COMPARISON OF DIFFERENT LAYOUTS OF A SCO2-BASED THERMALLY INTEGRATED-PUMPED THERMAL ENERGY STORAGE (TI-PTES)

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ABSTRACT

In a Renewable Energy Sources (RES) driven energy scenario, where more and more bulky quantities of RES should be introduced on the grid, the role of energy storages is crucial. Further to already available electric storage technologies (mostly based on batteries), it will be mandatory to have grid flexible large scale energy storages able to operate ramp-up/down with large capacity, whose behaviour/management should be as much similar as possible to traditional power plants (also to guarantee specific grid services like grid frequency regulation via rotating inertia etc.) which are currently used to instantaneously regulate the grid.

At this purpose Pumped Thermal Energy Storage (PTES) offers GWh scale storage without geographical constraints, at reasonable costs, and implementing power and heat pump cycles integrated with thermal energy storage (TES) solutions. A PTES system indeed stores heat in two high temperature and low temperature TES units in charging phase using heat pump (HP) that operates on electricity provided by renewable energy sources (solar, wind etc.). The stored heat is used to drive a power cycle at required times. The choice of the working fluid for power cycle as well as heat pump cycles have a significant importance based on the range of storage temperature. Working fluid in PTES has direct effect on the performance, capital cost and efficiency of the whole operation.

sCO2 as a working fluid has certain aspects that makes it the ideal candidate for large scale PTES applications. sCO2 cycles are indeed fully compatible with the temperature range of TES hot storage sources and sCO2 has already been used in commercial HP solutions (even targeting high temperature HPs). In addition, sCO2 allows energy storages to embody a compact design as well, making the whole PTES footprint smaller compared to technologies based on other working fluids. Nevertheless, sCO2 based PTES solutions cannot achieve significant Round Trip Efficiency (RTE): in this sense valorise freely available heat sources (like thermal RES or waste heat) could increase COP of the charging cycle and, at the end, RTE in what usually called Thermally Integrated Pumped Thermal Energy Storage (TI-PTES) as showed by authors in previous scientific papers [Maccarini et al., 2023], [Mehdi et al., 2023], with a sCO2 PTES cycle integrated with a single TES solution able to store electricity with good Round Trip Efficiency values.

Nevertheless, this thermal input could be valorised not only in the charging cycle, but also in the discharging cycle: different layouts of the proposed TI-PTES will be compared from a techno-economic point of view, assessing different KPIs also looking at how much WH is valorised both in charging and discharging cycles.

1 INTRODUCTION

The continuous increase of stochastic RES plants presence in energy systems [EU, 2024] and the promotion of electrification in industrial and mobility sectors [Pang and Cheng, 2024], pose the need of identification of energy storage solutions able to cover the high peaks and deep valleys of the “Duck Curves” [Krietemeyer et al., 2021] that are more and more pronounced all around the world [Naderi et al., 2023], [Hou et al., 2019] The Duck Curve shows us mostly two main needs that should be fulfilled by energy storage: to store a large amount of energy during central hours of the day as well as to be able to provide large amount of power in few hours along the “neck of the Duck curve”. For this purpose, bulky energy storages able to store large amount of energy for a significant number of hours as well as to provide large amount of power rapidly responding to electric market needs are necessary: this type

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of storages are often referred as long duration energy storage (LDES) technologies [Twitchell, DeSomber, and Bhatnagar, 2023] LDES need to ensure supply availability, reconcile variable generation resources with uncertain customer demands, and strengthen the electric grid against RES power plant driven congestions while replacing fossil fueled plants for grid stability. Furthermore this type of bulky energy storage [Steinmann, 2017] should not be CAPEX intensive, should be location independent and sustainable from a material point of view, being an alternative to battery storage [Hannan et al., 2021], power-to-hydrogen [Hassan et al., 2023] and pumped hydro storage solutions. Carnot batteries and particularly Pumped Thermal Energy Storage (PTES) systems [Benato and Stoppato, 2018] have progressively gained attention from the scientific and industrial community, being based on a power-to-heat-to-power system integrating a heat pump cycle and a heat-to-power cycle based on rotating machines (volumetric or turbo-machinery). Therefore, such a technology is able to offer grid services both during charging and discharging cycles [Sharma and Mortazavi, 2023]. Different solutions and operating fluids have been studied exploiting well-known technologies like ORC [Eppinger et al., 2020], Brayton [McTigue et al., 2016] and steam cycles [Steinmann, 2014] as well as innovative energy systems like sCO2 based cycles [Mehdi et al, 2023]. Among PTES [Blanquiceth, 2023], Thermally Integrated PTES (TI-PTES) are attracting more and more interest [Frate et al., 2023] being able to store electric energy with relevant round trip efficiency but also exploiting additional low-mid temperature thermal sources [Zhang et al. 2023], commonly from renewables waste heat recovery, to boost the charging and/or discharging phases [Jockenhöfer, Steinmann, and Bauer, 2017].

In this paper, starting from a concept already developed and presented by the authors in previous research study [Maccarini et al., 2023], [Mehdi et al., 2023], [Barberis et al., 2023] the full potential of sCO2 based TI-PTES is presented, highlighting the relevance of exploiting a waste heat source in both charging (heat pump) and discharging (power cycles) phases towards high RTE, trying to understand the relevance of specific operating parameters on the performances particularly of the discharging cycles where usually the WH is not valorised.

2 CONCEPT AND METHODOLOGY

2.1 Reference use case and goal of the study

As already studied in [Maccarini et al., 2023], [Mehdi et al., 2023], [Barberis et al., 2023] and in order to compare from a performance perspective the proposed layout with the previous research activities layout from a performance point of view, a cement plant is considered as case study [FIVES, 2020]. On a typical cement plant with a capacity of 5,000 t/day, the flue gas flow rate is 300,000 Nm3/h with a temperature of 330°C and around 1/3 of exhaust air - "quaternary air" - representing 116,000 Nm3 /h, which can be exploited thus having a WH source of around 10 MWth of maximum exploitable power at 330°C.

This temperature of the WH has been considered for the baseline evaluation of the discharging cycle and in the sensitivity analysis different WH temperature (or freely available heat sources temperature for example from thermal RES) in a range 270 ÷ 400°C as presented in chapter 3 are considered.

The idea is therefore to study a TI-PTES system (Fig.1) in which the waste heat acts as a heat source for the heat pump cycle that operates between the waste heat and the storage unit as well as heat source for a re-heat discharging cycle driven (as primary heat by the heat stored in the TES). The proposed TI-PTES layout is composed by: 1) a high temperature HP operating with sCO2 able to valorise available WH (CHARGING CYCLE – Fig.1a); 2) a High temperature Thermal Energy Storage (TES) able to store heat produced by the HP (STORAGE ASSET – in the study analysed in a temperature range between 400 and 520 °C thus foreseeing the use of molten salts as storage media); 3) a re-heated and recuperated sCO2 power cycle able to produce power once required exploiting the heat stored in the TES as well as exploiting WH in a re-heat cycle (DISCHARGING CYCLE).

The discharging cycle has been analysed in two potential layouts: i) a first one in which TES heat input is on top providing heat to the high pressure turbine and then WH providing heat to the second lower pressure turbine (Fig. 1b); ii) a second one in which WH heat input is on top providing heat to the high pressure turbine and then TES providing heat to the second lower pressure turbine (Fig.1c).

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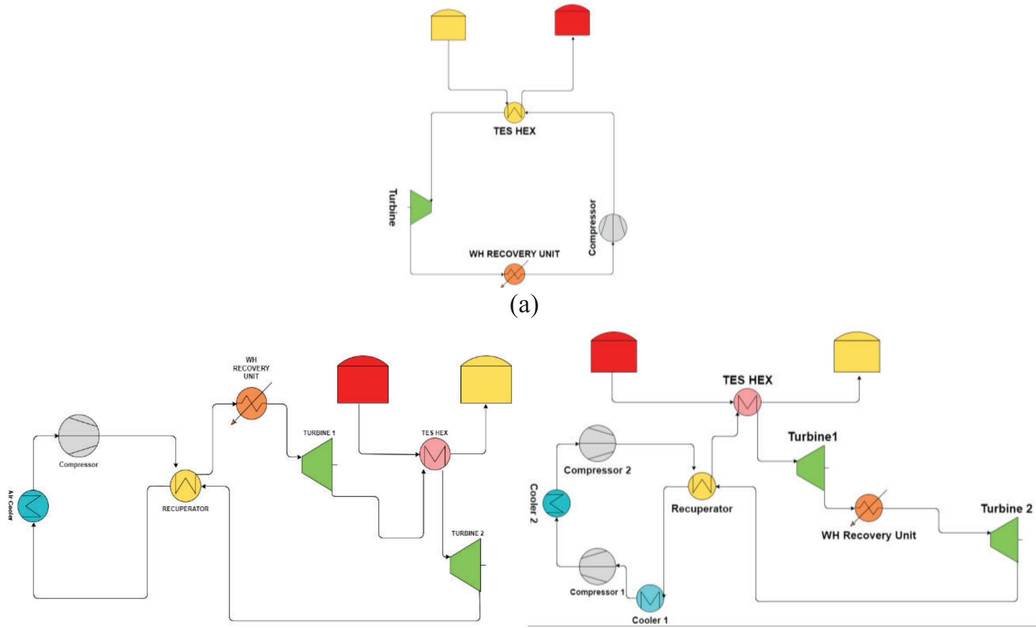
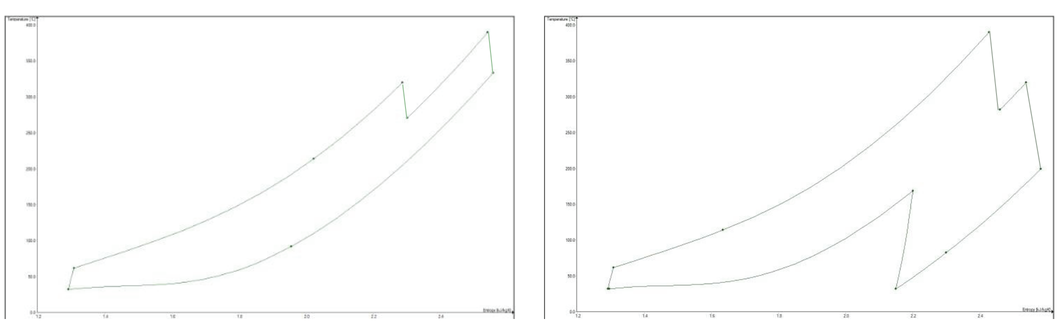


Fig. 1 Proposed TI-PTES layouts

Despite it would be more meaningful valorising higher temperature heat in higher pressure turbine ("TES on top" layout – Fig.1 b), according to the first thermodynamic calculations it has been clear that the first Turbine Outlet Temperature (TOT) would have been too high to guarantee WH input to the second lower pressure turbine with any meaningful intermediate pressure level. Thus the sensitivity analysis performed and presented in chapter 3 has been conducted on layout Fig.1c) ("WH on top").
The goal of the study has been to define re-heat discharging cycle operating conditions (particularly the intermediate pressure) exploiting heat inputs both of TES and WH and design parameters considering the proposed test case, studying both a "simple re-heat discharging cycle with WH on top" (Fig.1c – Fig.2a – to be called in the following Configuration 1) and a re-compressed one (Fig.2b - to be called in the following Configuration 2) that would guarantee lower turbine outlet pressure (TOP) for the second lower pressure turbine, thus making the re-heat option more valuable (as shown by T-S diagrams of the discharging cycles as described in Fig.2). In this way TOP values are not in supercritical conditions, but the discharging cycle would still operate in gaseous phase with a Brayton cycle.
In Configuration 2, it would be also possible to valorise "TES on TOP" as proposed in Fig.1b as it would be possible to operate up to lower pressures both at intermediate and inferior levels.



a) (b)

Fig. 2 Initial T-S diagrams of the proposed re-heat discharging layouts

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In order to study more valuable operating conditions of the proposed cycle, a sensitivity analysis of the discharging cycle operating conditions and design parameters towards RTE maximization and WH optimal valorisation has been performed also enabling the comparison of the different proposed solutions, operating conditions and layout ("simple re-heat" and "recompressed") from a thermodynamic performance point of view.

2.2 Methodology

The proposed TI-PTES plant model has been developed using the simulation software EBSILON Professional 16 by Iqony, the tool is useful to support the designer in the definition of thermodynamic cycles process in a visual interface environment and able to simulate thermodynamic cycles operating with different type of working fluids. Once selected the components through the software library and defined the boundary conditions of the plant, the software computes the thermodynamic point of the cycle and provide a preliminary sizing of the components.

The performance of the system has been evaluated using the following equations starting from approaches previously used by the authors, particularly to define the RTE [Barberis et al., 2023] representing the round trip efficiency which is based on co-efficient of performance (COP) of the charging cycle and thermal efficiency η of the discharging cycle.
In both analysed configuration, the following KPIs have been analysed for the discharging cycles: i) amount of WH valorised in the discharging cycles, ii) net power output of the discharging cycle, iii) power cycle efficiency (eq.3 – eq.4) considering Q_{TES} only and Q_{TES} + WH, iv) RTE calculated via eq.1 but foreseeing discharging cycle efficiency as calculated both via eq.3 and eq.4, considering or not considering WH input.

$$RTE_{el} = \frac{E_{DC}}{E_{CC}} = \frac{P_{DC} \cdot t_{DC}}{P_{CC} \cdot t_{CC}} = COP \cdot \eta \tag{1}$$

$$COP = \frac{\dot{Q}_{TES\_CC}}{P_{CC}} \tag{2}$$

$$\eta_A = \frac{P_{DC}}{\dot{Q}_{TES\_DC}} \tag{3}$$

$$\eta_B = \frac{P_{DC}}{\dot{Q}_{TES\_DC} + \dot{Q}_{WH}} \tag{4}$$

3 RESULTS AND DISCUSSION

3.1 Configuration 1 analysis

In the first configuration, starting from assumptions coming from [Maccarini et al., 2023], [Mehdi et al., 2023], [Barberis et al., 2023] as reference for the the design baseline layout, the following parameters have been setup: i) inferior pressure equal to 83 bar, ii) recuperator effectiveness equal to 85%, while the following parameters have been varied (Tab.1)

Table 1: Configuration 1 operating parameters for the sensitivity analysis

Parameter	Design Baseline Condition	Range for sensitivity
Superior pressure	250 bar	250 – 320 bar
Intermediate pressure	150 bar	100 – 220 bar
WH temperature	330°C	270°C – 370°C
TES Temperature	400°C	400°C – 520°C

Superior pressure has been varied in order to enlarge the possibility to valorise WH in the re-heat cycle as in this layout the CO_2 will be always operating in supercritical conditions (that's why the intermediate pressure is analysed between 100 and 220 bar), thus enlarging the TES and WH heat input

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valorisation viability and effectivenees. Such heat inputs have been analysed at different temperature ranges as well. TES temperature has to be varied once varying superior pressure in order to guarantee the possibility to recover heat via the recuperator: this increase of the TES temperature has obviously an effect on the charging cycle too and on its COP (and then on RTE as showed in §2.1).

3.1.1 Superior and Intermediate pressure influence analysis

As reported in the maps/values in Figure 3, one of the key parameters for configuration 2 is the definition of the intermediate pressure. The higher the intermediate pressure is the better it is for different KPIs analysed mostly because it would be possible to valorise a higher value heat input (the TES one that in Configuration 1 is valorised in the second turbine) at higher pressure, thus with a higher expansion ratio and enthalpy difference, particularly (obviously) the higher the superior pressure can be. On the other hand, the higher the intermediate pressure is, the lower the WH recovery is as the first turbine valorizes a quite marginal heat input producing a marginal amount of net power. This has an effect on efficiency (η_B) of the power cycle as the lower the WH recovery is, the lower the efficiency of discharging power cycle is. Nevertheless, looking at TES input only (η_A), the efficiency is positively affected by higher intermediate pressure because, as said, the TES higher temperature heat input is valorised at higher pressure. Working with high intermediate pressure obliges to increase TES temperature, in order to guarantee the possibility to operate with a recuperated discharging cycle: in this way, charging cycle COP is decreasing. Nevertheless, the possibility to operate with a recuperated discharging cycle at high intermediate pressure is enlarged if the superior pressure is increased, thus not obliging to increase the TES temperature and thus having a beneficial effect on COP of the charging cycle.

As already shown in [Maccarini et al., 2023], [Mehdi et al., 2023], [Barberis et al., 2023] ,RTE maximum values are achieved targeting higher COP values: it is worthy to highlight how the apparent electric RTE achieves very relevant values (particularly if compared with previous R&D works) particularly thanks to a significant increase of the discharging cycle efficiency from previously encountered values around 20% up to >30% values that bring.

RTE(TES)

Upper Pressure (bar) \ Intermediate Pressure (bar)	220	200	180	160	140	120	100
320	2.12	2.06	2.00	1.92	1.82	1.69	1.52
310	2.10	2.05	1.99	1.91	1.81	1.68	1.51
300	2.09	2.04	1.98	1.90	1.80	1.67	1.50
290	2.07	2.03	1.97	1.89	1.79	1.66	1.50
280	2.05	2.01	1.95	1.87	1.78	1.65	1.49
270	2.03	1.99	1.93	1.86	1.76	1.64	1.47
260	2.00	1.96	1.91	1.83	1.74	1.62	1.46
250	1.97	1.93	1.88	1.81	1.72	1.60	1.44

a) RTE (considering η_A)

RTE(TES+WH)

Upper Pressure (bar) \ Intermediate Pressure (bar)	220	200	180	160	140	120	100
320	0.92	0.97	1.01	1.04	1.06	1.07	1.04
310	0.90	0.94	0.99	1.02	1.04	1.05	1.03
300	0.87	0.92	0.96	1.00	1.03	1.03	1.02
290	0.85	0.89	0.94	0.98	1.01	1.02	1.00
280	0.82	0.87	0.91	0.95	0.98	1.00	0.99
270	0.78	0.84	0.89	0.93	0.96	0.98	0.97
260	0.75	0.80	0.86	0.90	0.93	0.95	0.95
250	0.71	0.77	0.82	0.87	0.91	0.93	0.93

b) RTE (considering η_B)

Figure 3 - Configuration 2: intermediate pressure Vs upper pressure sensitivity analysis

3.1.2 WH and TES temperature influence analysis

As reported in Fig.4, WH and TES temperature effect on the overall TI-PTES performances and discharging cycles performances are similar to those ones presented in [Mehdi et al., 2023: analysing the results of the sensitivity analysis keeping superior pressure and intermediate pressure at design level, the higher TES temperature is, the higher both discharging cycle power output and efficiency is, while the lower COP will be. The closer WH and TES temperature are, the higher the COP will be. thus having a beneficial effect on RTE despite maybe not targeting the higher power cycle efficiency:

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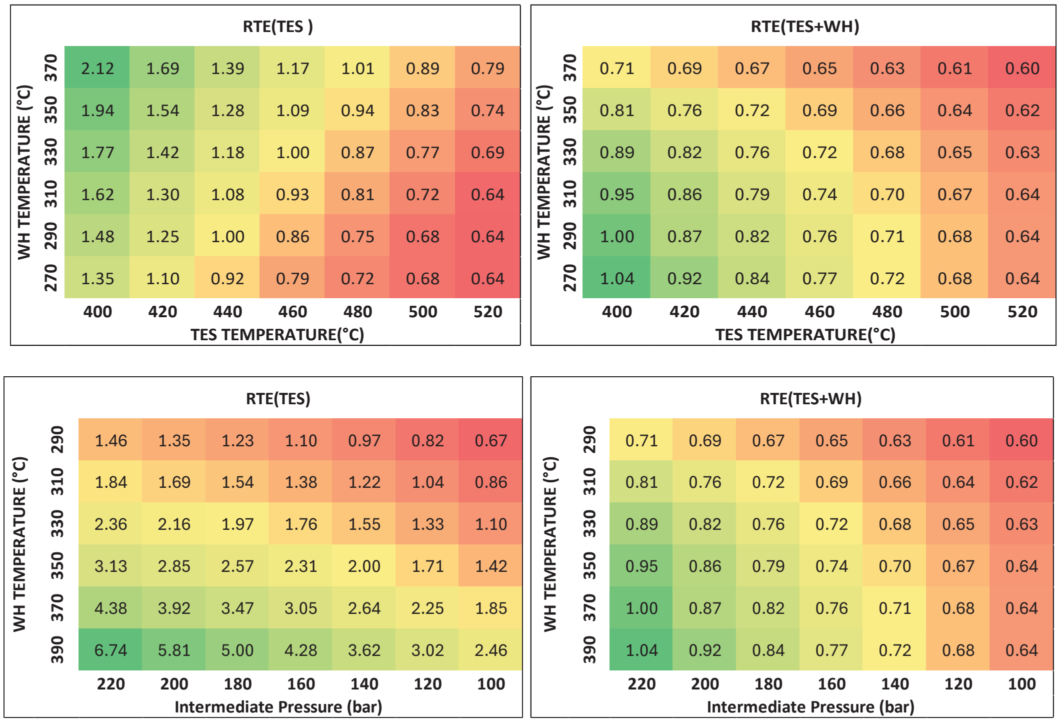
nevertheless, as highlighted in previous articles in this type of TI-PTES, the effect of COP on RTE is more markable than the power cycle efficiency one.



RTE (considering η_A) **b) RTE (considering η_B)**

Figure 4 - Configuration 1: WH and TES temperature sensitivity analysis and effect on intermediate pressure performance recap

3.2 Configuration 2 analysis

In the second configuration, starting from assumptions coming from [Maccarini et al., 2023], [Mehdi et al., 2023], [Barberis et al., 2023] as reference for the the design baseline layout, the following parameters have been setup: i) superior pressure equal to 250 bar, ii) recuperator effectiveness equal to 85%, while the parameters reported in Tab. 2 have been varied. It is relevant to highlight that operating pressure values are kept identical both at compression and expansion level, meaning that: a) first compression (before inter-cooling) will be evaluated between inferior pressure and intermediate pressure and the second compression (to be operated in supercritical conditions close to the critical point/sCO2 dome) between intermediate pressure and superior pressure (which is kept constant at 250 bar); b) first expansion (driven by TES heat input) will be evaluated between superior pressure and intermediate pressure and the second expansion (to be operated in gaseous conditions) between intermediate pressure and inferior pressure.

Table 2: Configuration 2 operating parameters for the sensitivity analysis

Parameter	Design Baseline Condition	Range for sensitivity
Inferior pressure	50 bar	30 – 55 bar
Intermediate pressure	80 bar	75 – 100 bar
WH temperature	330°C	300°C – 400°C
TES Temperature	400°C	400°C – 520°C

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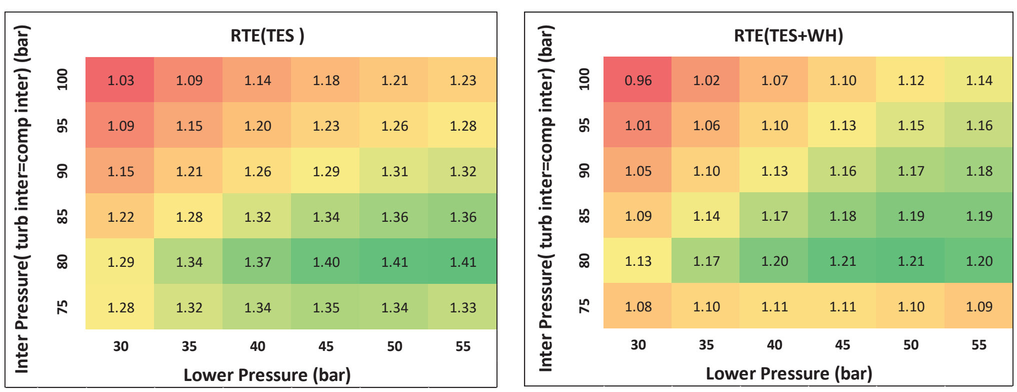
In this second configuration, the inferior and the intermediate pressure can vary, having a fixed superior pressure at 250 bar. Inferior pressure has been varied in order to enlarge the possibility to valorise WH in the re-heat cycle as in this layout the CO2 can operate in the second turbine not in supercritical conditions, while the first turbine has been kept in supercritical condition (that's why the intermediate pressure is analysed between 75 and 100 bar), thus enlarging the TES and WH heat input valorisation viability and effectiveness. The lower inferior pressure could be, the larger the expansion could be: obviously this has an impact on the compression work as well, but having the chance to operate (at least for the second compression) in conditions close to the critical point, the compression work increase would be lower than the turbine work enhancement. The identification of the intermediate pressure has the goal to minimize the work done in the first compressor but to keep the second one in supercritical conditions and close to the critical point on the T-S diagram in order to minimize the compression work and maximize the discharging power output.

3.2.1 Intermediate and Lower pressure Sensitivity analysis

As reported in the maps/values in Figure 4, the lower the Δp (between the intermediate and the lower pressure) can be the better it is for different KPIs as it would be possible to valorise a higher value heat input (the TES one that in Configuration 2 is valorised in the first turbine) at higher pressure. In this way in this configuration the benefit will be two-fold

a) The first expansion (higher temperature heat by TES) will see a larger expansion ratio, while the second one (lower temperature heat by WH) will have a role of "complimentary/additional" heat to really maximise the WH recovery and the overall heat inputs valorisation thus increasing both net power and efficiency of the power cycle
b) The first compression (operated not in supercritical conditions, thus foreseeing higher compression work) is operated with a lower Δp thus reducing the compression work and increasing net power and efficiency of the power cycle.

Furthermore the lower the intermediate pressure is, the higher the WH recovery is as the second turbine can valorize a larger ΔT to be delivered by the WH. This has an effect on efficiency (η_B) of the power cycle as the higher the WH recovery is, the higher the efficiency of discharging power cycle is. As presented for configuration 1 and already shown in [Maccarini et al., 2023], [Mehdi et al., 2023], [Barberis et al., 2023] the maximum values of RTE are present where COP values are higher: it is worthy to highlight how the apparent electric RTE achieves relevant values (particularly if compared with previous R&D works) particularly thanks to a significant increase of the discharging cycle efficiency from previously encountered values around 20% up to values around 22 ÷ 27%.



e) RTE (considering η_A) **f) RTE (considering η_B)**

Figure 5 - Configuration 2: intermediate pressure Vs lower pressure sensitivity analysis

3.2.2 Inter-refrigeration and intermediate expansion pressure influence Analysis

It is also relevant to highlight the effect of the variation of the intermediate expansion pressure Vs the inter-refrigerated intermediate compression pressure, in order to potentially discouple these two pressure levels and from one side minimize the compression work (lower compression work with lower

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pressure) as well as maximize the turbine work (higher work with lower intermediate pressure, thus valorising better the WH)

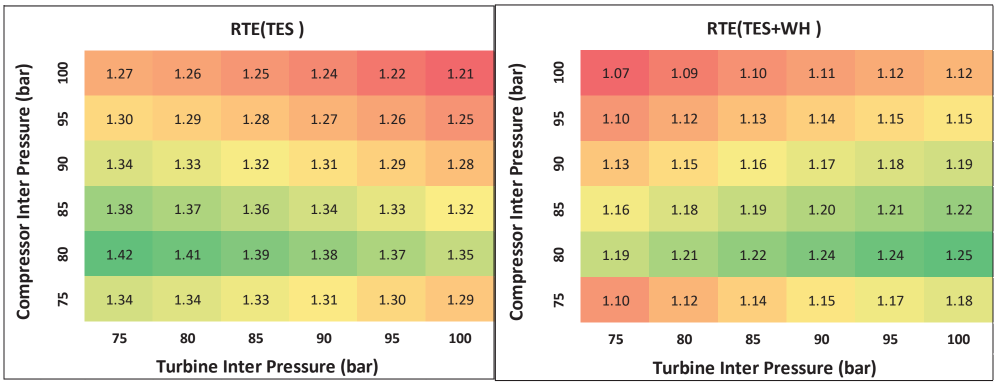
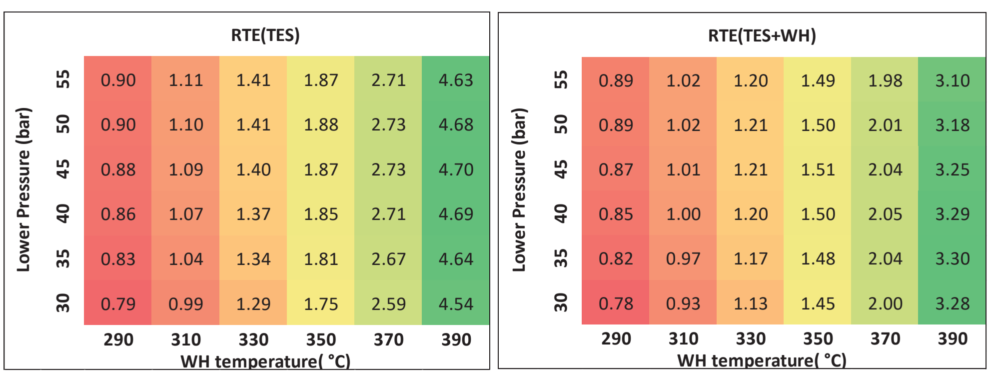


Figure 6 - Configuration 2: effect of compressor and turbine intermediate pressure levels

3.2.3 WH temperature influence analysis

Further than the results presented in §3.2.1, a second sensitivity analysis has been performed at fixed intermediate pressure of 75 bar (thus guaranteeing to have the second compression and the first expansion fully in supercritical conditions to guarantee above described benefits in this sense).
It is relevant to highlight that keeping lower intermediate pressure looks a valuable approach (Fig.7), even in presence of lower temperature of WH (obviously the higher WH temperature is, the better it is as the second turbine can see a higher enthalpy difference and therefore a larger net power output can be valorised). This is a relevant aspect that can open the possibility to study the valorization of lower temperature WH/freely available heat sources (previously considered not valuable by the authors [Mehdi et al., 2023], in TI-PTES solutions via configuration 2 approach. Nevertheless, low WH temperature, pose challenges to operate with higher intermediate temperature and thus to exploit large delta enthalpy [Fig.7 – c) -d)]



a) RTE (considering η_A) **b) RTE (considering η_B)**

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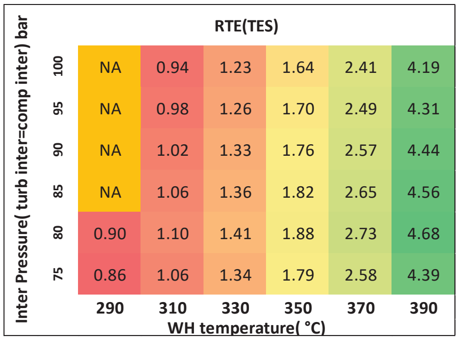
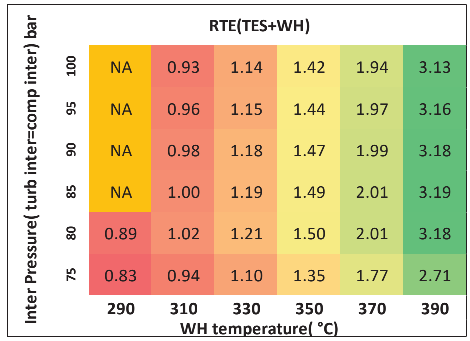


c) RTE (considering η_A)



d) RTE (considering η_B)

Figure 7 - Configuration 2: WH temperature sensitivity analysis performance recap

3.3 Optimization of the above presented configuration

Sensitivity analysis results presented in the previous chapters 3.1 (for configuration 1) and 3.2 (for configuration 2) showed the cross effects that WH temperatures and pressure levels can have in the maximization of proposed TI-PTES performances, particularly looking at intermediate (that can maximise work) and lower one (that can maximise efficiency and WH/heat input valorisation). In this sense, the authors promoted an optimization (via EBSILON genetic algorithm according to the features presented in Table 3) of the pressure levels (fixing the superior one at 250 bar) towards the maximization of RTE_A and RTE_B respectively. Such optimization brought to the optimized operating layouts as reported in Tab.4 and in Fig. 8 (a-b-c-d). Such analysis has been performed with unitary mass-flow rate.

Table 3 : Initialization values of Evolutionary Algorithm for optimization

Population size	15	Number of Generations	200
Probability of Cross over	0.6	Generation Distance	20
Probability of Mutation	0.5	Target values	Maximize(RTE A), Maximize (RTE B)
Replacement	0.75	Parameters	Pressures (Intermediate, Lower)

Table 4 : Optimized thermodynamic points and RTEs

CONFIGURATION	1					
OPTIMIZATION FOR:	A			B		
DC(Inlet points)	P(bar)	T(°C)	m(kg/s)	P(bar)	T(°C)	m(kg/s)
Comp	83.65	32	1	83.65	32	1
RECUP HOT	250	61.54	1	250	61.54	1
WH HEX	247.5	181.55	1	247.5	235.132	1
TURB			1	245.025	320	1
TES HEX	245.025	320	1	111	242.146	1
TURB	242.451	390	1	109.89	390	1
RECUP COLD	85.348	284.598	1	85.34	364.12	1
COOLER	84.49	86.12	1	84.49	95.544	1
CC(inlet points)						
COMP	129.579	320	1.01	129.579	320	0.92
TES HEX	250	410	1.01	250	410	0.92
TURB	247.5	339.94	1.01	247.5	262.14	0.92
WH HEX	129.57	274.61	1.01	129.57	200.4	0.92
RTE A	200.7	%		153	%	

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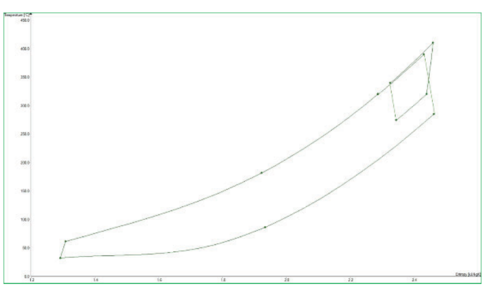
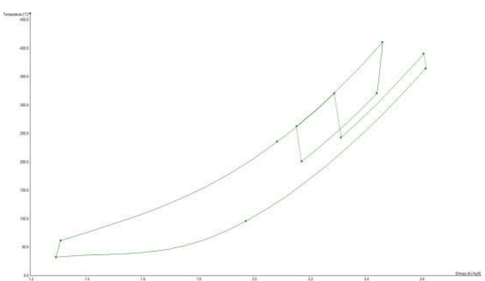
RTE B	64 %			93.07 %		
CONFIGURATION	2					
OPTIMIZATION FOR:	A			B		
DC(Inlet points)	P(bar)	T(°C)	m(kg/s)	P(bar)	T(°C)	m(kg/s)
Comp 2	76.5	32	1	76.5	32	1
RECUP HOT	250	71.963	1	250	71.963	1
TES HEX	247.5	182.27	1	247.5	154.719	1
TURB 1	245.025	390	1	245.025	390	1
WH HEX	58.5	250.051	1	115	331.7	1
TURB 2	57.915	320	1	113.85	320	1
RECUP COLD	48.669	303.72	1	55.09	252.35	1
COOLER 1	48.182	105.22	1	54.54	97.069	1
COMP 1	47.7	32	1	54	32	1
COOLER 2	77.293	74.013	1	77.273	62.29	1
CC(inlet points)						
COMP	130.504	320	1.217	130.504	320	1.207
TES HEX	250	409	1.217	250	409	1.207
TURB	247.5	232.27	1.217	247.5	204.71	1.207
WH HEX	130.504	172.76	1.217	130.5	146.95	1.207
RTE A	145 %			132 %		
RTE B	113 %			129 %		

As presented in previous sensitivity analysis, looking at Configuration 1, RTE_A is optimized without any "Re-heating" and exploitation of the WH is in the heating up of the compressed fluid before the TES HEX: at this purpose, inferior pressure is evaluated to maximise the expansion of the turbine. Looking at maximization of RTE_B, intermediate pressure is determined to maximize the WH valorisation and inferior pressure is again minimized as per RTE_A. Following what presented in §3.2, looking at configuration 2, RTE_A is again optimized minimizing any "Re-heating" and the work of the second turbine also to minimize the work of the first compressor, while RTE_B is again optimized looking at pressure level that can guarantee an optimal valorisation of WH up to 320°C as second TIT value.



a) Configuration 1 – Maximum RTE_A



b) Configuration 1 – Maximum RTE_B

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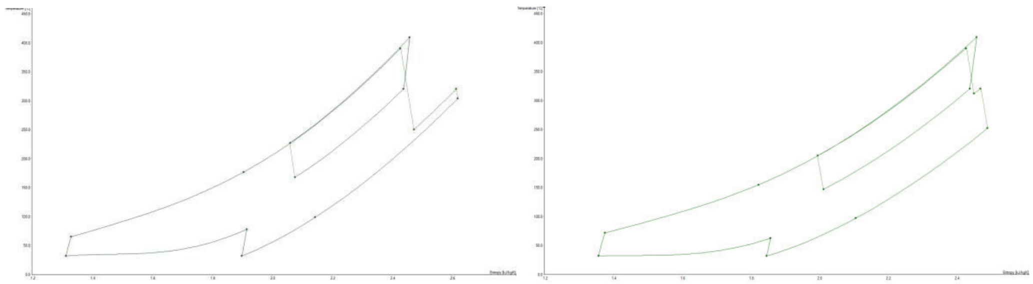

c) Configuration 2 – Maximum RTE_A b) Configuration 2 – Maximum RTE_B

Fig. 8 T-S diagrams of the proposed optimized re-heat discharging layouts

4 CONCLUSIONS

This study presents, through a mapping technique and a sensitivity analysis, the possibility to valorise a freely available heat source for the purpose of a sCO2 based thermally integrated pumped thermal energy storage(TI-PTES), valorising such heat input both in charging and discharging phase, as a first of its kind analysis of a "double valorisation" and a follow up of previous authors' research. Two configurations of discharging cycles to be integrated in the TI-PTES have been studied analysing different operating parameters with a focus on the relevance and definition of intermediate pressure as key design feature and the influence of WH temperature.

The study finds that the possibility to valorise WH in both charging and discharging cycle looks feasible via a proper identification of intermediate pressure as key parameter to maximise WH and efficiency of the power cycle, but having effects on the charging cycle too, particularly looking at configuration 1 analysed where, also considering an optimization analysis performed starting from sensitivity results, the minimization of the intermediate pressure level seems crucial, up to not split in two expansion the overall expansion. The possibility to valorise WH in the discharging cycle is particularly beneficial in configuration 2 layout which can open the possibility to valorise lower temperature WH/freely available heat sources in TI-PTES solutions even in ranges that were previously considered not valuable by the authors (lower to 150°C). For both configurations two type of RTE (considering and not considering WH in the overall calculation - RTE_A and RTE_B, the latter more targeting WH valorisation in DC) were calculated bringing to different target optimized values up to RTE_A = 200% and RTE_A = 129%

From an economic and technological integration point of view, it's relevant to highlight that the two proposed configurations would have a different level of CAPEX and complexity increase if compared to the analysed TI-PTES in [Maccarini et al., 2023], [Mehdi et al., 2023], [Barberis et al., 2023] particularly due to the need of more sCO2 operating machines: one good aspect is the fact that the same WH recovery unit could be exploited in both charging and discharging cycles with no specific issues (even in configuration 2 in which sCO2 can operate in pressure ranges).

The study present a first detailed thermodynamic assessment of the possibility of valorising WH in both charging and discharging cycles: future studies can study the proposed layouts and operating envelopes also from a CAPEX point of view also encompass the analysis of the performances of these configurations in different energy markets to evaluate which can be a more beneficial configuration from a thermo-economic perspective in the current energy scenario.

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