SIMILITUDE-BASED REVERSIBLE BRAYTON PUMPED THERMAL ENERGY STORAGE

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ABSTRACT

As the adoption of renewable power sources grows, the interest in long-duration electric energy storage solutions also increases. Pumped Thermal Energy Storage (PTES) based on Brayton cycles and solid thermal storage materials (SBPTES) is one promising alternative whose economic viability could be further improved by significantly reducing its capital cost, particularly regarding the devices used for charging and discharging the storage. Therefore, the primary objective of this study is to investigate the economic impact of merging said pieces of equipment, that is, re-using the same components in both phases, reducing their number and the overall plant cost. This means designing a system that reversibly operates during both phases. Since BPTES typically employs separate systems for charging and discharging, a reversible system that does both always operates in off-design conditions, compromising the entire storage performance unless particular design criteria are adopted. In particular, the turbomachines can be operated in similitude (perfect or partial), which means designing the charging and discharging cycles to maintain the allowed corrected mass flow rate and specific speed to operate with satisfactory performance during both phases. A similar design criterion profoundly influences the component sizing and the SBPTES nominal charging and discharging rates. Therefore, an economic comparison between standard (non-reversible) systems and the proposed novel approach (reversible) was performed. The results show that the reversible systems may cost up to 25% less than their standard counterpart at the cost of a limited penalty on the roundtrip efficiency, which is reduced by two percentage points compared to the standard configuration.

1 INTRODUCTION

The increase in non-programmable renewable production in the upcoming years necessitates a corresponding expansion in energy storage capacity. Various technologies are being explored in the quest for durable, cost-effective, and sustainable storage solutions, with thermomechanical technologies emerging as prominent alternatives. The strong point of these technologies lies in the utilization of standard apparatuses (like turbomachines, heat exchangers, and thermal storages) well-known and used in many other prominent applications (Liang et al., 2022) within a similar range of operating temperatures, pressures, and flow rates.

Pumped Thermal Energy Storage (PTES) systems are part of the thermomechanical technologies, and they are mainly differentiated by the thermodynamic cycle they are based on, distinguishing between Rankine or Brayton, RaPTES or BPTES, respectively (Dumont et al., 2020).

Concerning Brayton PTES, solutions with roundtrip efficiency above 60% have been found as in (Desrues et al., 2010) and even more with an addition of latent storage (Albert et al., 2022) or a regenerative heat exchanger (McTigue et al., 2022). On the other hand, despite significant advancements, this thermomechanical energy storage technology continues to face challenges in achieving competitive capital costs, primarily due to using separate (and often costly) charging and discharging equipment (McTigue et al., 2022). Hence, to overcome this issue and make PTES affordable, systems that use reversible volumetric machines have been developed, showing a roundtrip efficiency of 60% in the case of the world's first experimentally tested BPTES (Ameen et al., 2023).

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Furthermore, this cost reduction allows reversible BPTES to become cost-competitive with other storage solutions, such as CAES (Ameen et al., 2023).
Other methods to achieve reversibility in the Brayton PTES system are based on the utilization of reversible axial turbomachines, even if the importance of a careful design is remarked in order not to lose in the roundtrip efficiency (Chiapperi et al., 2023). As reported in (Parisi & Haglind, 2023) and (Harris et al., 2020), an efficiency comparable to that of a standard turbine can be achieved with a reversible axial compressor/turbine. However, it requires a profound revision of how machines are generally designed and the specific requirements of the cycle have to be taken into account for further efficiency improvements. At the same time, it can be challenging to establish the associated economic advantage beforehand. Nevertheless, (Parisi et al., 2023) developed new cost correlations to asses the expenditure for reversible turbomachines, concluding that BPTES with liquid storage has the lowest LCOS among other PTES variants.

This paper presents a novel concept of storage based on the well-known Brayton PTES technology. The newly proposed method uses turbomachine similitude to merge some equipment and employ the same components during the charging and the discharging phase, reducing the overall plant cost.
A standard Brayton PTES has been compared with two different systems in which similitude has been imposed partially (partial similitude system) or perfectly (perfect similitude system). In order to assess the techno-economic performance of these three configurations, an optimization of the roundtrip efficiency has been pursued, and an economic analysis has been undertaken to show the economic advantage of such a new methodology.

2 METHODOLOGY

2.1 Model description

The operations of a reversible system mirrors that of a standard one: during charging, electric exergy is transformed into thermal exergy via a Brayton heat pump and stored, while during discharging, the stored thermal exergy is utilized to generate electricity through a Brayton heat engine (Frate et al., 2022). Notably, SBPTES necessitates two coolers to dissipate the excess heat generated by the irreversibilities throughout the system (McTigue et al., 2015) unless a higher pressure ratio is applied during the discharging cycle compared to the charging phase. In this case, only one cooler is sufficient.

The analysis proposed in this paper shows a techno-economic comparison between three different cases:

1. Non-reversible "Standard" system:
   The system has different components and turbomachines for the charging and discharging phase. Since this configuration is detailed in (Frate et al., 2022), its analysis is omitted here.
2. Reversible system realized through "Partial similitude":
   The system has only one compressor, which works in both the charging and discharging phases. The two different operating conditions are chosen through optimization and belong to the compressor's map.
3. Reversible system realized through "Perfect similitude":
   The system has only one compressor that works in both the charging and discharging phases, with perfect similitude being imposed, meaning that the corrected air flow rate and rotational speed are the same in the charging and discharging phases.

The scenario "Perfect similitude" is a particular case of the more general "Partial similitude", for which the compressor operating point during the discharging is not optimized but assumed equal to the charging phase one; that is, it operates with the same pressure ratio, corrected air flow rate, isentropic efficiency and corrected rotational speed during charging and discharging.
The thermodynamic cycles of these three configurations are reported in Figure **1**.
The reversible system's unique feature lies in utilizing the same turbomachines for both the charging and discharging phases, thereby minimizing the required equipment. Consequently, the turbomachines are designed in similitude imposed using the same operating map for the compressor, or the same corrected mass flow rate for the turbine. Since turbomachine similitude is imposed, the working conditions of charging and discharging, in terms of pressure ratio, corrected air flow rate, isentropic

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efficiency and corrected rotational speed, will be different both in "Perfect similitude" and in "Partial similitude". This has two consequences that apply both to the case of "Perfect similitude" and "Partial similitude":

- The following section explains that two turbines are needed for the discharging phase.
- The compressor and turbine cannot use the same shaft, and a gearbox is required since the motor and the generator work at different speeds during the charging and discharging phases.

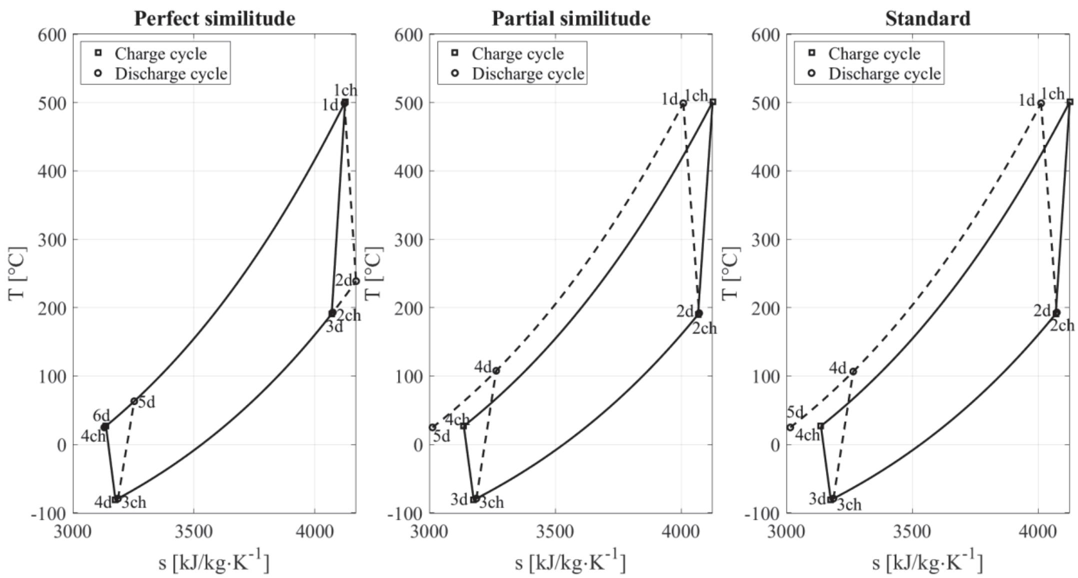

Figure 1 – Charging and discharging thermodynamic cycles of BPTES in the cases with "Perfect similitude", "Partial similitude", and "Standard" systems. The last two configurations are almost identical from the point of view of thermodynamic cycles (thanks to the cycle optimization), even though the reversible system operates with a unique compressor.

2.1.1 Turbomachine similitude: For turbomachines, similitude is achieved through the use of their performance map. Particularly, the performance map for the compressors has been taken from (Dixon, 2014)and adapted to the analyzed problem. The maximum isentropic efficiency value reported on the map is 82%, while 87% has been chosen in line with the dedicated literature (McTigue et al., 2022). Subsequently, the second scaling is used to adapt the map to the matter case in terms of pressure ratio and corrected air flow rate.

For the sake of simplicity, no performance map of the turbine has been used. Indeed, the turbine employed always works in choked conditions, which means that the variation of the pressure ratio does not affect the corrected air flow rate. In other words, it is enough to impose the same corrected air flow rate in charging and discharging, allowing the pressure ratio to vary.

Moreover, it is essential to point out that in this analysis, while one turbine is used during the charging phase, two are needed during discharging. As stated before, to reach the similitude, the turbine should work with the same corrected air flow rate in both phases, but since this constraint would have limited the working range of the compressor without finding a feasible solution, it has not been imposed. This applies both in the case of "Perfect similitude" and "Partial similitude".

Therefore, to address this inconsistency, the paper proposes a solution wherein the turbine used both in charging and discharging operates in perfect similitude, but since the discharging air flow rate is larger than the charging one, the flow in excess remaining is sent to another turbine functioning in parallel with the first one. Consequently, while only one compressor is utilized for both phases, two turbines are required to achieve this adjustment.

The scheme of "Partial similitude" and "Perfect similitude" is practically the same apart from the cooler after the two turbines, not present in the "Partial similitude" system. The charging and the discharging layouts are reported in Figure **2**, while the "Standard" system layout is in (Frate et al., 2022).

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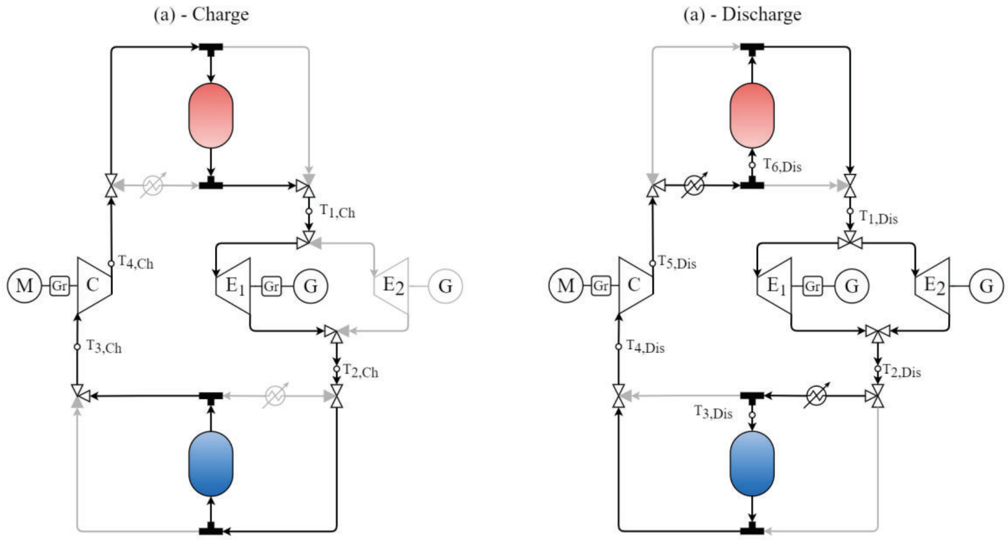

Figure 2 – Brayton PTES system: (a) charge system; (b) discharge system. Subscripts Ch and Dis denote the thermodynamic states during the charging and discharging phases. C, E, M, G and Gr denote compressors, expanders, electrical motors, generators, and gearboxes.

2.1.2 Differences among the three configurations In this section, the different amounts of pieces of equipment among "Standard", "Partial similitude" and "Perfect similitude" are reviewed.

Table 1 – Comparison of the number of components among standard, reversible with performance map and reversible with perfect similitude.

	Standard	**Reversible**	
		Partial similitude	Perfect similitude
Turbine	2	2	2
Compressor	2	1	1
Reservoir	2	2	2
Cooler	1	1	2
Motor	1	1	1
Generator	1	2	2
Gearbox	-	2	2
Total	**11**	**11**	**12**

In Table **1** four main differences can be noted between "Standard" and "Reversible" systems:

- Thanks to the similitude the reversible systems have only one compressor, but still two turbines.
- Two coolers are needed in the reversible system with perfect similitude imposed since the pressure ratio does not change between charging and discharging. Consequently, without using an additional cooler, the outlet temperature of the cold TES during discharging cannot be equal to the inlet temperature of the cold TES during charging.
- Because the two turbines operate at different rotational speeds, two generators are needed in the reversible systems.
- The two gearboxes are necessary for the reversible systems since the compressors' and turbines' rotational speeds are different.

The consequences of these differences are:

- The gearbox and the fact that the compressor and the turbines are not on the same shaft result in more electric power being supplied to the compressor than the standard layout. This is because of the gearbox and motor efficiencies and the fact that the turbine cannot offset some

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of the compressor's electric power consumption, implying that a significantly larger motor is used in the reversible system to power the compressor.
- The flexibility of reversible systems is limited compared to that of the standard system. In particular, this regards the possibility of freely setting the desired power input and output of the charging and discharging phases, which is directly linked to the mass flow rate in both phases. This is allowed in standard systems, as they use independently designed devices for charging and discharging.

2.2 Optimization model

This section outlines the methodology employed to assess SBPTES performance. Calculating roundtrip efficiency and equipment cost relies on the findings and methodologies detailed in (Frate et al., 2022). The roundtrip efficiency, denoted as η_{RT}, has been assessed as the product of the charge and discharge exergy efficiencies, represented by ψ_{Ch} and ψ_{Dis}, respectively:

$$\eta_{RT} = \psi_{Ch} \cdot \psi_{Dis} \quad (1)$$

While evaluating exergy efficiencies, it is essential to note that neither heat leakages nor pressure drops have been considered. The SBPTES system costs have been calculated as follows:

$$cost = \sum_i C_i \cdot \frac{CEPCI_{2022}}{CEPCI_i} \cdot \gamma_{\$\rightarrow€} \quad (2)$$

Where C_i represents the cost in USD of the i-th piece of equipment (detailed expressions are reported in (Frate et al., 2022), while the cost correlation of compressor and turbines refers to (Mctigue et al., n.d.)), the conversion factor from dollar to euro, $\gamma_{\$\rightarrow€}$, is 1.14, the Chemical Engineering Plant Cost Index referred to 2022 $CEPCI_{2022}$, is 816 and $CEPCI_i$ refers to the year of publication of the i-th cost correlation.
Eventually, an optimization has been devised, aiming to find a solution that maximizes roundtrip efficiency. Formally, the optimization problem can be represented as follows:

$$\max_{x \in F} \eta_{RT}(x) \quad (3)$$

In this case, the vector of optimization variables, x, is composed of the temperatures of the state points of the charging and discharging cycles in Figure **1** (T_{Ch}, T_{Dis}), the two pressure ratio (β_{Ch}, β_{Dis}) and the design point of the compressor's map ($\dot{m}_{Cor,map,design}$, $\eta_{map,design}$). F is the so-called feasible region defined by the optimization problem constraints. The complete list of constraints used in Equation (3) is reported in (Frate et al., 2022) with the addition of the following equations valid for both reversible cases:

$$\dot{m}_{Ch} = \frac{W_{Nom}}{\frac{h_{Ch,1} - h_{Ch,2}}{\eta_{El} \cdot \eta_{Gear}} - (h_{Ch,5} - h_{Ch,4})\eta_{El} \cdot \eta_{Gear}} \quad (4)$$

Whereas the other following Equations only apply to the perfect similitude scenario:

$$\frac{\dot{m}_{Ch}\sqrt{T_{Ch,2}}}{p_{Ch,2}} = \frac{\dot{m}_{Dis}\sqrt{T_{Dis,4}}}{p_{Dis,4}} \quad (5)$$

$$\beta_{Ch} = \beta_{Dis} \quad (6)$$

$$\eta_{Is,Comp,Ch} = \eta_{Is,Comp,Dis} \quad (7)$$

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The constraints not reported generally impose mass and energy conservation and specific component constitutive equations like isentropic efficiency for machines or thermal conductance for heat exchangers, ensuring consistency with system operation (Frate et al., 2022).

2.2.1 Adopted parameters: The parameters utilized to evaluate the performance of reversible and standard SBPTES systems are presented in Table **2** and Table **3**, respectively, as documented in (Frate et al., 2022). In this study, air is the cycle's operating fluid. The simulated storage systems are sized by choosing the nominal electrical charging rate, with simulations conducted for three dimensions: 25 MW, 50 MW, and 100 MW, with a charging duration of 8 hours each.

Table 2 – Turbomachines and TES parameters. Data from (Frate et al., 2022)

Parameter	η_{Comp}^{Is}	η_{Turb}^{Is}	η_{El}	η_{Gear}	pp_{Hot}	pp_{Cold}	pp_{Cool}	T_{Cmp}^{Max}
	[-]	[-]	[-]	[-]	[K]	[K]	[K]	[°C]
SBPTES	Optimized	0.92	0.95	0.97	1	1	10	580

Table 3 – Hot and cold reservoir operating temperatures. Data from (Frate et al., 2022)

Parameter	$T_{Hot,1}$	$T_{Hot,2}$	$T_{Cold,1}$	$T_{Cold,2}$
	[°C]	[°C]	[°C]	[°C]
SBPTES	500	Optimized	Optimized	-80

3 RESULTS

3.1 Roundtrip efficiency and overall plant cost

The first assessment focuses on the roundtrip efficiency and the overall plant cost for the modelled layouts with three different charging power inputs (25, 50, and 100 MW) and a charging time of 8 hours. The roundtrip efficiency remains constant in all three scenarios in the following figure. On the other hand, the plant cost increases slightly less than linearly with the nominal charging power input.

As a result, the "Perfect similitude" system shows the lowest roundtrip efficiency with the lowest plant cost, whereas the "Standard" system provides the highest roundtrip efficiency in view of the highest costs while the "Partial similitude" system is in between the two configurations.

The roundtrip efficiency behaviour can be explained by considering the coolers' presence (or absence). Indeed, the "Perfect similitude" system has two coolers that reject heat to the environment during the discharging phase before the hot and the cold TES, reducing exergy efficiency in that phase. On the contrary, the other two systems ("Partial similitude" and "Standard") have only one cooler before the hot TES, resulting in a higher discharging efficiency. Moreover, the "Standard" system shows the greatest roundtrip efficiency thanks to the different compressors used for the charging and the discharging phases, which operate at the maximum isentropic efficiency. On the other hand, since only one compressor is used in the "Partial similitude" case, its isentropic efficiency is optimized and not fixed at the maximum, resulting in a slight reduction in the roundtrip efficiency.

Furthermore, it can be seen from Figure **3** that, concerning the plant's overall cost, the number of coolers does not sensibly affect the result. Indeed, apart from the "Standard" system, which has one more compressor that impacts the overall cost, in general, due to the higher flexibility, the "Standard" and the "Partial similitude" tend to have a larger mass flow rate and pressure ratio in the discharging phase compared to the "Perfect similitude", which results in a larger expenditure due to the larger size of the additional turbine used for discharging.

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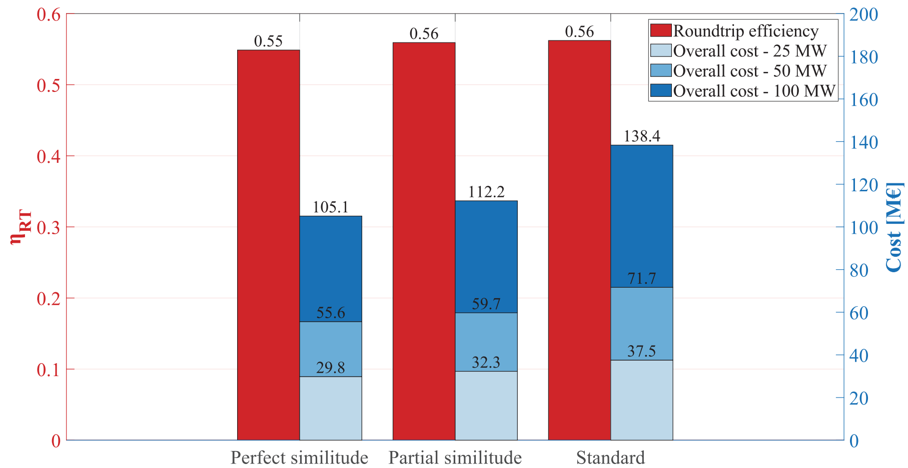

Figure 3 – Roundtrip efficiency and overall plant cost of three different solutions ("Perfect similitude", "Partial similitude", and "Standard") for three different charging power inputs (25, 50, and 100 MW).

3.2 Cost breakdown

The cost breakdown for the three system configurations is reported in Figure **4** to give a better view of the cost contribution of each component.

From the provided figure, it can be observed that the systems with imposed similitude show lower costs for turbomachines. This is primarily attributed to the utilization of a single compressor for both charging and discharging, and the additional turbine used during the discharging phase does not elaborate the discharging air flow rate on the whole since the turbine used for charging also contributes during discharging elaborating a part of the entire air flow rate. This contrasts with the "Standard" system, where distinct turbomachines are utilized for each phase, leading to higher expenditures for compressors and turbines. However, it is important to note that electromechanical conversion devices (motors and generators) are more expensive than those of similitude scenarios because the turbomachines do not share the same shaft for both the charging and discharging phases, as discussed in Section 2.1.2. Consequently, the "Standard" system, with turbomachines dedicated to each phase, has cheaper motors and generators due to the absence of gearboxes and the machines being on the same shafts.

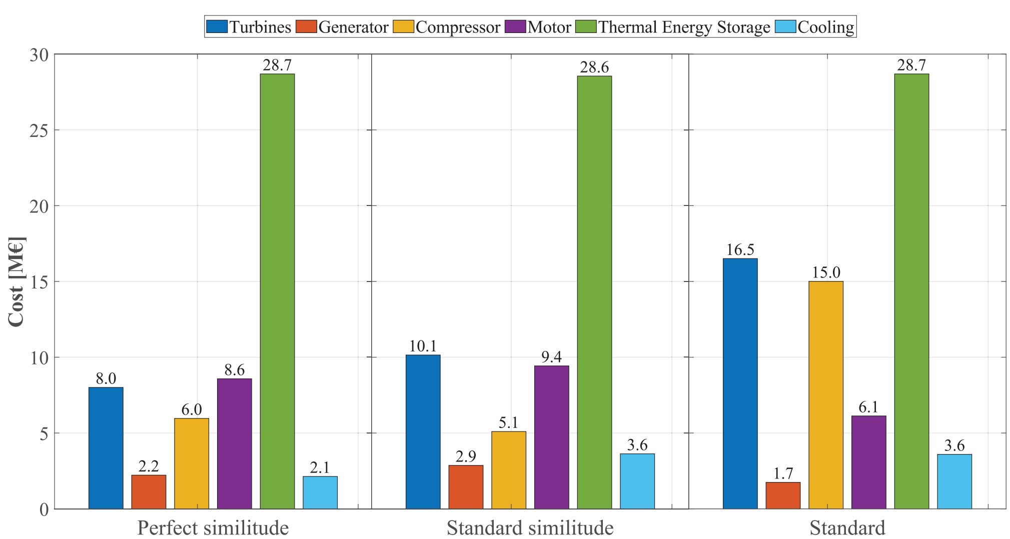

Figure 4 – Cost breakdown of "Perfect similitude", "Partial similitude", and "Standard" systems with 50 MW of charging power

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3.3 Optimized compressor map

The results from the optimization of the compressor's charging and discharging design points are reported in Figure 5, to analyze the effects of the three different types of configurations on the functioning of these turbomachines.

It can be seen that the charging point remains the same in all scenarios. On the contrary, the discharging point changes from the scenario:

- Perfect similitude: the two points are the same, as the charging and discharging phase design points overlap by design.
- Standard similitude: the discharging point shows a larger corrected air flow rate and pressure ratio than during the charging phase.
- Standard: even in this case, the discharging design point is characterized by a larger corrected mass flow rate and pressure ratio than the charging one, but here, the difference is that since two different compressors are used, different maps are used and reported in the figure, showing that the two compressors always operate at maximum isentropic efficiency.

The difference in the compressor isentropic efficiency between "Partial similitude" and "Standard" configurations drives the difference in roundtrip efficiency between the two configurations.

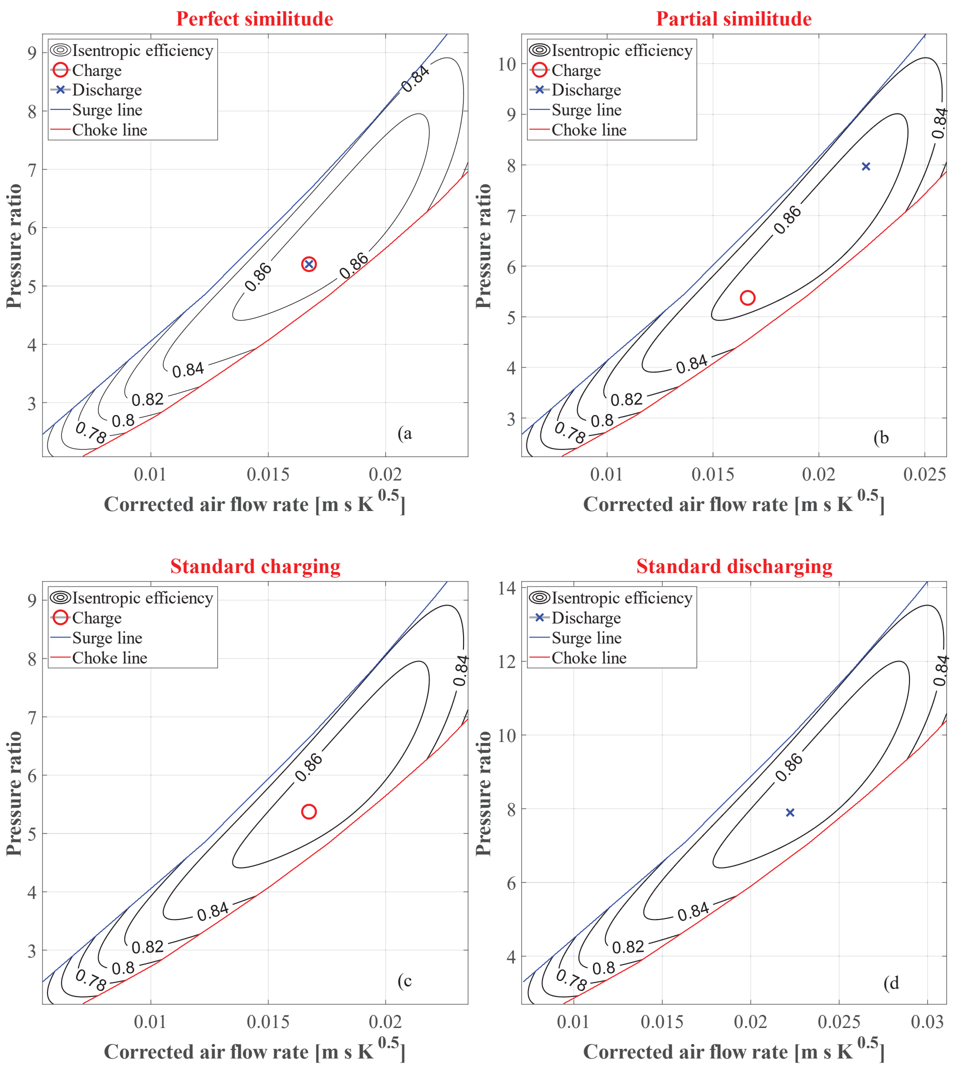

Figure 5 – Compressor map of the three analyzed scenarios with a charging power of 50 MW and a charging time of 8 hours. A unique map is used for the perfect and partial similitude, whereas two distinct maps are needed in the standard (non-reversible) systems.

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3.4 Discharging power and time

Due to the limitations imposed by the turbomachines' similitude, once the charging power and duration are set, those of the discharging phase are calculated accordingly. Consequently, the discharging phase cannot be designed independently, and the resulting discharging power output and durations must be evaluated to understand if they are compatible with the envisioned energy storage applications.

Figure **6** suggests that the discharging power is always lower than the charging one, even though the phases' durations are comparable. The discharging power output is around 40% lower than the charging power for the "Perfect similitude" system, while in the other two cases, the reduction is around 20% of the charging power. This difference is because the discharging phase operates with higher pressure ratios and mass flow rates than the "Perfect similitude" case, leading to a higher discharging nominal power output and vice versa. Eventually, the ratio between the charging and the discharging duration is equal to the ratio between the discharging and the charging power divided by the roundtrip efficiency. Hence, the higher the charging-to-discharging power ratio, the lower the charging-to-discharging time ratio will be. Consequently, the "Perfect similitude" scenario shows the highest discharging time thanks to the reduced charging-to-discharging power ratio.

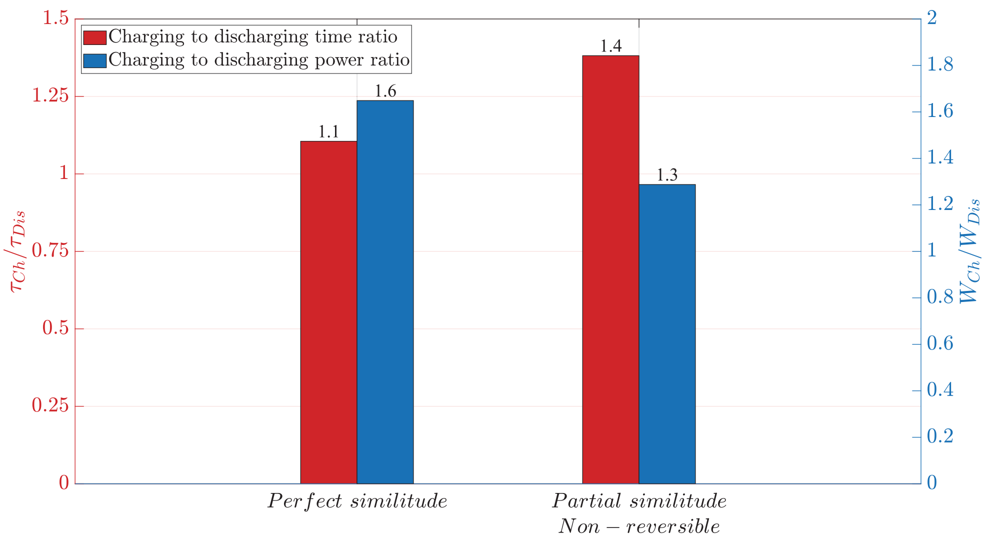

Figure 6 – Charging to discharging time ratio and charging to discharging power ratio. These quantities are independent of the charging power.

3.5 Design conditions

An example of the different design conditions is reported in Table **4**, where the three scenarios are compared.

In general, it can be seen that the parameters of the charging phase phase remain largely consistent across all scenarios. Consequently, the discharging phase drives differences in performance and costs. As a result, in the first scenario, where the discharging pressure ratio is fixed to that of the charging phase, the system tends to exhibit smaller values for discharging parameters. Conversely, the "Partial similitude" scenario, which lacks the constraint on the discharging pressure ratio, yields a solution closer to the one with the best performance, namely the "Non-reversible" system.

Furthermore, the varying turbomachine expenditures in the similitude scenarios depicted in Figure **4** can be explained. The compressor of the "Standard Similitude" system is less expensive than that of the "Perfect Similitude" system, owing to the decrease in air flow rate and the increase in air density at the inlet. Additionally, the "Standard Similitude" system exhibits a higher pressure ratio during the discharging phase compared to the "Perfect Similitude" system, resulting in greater power delivered by the additional turbine, albeit at a higher cost.

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Table 4 – Design conditions of the three scenarios. The results are related to the nominal power of 50 MW and a charging duration of 8 hours. The second number in the power of the discharging turbine represents the power of the turbine used only for discharging

Scenarios	Charging phase				Discharging phase					η_{RT}
	β	$\dot{m}$	W_{Turb}	W_{Comp}	β	$\dot{m}$	W_{Turb}		W_{Comp}	
	[-]	[kg/s]	[MW]	[MW]	[-]	[kg/s]	[MW]		[MW]	[%]
Perfect similitude	5.4	194.2	19.1	69.0	5.4	300.3	30.8	47.1	46.2	54.8
Partial similitude	5.4	193.3	19.0	69.0	8.0	398.8	53.5	67.9	80.7	55.9
Non-reversible	5.4	194.2	19.1	69.0	7.9	398.8	119.0		80.2	56.2

4 CONCLUSIONS

This paper examines the economic implications of reducing the number of components in SBPTES by enforcing similitude on turbomachines. This approach enables the utilization of the compressor and turbine in both the charging and discharging phases, albeit necessitating two turbines for the discharging phase. Consequently, the roundtrip efficiency is maximized to assess the performance of these proposed solutions.

The results indicate that both reversible systems exhibit a slightly lower roundtrip efficiency than the standard one but with a larger reduction in plant cost. Indeed, it is noteworthy that with a maximum cost reduction of 25%, the roundtrip efficiency experiences only a 2% reduction when comparing the "Standard" and "Perfect similitude" systems with a nominal charging power of 100MW.

The reduction in roundtrip efficiency primarily stems from the presence of an additional cooler and additional electromechanical losses in the "Perfect similitude" configuration compared to the "Standard" one. On top of this, in the "Standard similitude" configuration, a further roundtrip efficiency loss due to the compressor operating outside the maximum isentropic efficiency region is added. Nevertheless, these effects have a limited impact on roundtrip efficiency. Conversely, using only one compressor in the two reversible configurations significantly impacts the overall plant cost, reducing it by a value comprised between 13% and 25%, depending on charging power nominal power input. Notwithstanding that, part of the economic benefit is eroded by the second turbine used to elaborate part of the discharging cycle’s mass flow rate.

NOMENCLATURE

Acronyms

SBPTES Solid-based Brayton Pumped Thermal Energy Storage
TES Thermal Energy Storage
CEPCI Chemical Engineering Plant Cost Index

Symbols

$\dot{m}$	Air flow rate	(kg/s)
β	Pressure ratio	(-)
η	Efficiency	(-)
ψ	Exergy efficiency	(-)
$cost$	Overall cost	(€)
C	Component's cost	(€)
T	Temperature	(K)
W	Power	(W)
h	Enthalpy	(J/kg)
pp	Pinch point	(K)

Subscript

Cor	Corrected
Is	Isentropic
RT	Roundtrip
Ch	Charging phase
Dis	Discharging phase
El	Electric
Gear	Gearbox
Comp	Compressor
Turb	Turbine
Hot	Hot thermal energy storage
Cold	Cold thermal energy storage
Cool	Cooler
Comp	Compressor

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