2022). Techno-Economic Comparison of Brayton Pumped Thermal Electricity Storage (PTES) Systems Based on Solid and Liquid Sensible Heat Storage. *Energies*, *15*(24). https://doi.org/10.3390/en15249595

Frate, G. F., Ferrari, L., Sdringola, P., Desideri, U., & Sciacovelli, A. (2023). Thermally integrated pumped thermal energy storage for multi-energy districts: Integrated modelling, assessment and comparison with batteries. *Journal of Energy Storage*, *61*(September 2022), 106734. https://doi.org/10.1016/j.est.2023.106734

Frate, G. F., Paternostro, L., Ferrari, L., & Desideri, U. (2022). Off-Design of a Pumped Thermal Energy Storage Based on Closed Brayton Cycles. *Journal of Engineering for Gas Turbines and Power*, *144*(2), 1–11. https://doi.org/10.1115/1.4052426

Ghilardi, A., Frate, G. F., Piazzi, A., Tucci, M., Kyprianidis, K., & Ferrari, L. (2023). Pumped Thermal Energy Storage for Multi-Energy Systems Optimization. *Proceedings of the 64th International Conference of Scandinavian Simulation Society, SIMS 2023 Västerås, Sweden, September 25-28, 2023*, *200*, 21–28. https://doi.org/10.3384/ecp200004

Lykas, P., Bellos, E., Korres, D. N., Kitsopoulou, A., & Tzivanidis, C. (2023). Energy, exergy, economic, and environmental (4E) analysis of a pumped thermal energy storage system for trigeneration in buildings. *Energy Advances*, *2*(3), 430–440. https://doi.org/10.1039/d2ya00360k

Mancarella, P. (2014). MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, *65*, 1–17. https://doi.org/10.1016/j.energy.2013.10.041

Olympios, A. V., McTigue, J. D., Sapin, P., & Markides, C. N. (2022). Pumped-Thermal Electricity Storage Based on Brayton Cycles. *Encyclopedia of Energy Storage*, 6–18. https://doi.org/10.1016/B978-0-12-819723-3.00086-X

https://doi.org/10.52202/077185-0078

Østergaard, D. S., Smith, K. M., Tunzi, M., & Svendsen, S. (2022). Low-temperature operation of heating systems to enable 4th generation district heating: A review. *Energy*, *248*, 123529. https://doi.org/10.1016/j.energy.2022.123529

Østergaard, P. A., Werner, S., Dyrelund, A., Lund, H., Arabkoohsar, A., Sorknæs, P., Gudmundsson, O., Thorsen, J. E., & Mathiesen, B. V. (2022). The four generations of district cooling - A categorization of the development in district cooling from origin to future prospect. *Energy*, *253*, 124098. https://doi.org/10.1016/j.energy.2022.124098

Parisi, S., Desai, N. B., & Haglind, F. (2024). Techno-Economic Analysis of Using Reversible Turbomachinery for Pumped Thermal Energy Storage Systems. *Journal of Solar Energy Engineering*, *146*(5), 1–9. https://doi.org/10.1115/1.4065041

Ramsebner, J., Haas, R., Ajanovic, A., & Wietschel, M. (2021). The sector coupling concept: A critical review. *Wiley Interdisciplinary Reviews: Energy and Environment*, *10*(4), 1–27. https://doi.org/10.1002/wene.396

Smallbone, A., Jülch, V., Wardle, R., & Paul, A. (2017). Levelised Cost of Storage for Pumped Heat Energy Storage in comparison with other energy storage technologies. *Energy Conversion and Management*, *152*(May), 221–228. https://doi.org/10.1016/j.enconman.2017.09.047

Steinmann, W. D., Bauer, D., Jockenhöfer, H., & Johnson, M. (2019). Pumped thermal energy storage (PTES) as smart sector-coupling technology for heat and electricity. *Energy*, *183*, 185–190. https://doi.org/10.1016/j.energy.2019.06.058

Urbanucci, L. (2018). Limits and potentials of Mixed Integer Linear Programming methods for optimization of polygeneration energy systems. *Energy Procedia*, *148*, 1199–1205. https://doi.org/10.1016/j.egypro.2018.08.021

Vecchi, A., Li, Y., Mancarella, P., & Sciacovelli, A. (2021). Multi-energy liquid air energy storage: A novel solution for flexible operation of districts with thermal networks. *Energy Conversion and Management*, *238*(January), 114161. https://doi.org/10.1016/j.enconman.2021.114161

Victoria, M., Zhu, K., Brown, T., Andresen, G. B., & Greiner, M. (2019). The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. *Energy Conversion and Management*, *201*(August), 111977. https://doi.org/10.1016/j.enconman.2019.111977

Vijayaraghavan, S., & Goswami, D. Y. (2003). *On Evaluating Efficiency of a Combined Power and Cooling*. *125*(September), 221–227. https://doi.org/10.1115/1.1595110

Wang, L., Lin, X., Zhang, H., Peng, L., & Chen, H. (2021). Brayton-cycle-based pumped heat electricity storage with innovative operation mode of thermal energy storage array. *Applied Energy*, *291*(December 2020), 116821. https://doi.org/10.1016/j.apenergy.2021.116821

Wirtz, M. (2023). nPro: A web-based planning tool for designing district energy systems and thermal networks. *Energy*, *268*(November 2022), 126575. https://doi.org/10.1016/j.energy.2022.126575

Zhang, H., Wang, L., Lin, X., & Chen, H. (2020). Combined cooling, heating, and power generation performance of pumped thermal electricity storage system based on Brayton cycle. *Applied Energy*, *278*(April), 115607. https://doi.org/10.1016/j.apenergy.2020.115607

ACKNOWLEDGEMENT

This research was funded in the Program Agreement between the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and the Ministry of Environment and Energy Security (MASE) for Electric System Research, in the framework of its Implementation Plan for 2022–2024. The activity is included in Project 1.5 "Edifici ad alta efficienza per la transizione energetica".

Dr. Guido Francesco Frate acknowledges the financial contribution received by the Ministry of University and Research (MUR) as part of the FSE REACT-EU - PON 2014-2020 "Research and Innovation" resources – Green/Innovation Action - DM MUR 1062/2021 - Title of the Research: *Soluzione e tecnologie innovative per la generazione di potenza e le macchine a fluido nella transizione verde*.

https://doi.org/10.52202/077185-0078