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Supercritical CO_2
Power Cycles
Symposium

Paper #08

Design of a sCO2-based Pumped Thermal Energy Storage (PTES) test rig integrated with industrial waste heat recovery

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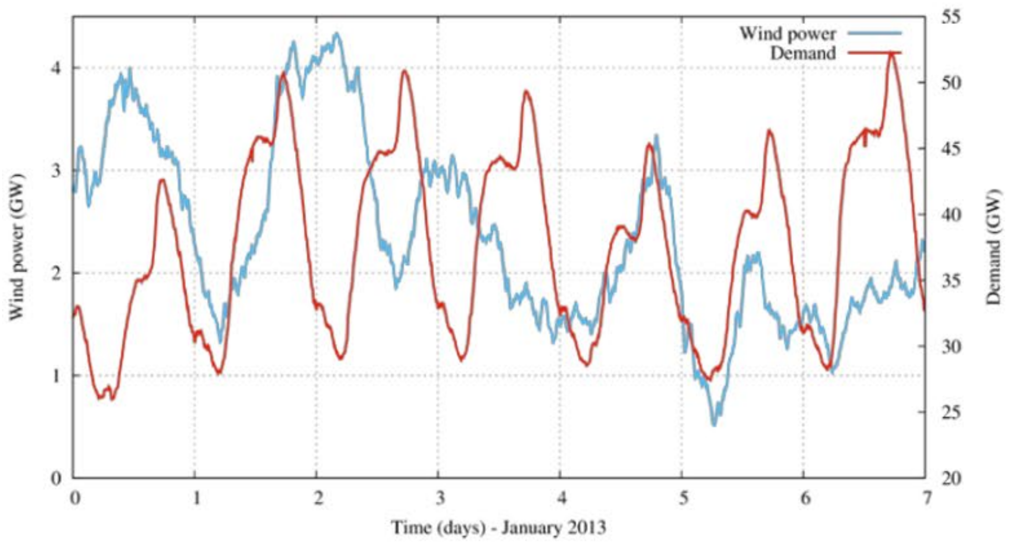
Introduction

Context and Purpose

The further increasing need to reduce carbon dioxide **emissions** is influencing more and more aspects in all the energy sector.

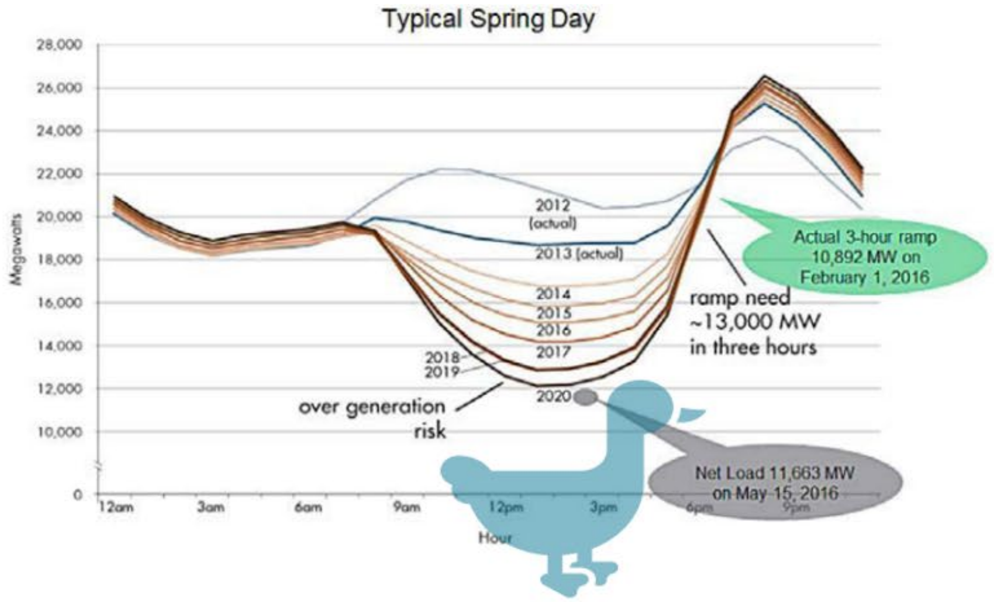
High share of **RES** in the grid leads to the need to improve the electric system flexibility.



Variable wind and demand (UK January 2013)

Lulls: long periods with small renewable production)

Slews: short-term changes in either supply or demand).



The Duck Curve (California)

Net load = Total demand – variable renewables

https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Introduction

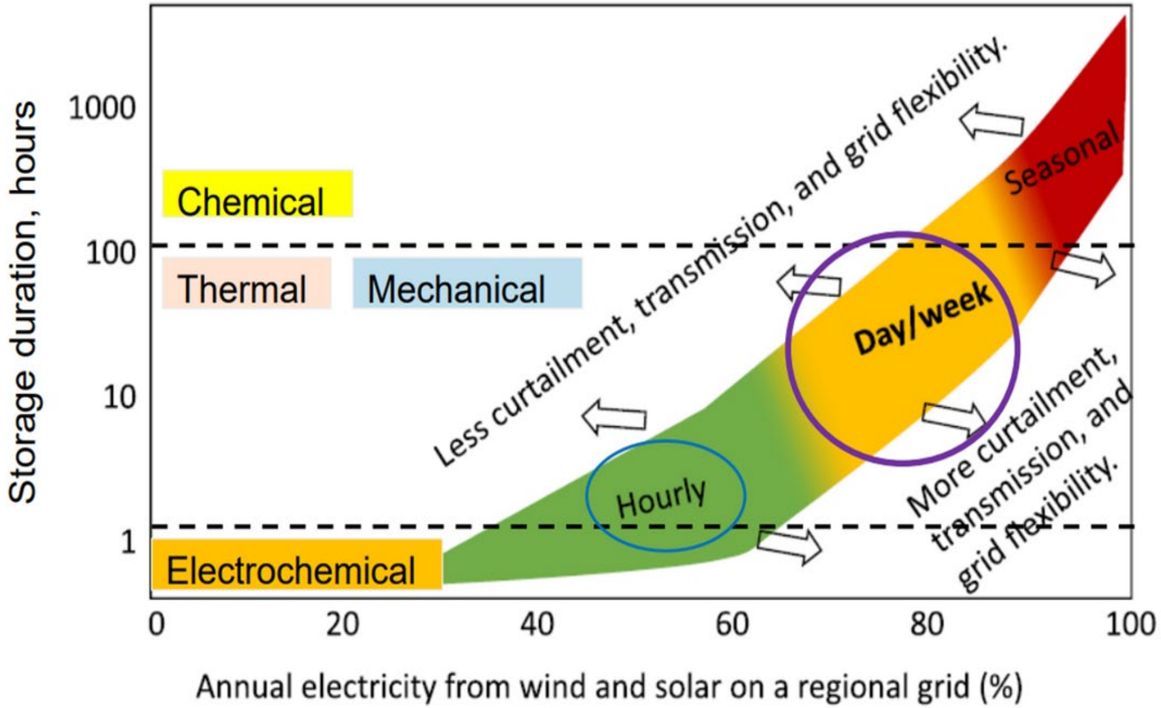
Context and Purpose

Moreover, recent global policies are strongly pushing **electrification** not only in transport and residential, but even in industrial processes.

All these factors lead to the necessity of having many and different solutions to **store energy** to effectively couple demand and production in a sustainable way.

At the same time, still there is a quota of **waste heat** that should be recuperated in the low to medium temperature range, were traditional recovery methods are not always cost-effective.

In the medium-long duration energy storage range, a storage technology of interest is constituted by the **thermo-mechanical** ones, and some of them showed a benefit from the integration of thermal energy.



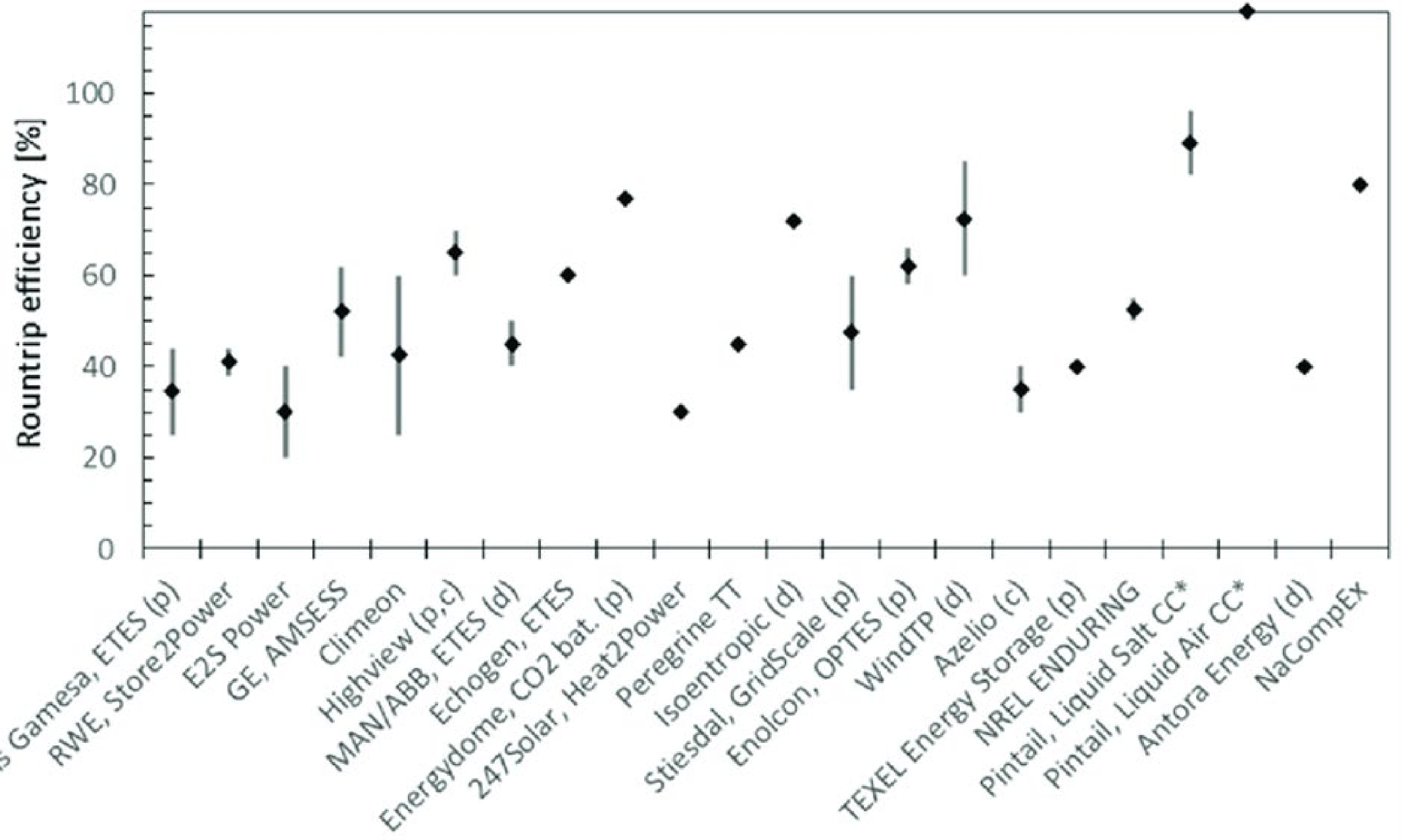
Ref (Annotated version of): Albertus P et al, Joule 4, 21-32,2020; https://doi.org/10.1016/j.joule.2019.11.009

Introduction

The Pumped Thermal Energy Storage

Overview of round-trip efficiency in the commercially CB-like systems (mostly declared as experimental values are limited).
In notation (d) stands for demo, (p) pilot, (c) commercial units (built or under construction).

* for systems with additional fuel firing.



Novotny V, Bašta V, Smola P, Špale J. (2022). Review of Carnot Battery Technology Commercial Development. Energies. 15. 10.3390/en15020647.

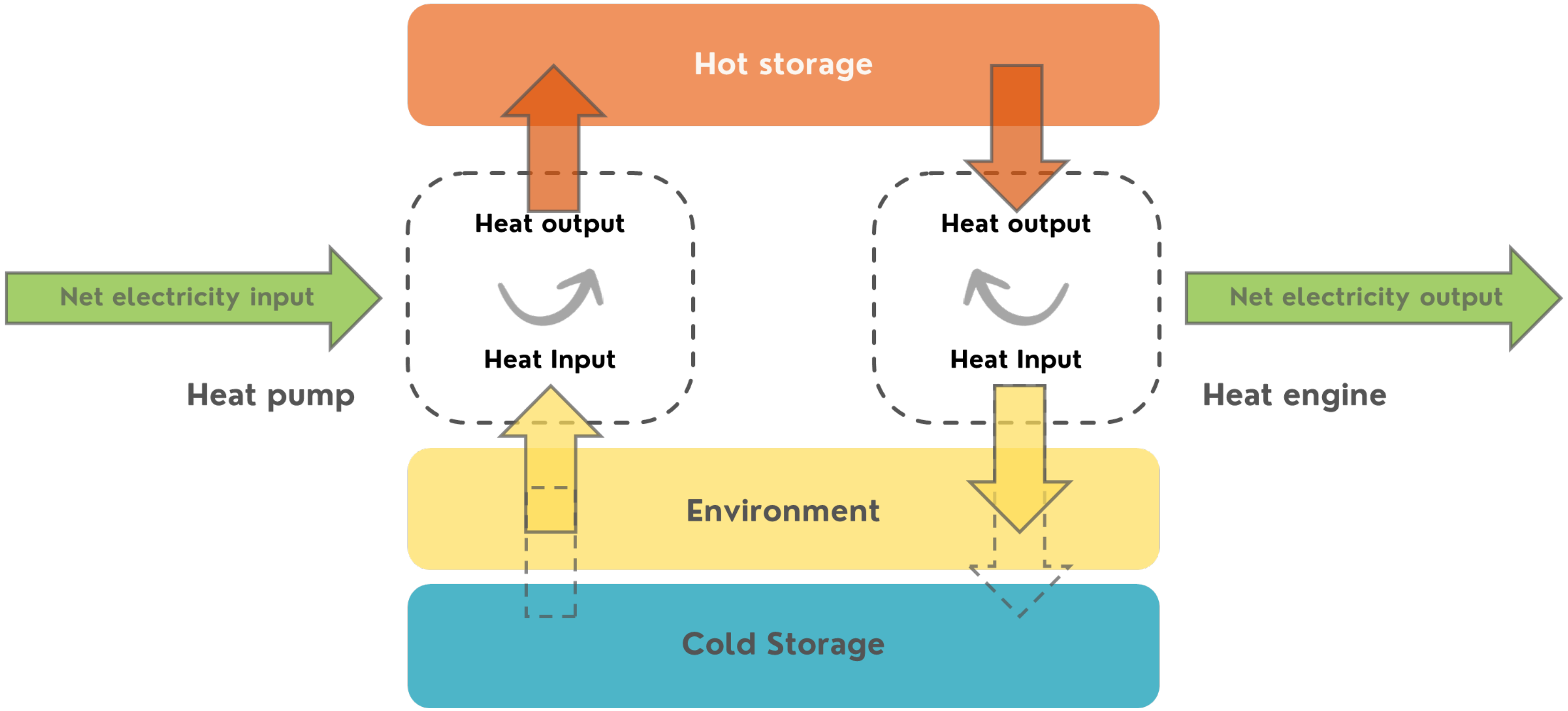
Concept

The Pumped Thermal Energy Storage

Carnot Batteries are Thermo-mechanical Storage

One heat pump and one power cycles are used to store energy into heat in a TES

Usually these system require perfect alignment of the temperature and heat capacity values between the two cycles.



Concept

The Thermally Integrated PTES

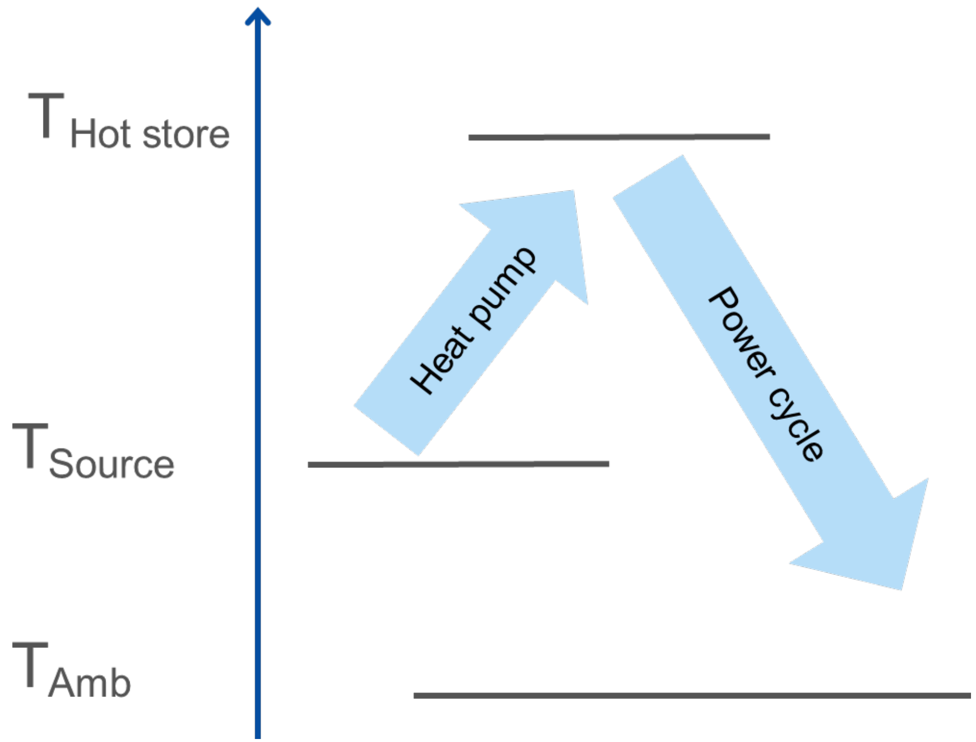
The TI-PTES allows to decouple the heat pump and power cycles

It increases the electrical RTE of the battery system, theoretically above 100%

It can valorize the low temperature waste heat, otherwise not easily exploitable.

It can make industries more flexible on the grid and open to exploit grid services.

The need of a source of heat adds a constraint.



The SCO2OP-TES Project

EU funded project

Carbon dioxide has advantages in being used as working fluid,
being non-toxic, non-flammable, and with a high density near critical point.

Aim of the project is to develop and validate a cost-effective and reliable sCO2 PTES.
Validation (at TRL5) is foreseen through the operation of a lab-scale pilot at UniGe premises.

Proposed PTES solutions will be able to operate to valorize industrial or power-plant WH and local industrial energy production and will have four main goals:

- Make EU fossil-based power plants and **industries** (increasingly electrified) **more grid flexible** and also **less grid bothering**, considering local RES production, making EU industries grid flexibility actors;
- **Valorize WH** from fossil-based power plants for energy storage solutions;
- Using **rotating machines** enables faster and more resilient grid services;
- Enable power-to-heat-to-power solutions that can serve as **grid storage**, to facilitate, at local and Regional/National level, higher RES penetration.

Preliminary Lab Design

Loop for the sCO2OP-TES project

WH Driven PTES to be studied in a dedicated loop to be installed in UNIGE (~100 kW_{el} Scale)

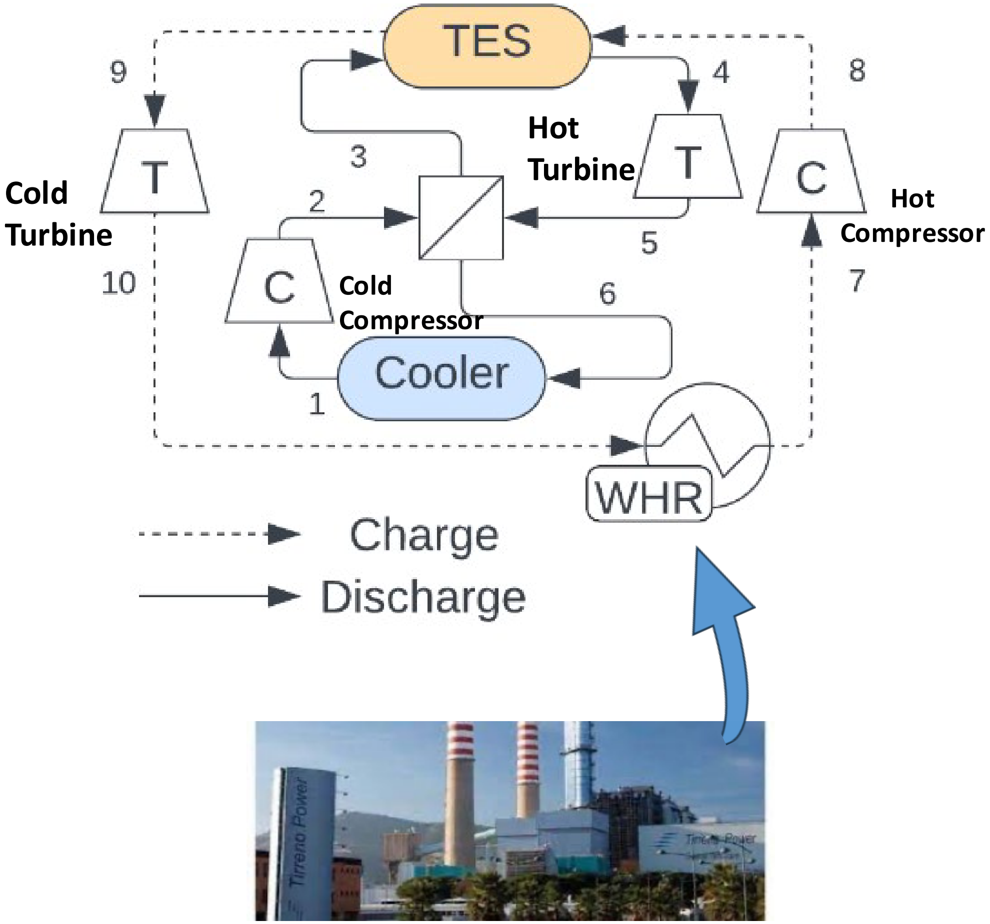
WH from auxiliary steam available at ~250°C, used as low-T source of a heat pump, to store electricity into heat into a TES.

Later use the TES to feed a power cycle up to ambient.

Tesla Bladeless Cold Expander is studied to operate as the cold turbine.

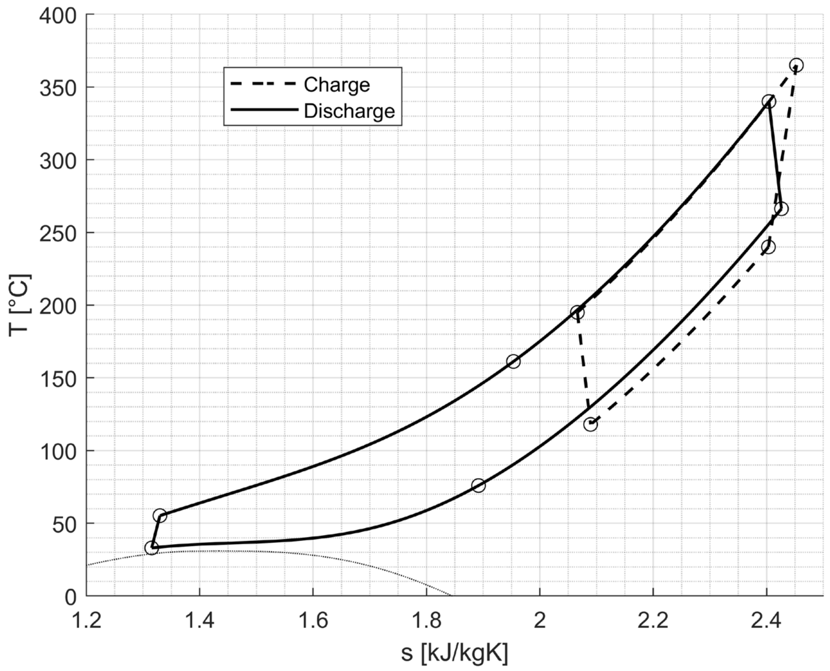
Volumetric compressor is foreseen in the power cycle.

Other machines are “traditional” radial sCO_2 components.



Preliminary Lab Designs

Assumptions



Expected **67% of RTE** in a first analysis for the laboratory demonstration loop

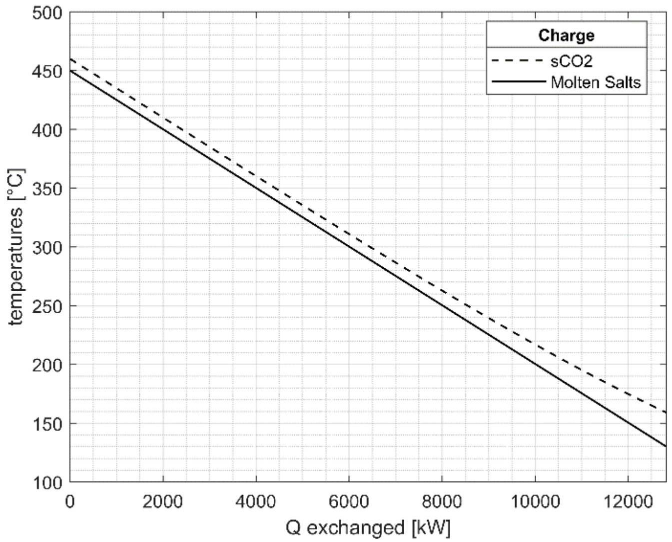
Parameter	Unit	Value
TES max Temp.	350	°C
TES min Temp.	171	°C
TES mass flow	1	kg/s
Cycles superior pressure	200	bar
WH Inlet Temp.	250	°C
min ΔT in HEX	10	°C
Pressure losses in HEX	1	%
Ambient temperature	25	°C
Hot Compressor Efficiency	80	%
Cold Compressor Efficiency	75	%
Hot Turbine Efficiency	90	%
Cold Turbine Efficiency	85	%

Modelling

Simulation Tool

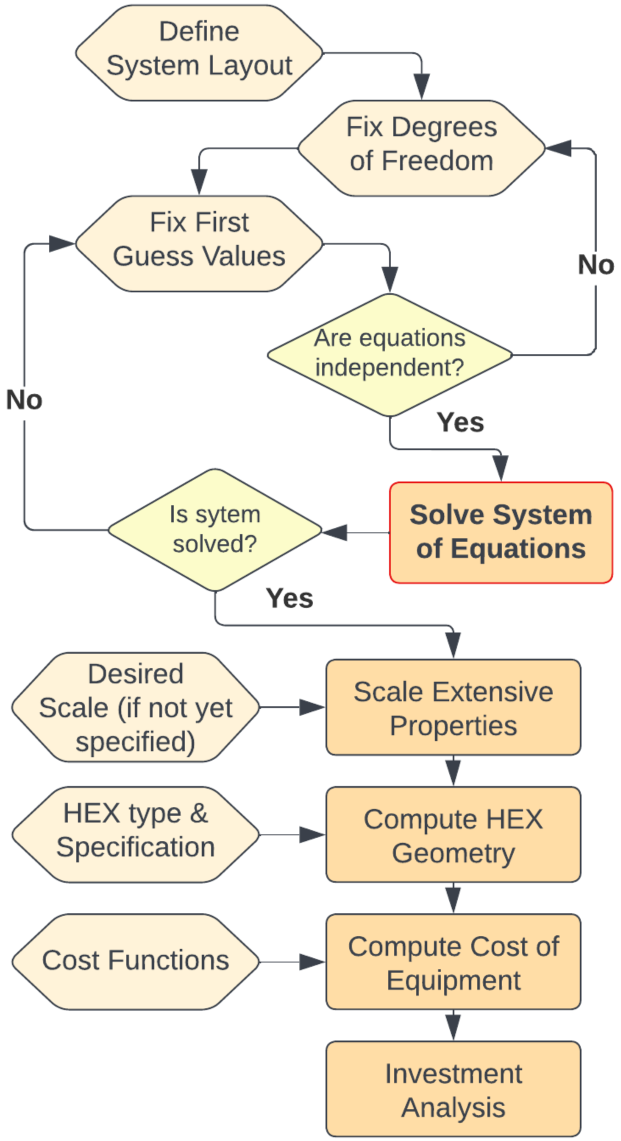
Performance computations are evaluated using TEMP-EVO, a component-based in-house thermo-economic simulation tool.

It is developed in MATLAB®, integrating open-source Coolprop libraries for fluid properties, and it can simulate energy systems through the assembly of the desired layout.



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

$$RTE_{ex} = \frac{P_{DC} \cdot t_{DC}}{\left(P_{CC} + \dot{E}x_{WHRU}\right) \cdot t_{CC}}$$



Assumptions

Design sensitivity Analysis

TES values were fixed constraints. From that, sensitivity on the influence of efficiencies around the system was investigated.

Logic flow -> Starting from TES temperatures, determine pressure ratio

Performance is mostly analyzed:

- Power cycle efficiency
- Coefficient of Performance of Heat Pump
- Round Trip Eff. of the entire system

Parameter	Unit	Value
TES max Temp.	350	°C
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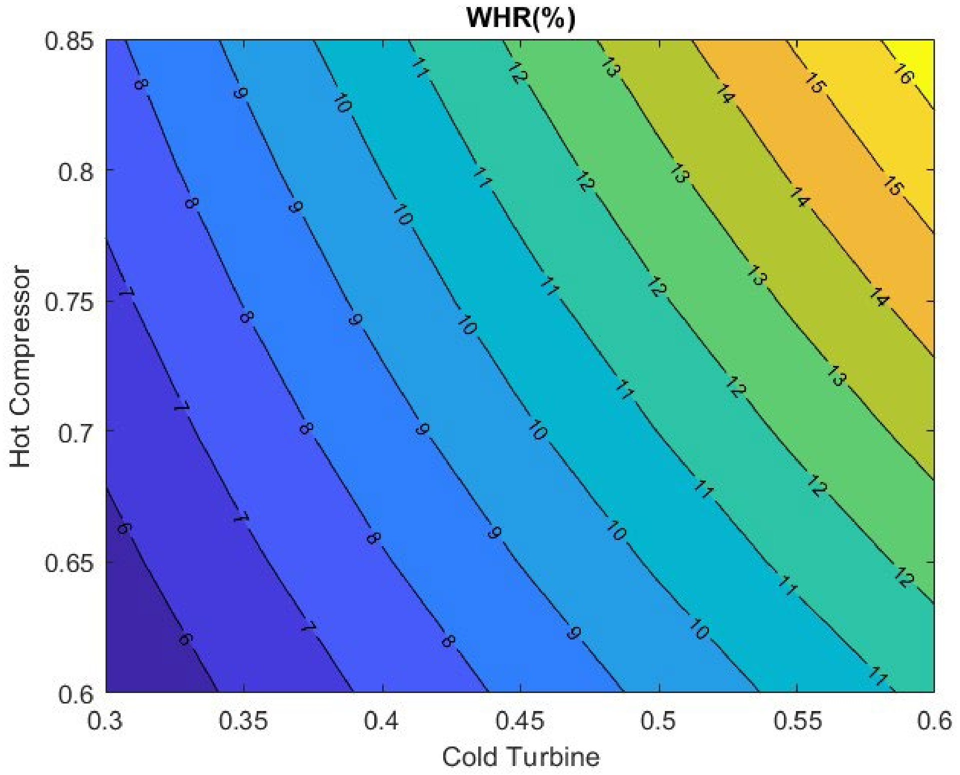
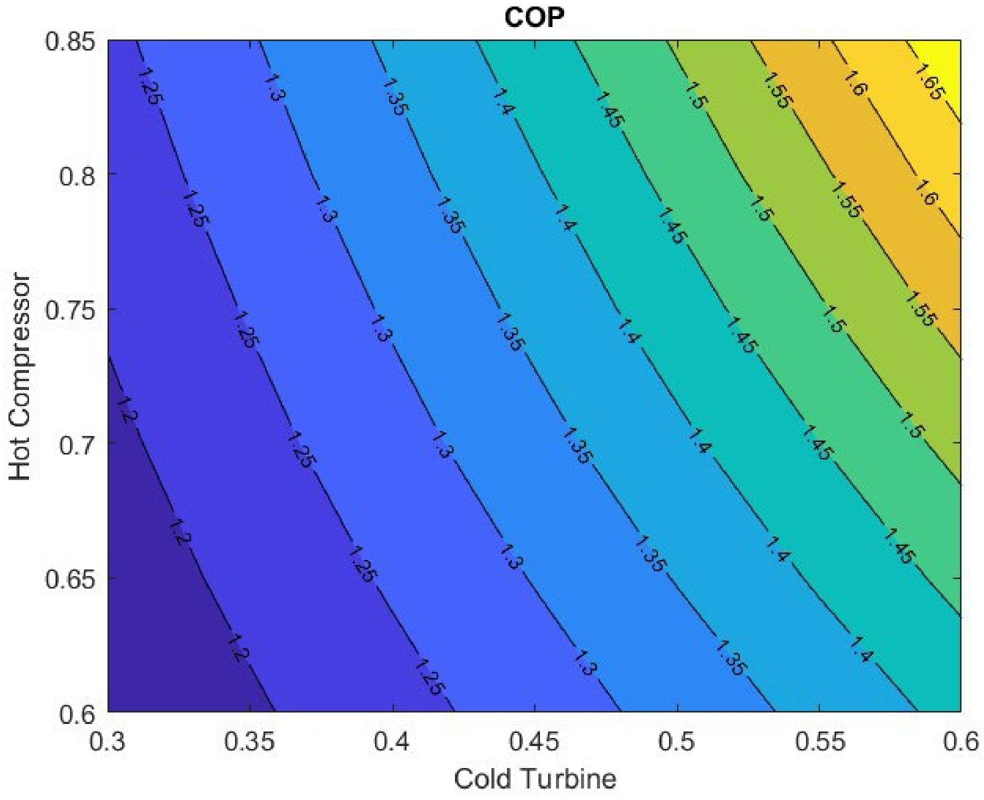
TES mass flow	1	kg/s
Cycles superior pressure	200	bar
WH Inlet Temp.	250	°C
min ΔT in HEX	10	°C
Pressure losses in HEX	1	%
Ambient temperature	25	°C
Hot Compressor Efficiency	60-85	%
Cold Compressor Efficiency	70-85	%
Hot Turbine Efficiency	70-90	%
Cold Turbine Efficiency	30-60	%
Recuperator Effectiveness	80-90	%

Sensitivity

Results

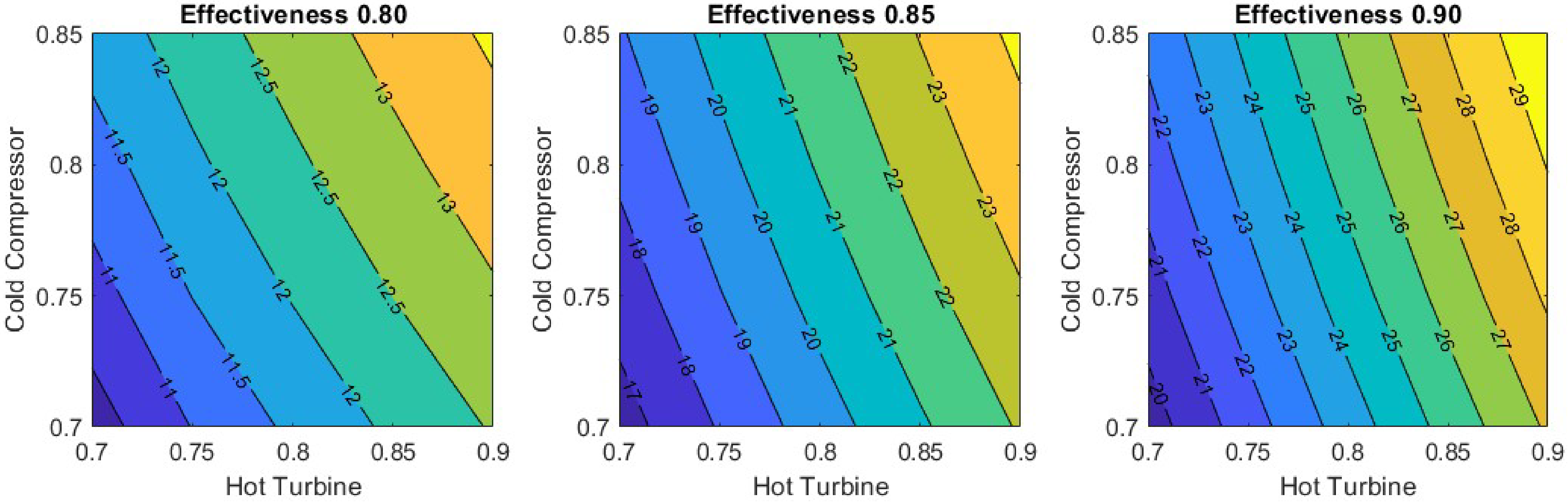
Charging Cycle





Results

Discharging Cycle

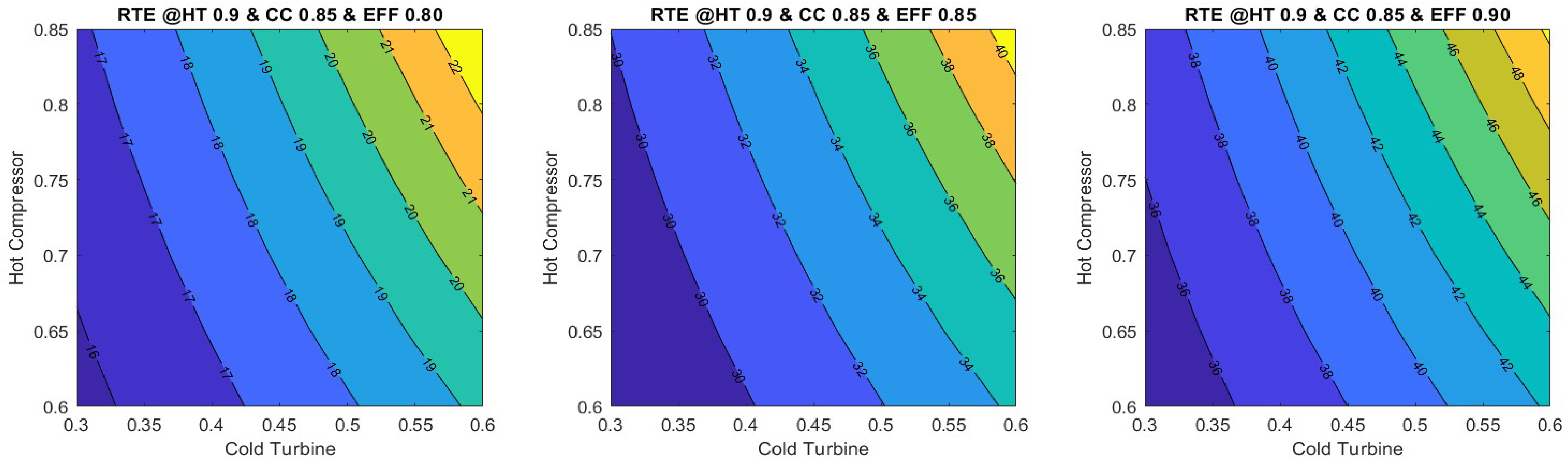


Results

Round Trip Efficiency

Parameters set at the maximum values considered.

Sensitivity on **heat pump** turbomachinery performance

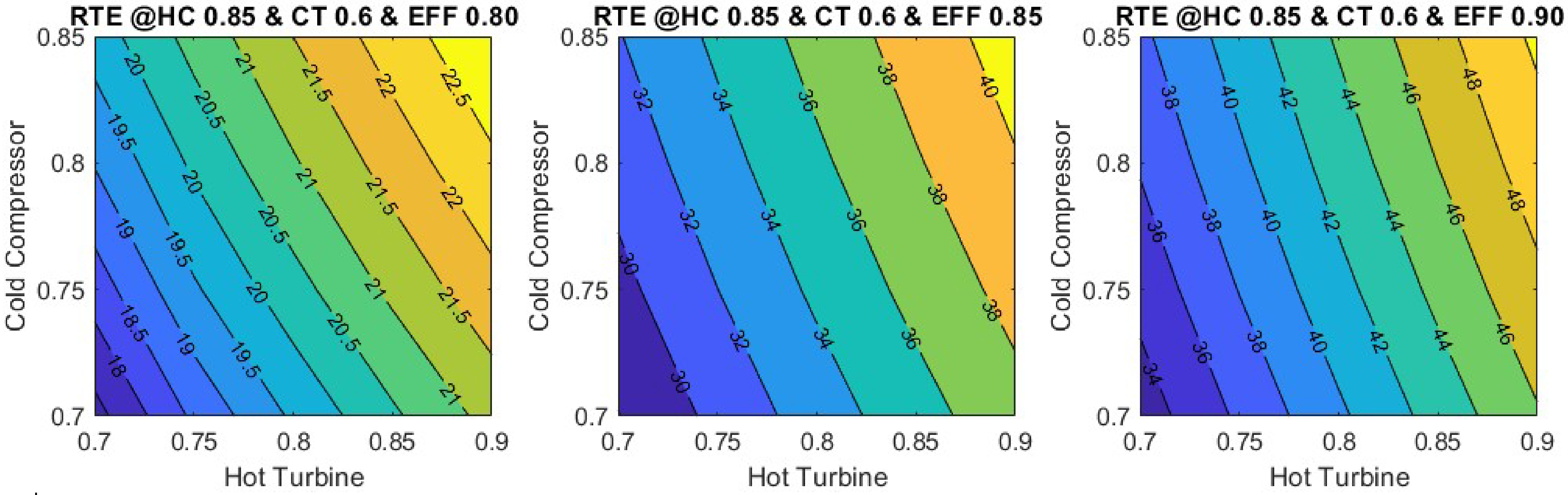


Results

Round Trip Efficiency

Parameters set at the maximum values considered.

Sensitivity on **power cycle** turbomachinery performance

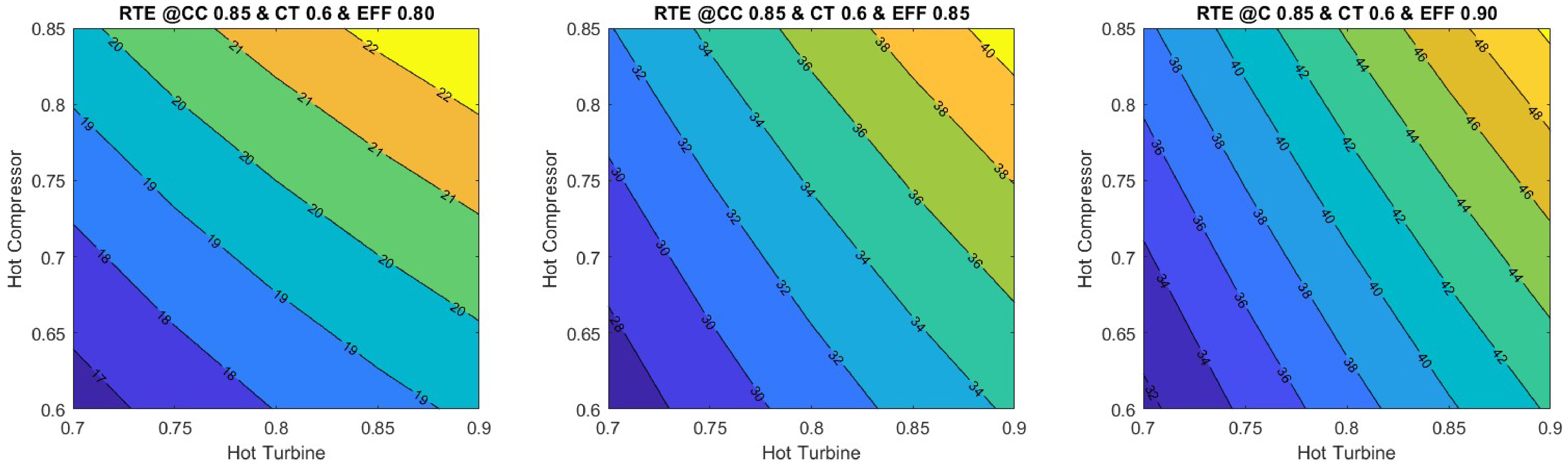


Results

Round Trip Efficiency

Parameters set at the maximum values considered.

Sensitivity on **hot machines** performance

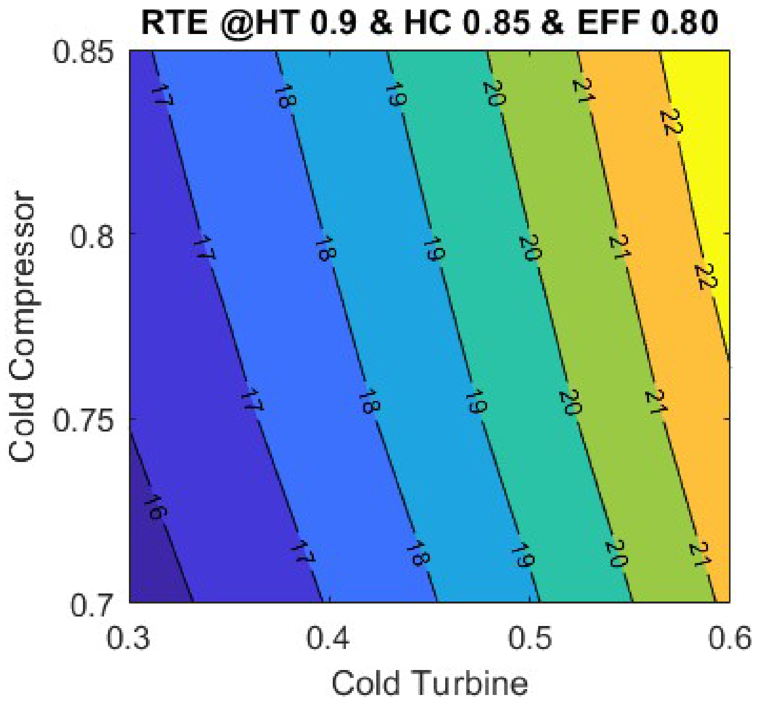


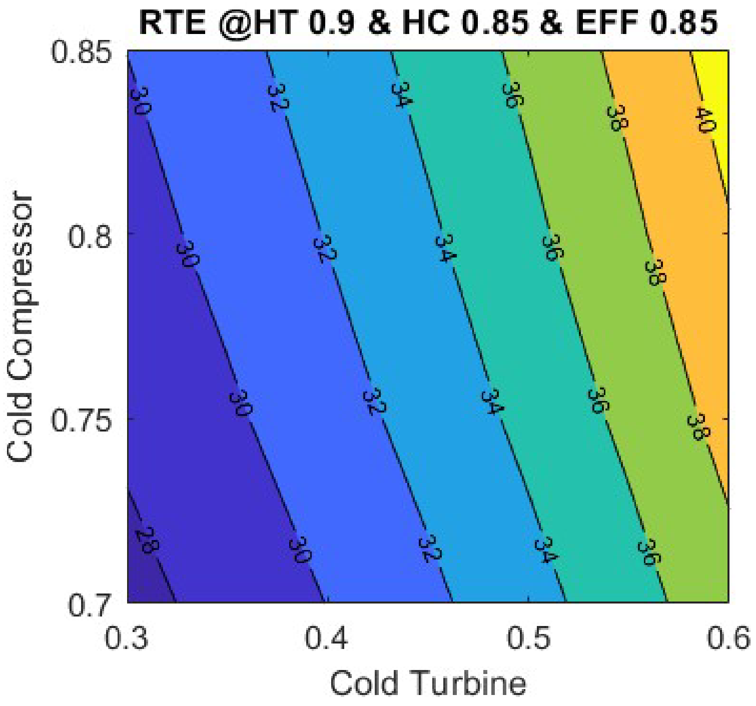
Results

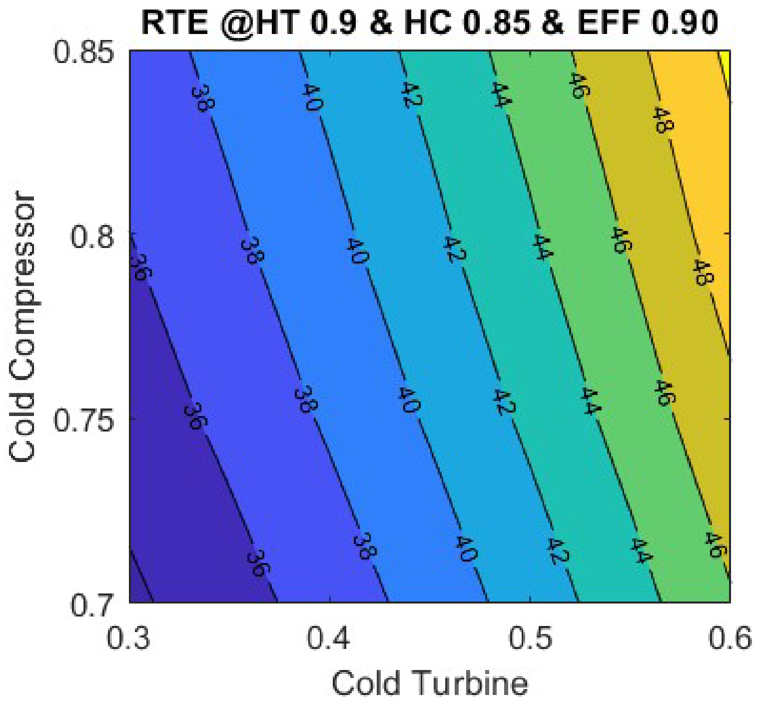
Round Trip Efficiency

Parameters set at the maximum values considered.

Sensitivity on **cold machines** performance





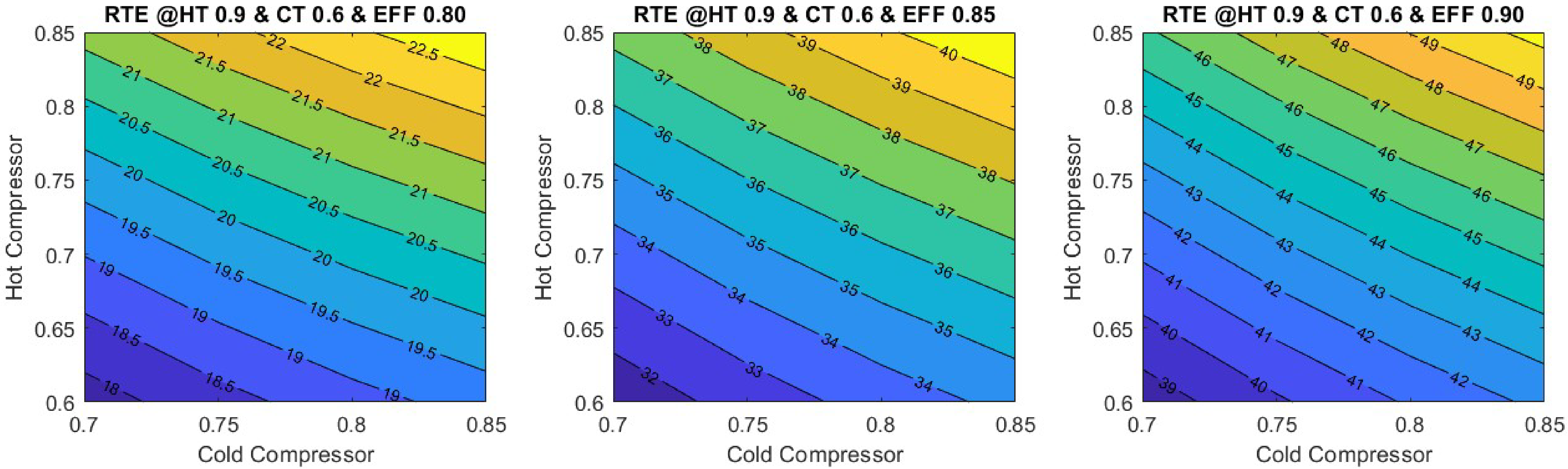


Results

Round Trip Efficiency

Parameters set at the maximum values considered.

Sensitivity **compressors** performance

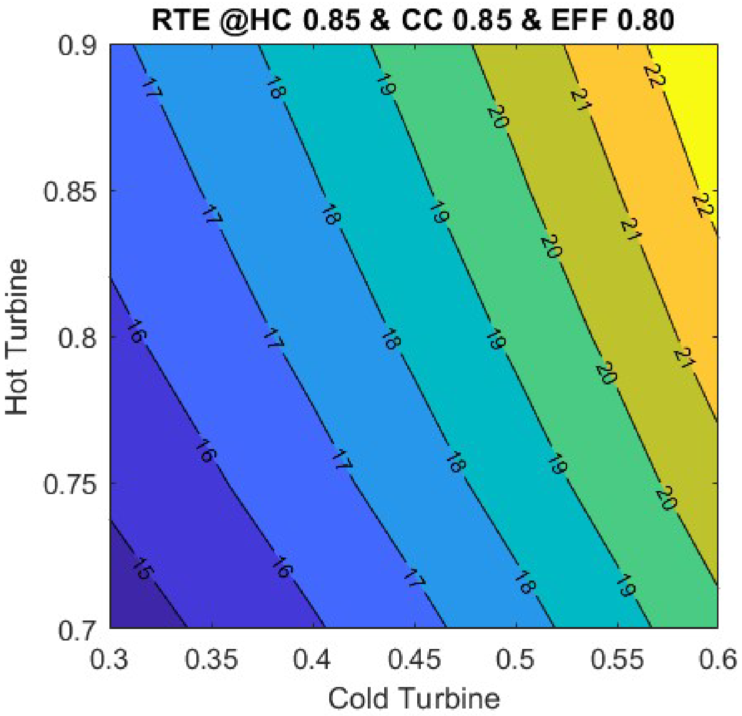


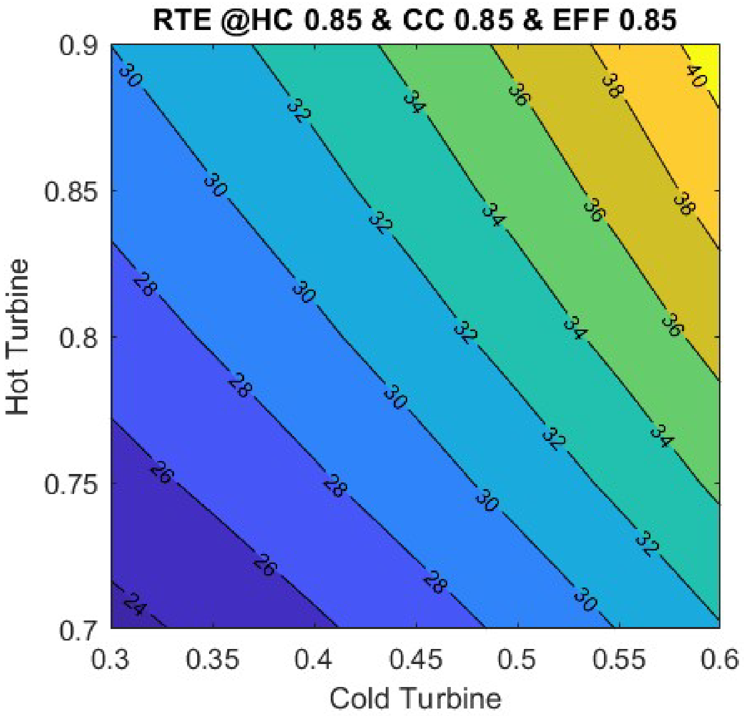
Results

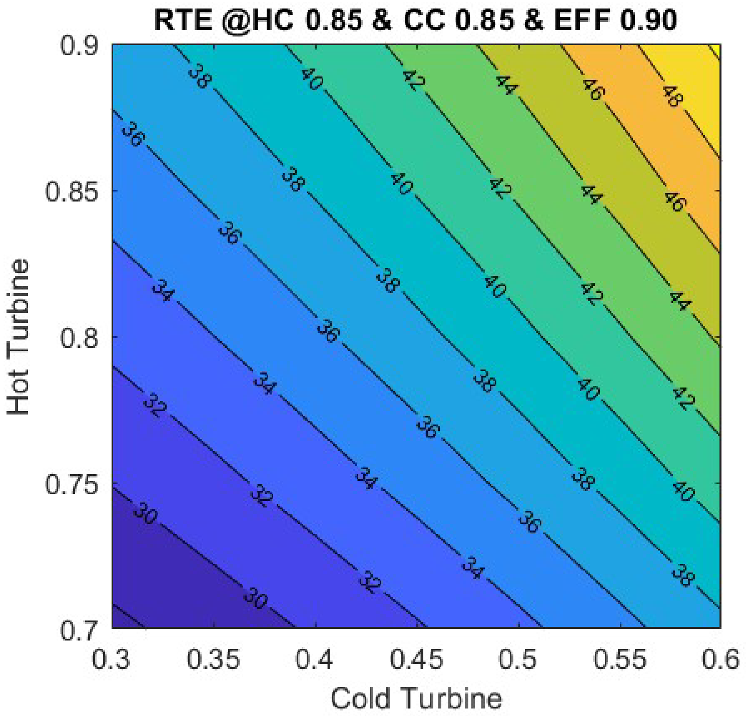
Round Trip Efficiency

Parameters set at the maximum values considered.

Sensitivity on **turbines** performance







Conclusions

Impact of efficiencies in the analysis

For the specific analysis, the rate of change of the RTE for each component efficiency has been analyzed.

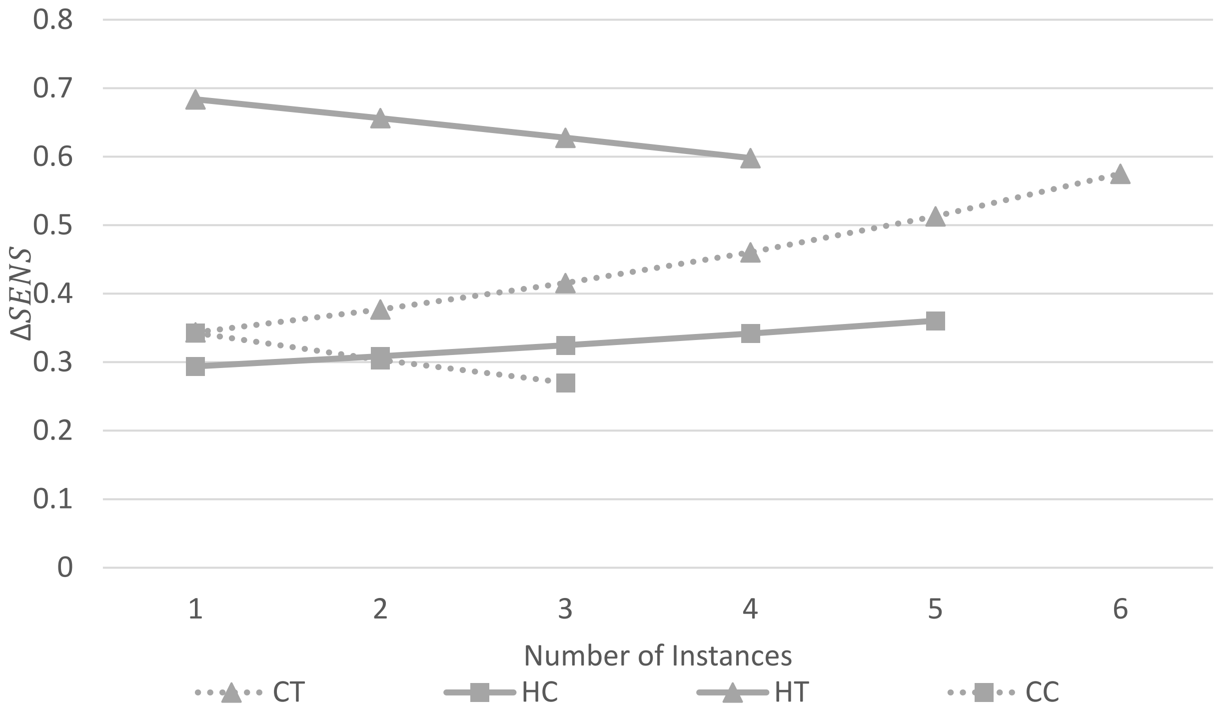
Small numbers correspond to small values of efficiency and vice versa.

Power cycle components impact decrease.

Heat pump components impact increase.

$$\Delta SENS = \frac{RTE_{i+1} - RTE_i}{n_{i+1} - n_i} = \frac{\Delta RTE}{\Delta n}$$

Component	Range of parameter	Number of instances of $\Delta SENS$
Cold Turbine	0.30 - 0.60	6
Hot Compressor	0.60 - 0.85	5
Hot Turbine	0.70 - 0.90	4
Cold Compressor	0.70 - 0.85	3



Conclusions

Impact of efficiencies in the analysis

- **Hot turbine**: The recuperator has a major impact on the power cycle and thus RTE. This increase the impact of the hot turbine. Also the low COP leads to an increase in the importance of this component.
- **Cold Turbine**: The efficiency starts from a low expected value. Cold turbine outlet conditions are responsible for the amount of waste heat recovered.
- **Hot Compressor**: For a fixed thermal gradient on the hot compressor side (as inlet temperature of the compressor is fixed by WH source and TES temperature is fixed in this analysis) hot compressor efficiency influences only pressure ratio of the charging cycle, thus influencing the RTE. As showed in previous work, varying hot compressor temperature glide has a relevant impact on RTE.
- **Cold Compressor**: Always working at high density, its impact on the total performance of the battery system is secondary

sCO2OP-TES Project

SCO2OP-TES

sCO2 Operating Pumped Thermal Energy Storage

for grid/industry cooperation

SCO2OP-TES Project

Project Coordinator

Stefano.barberis@unige.it

Funded by the European Union

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UniGe

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