Optimized waste heat valorization by integrated thermal energy conversion and storage technologies

Prof Adriano Sciacovelli[1,2]

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Outline

- Research Expertise and Mission

- ZHENIT learnings on:

    - On-board waste heat & decarbonization of the maritime sector
    - Optimized Waste Heat Recovery by integrated technologies
    - Advanced thermal energy storage

- Final remarks

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Engineering and Physical Sciences Research Council

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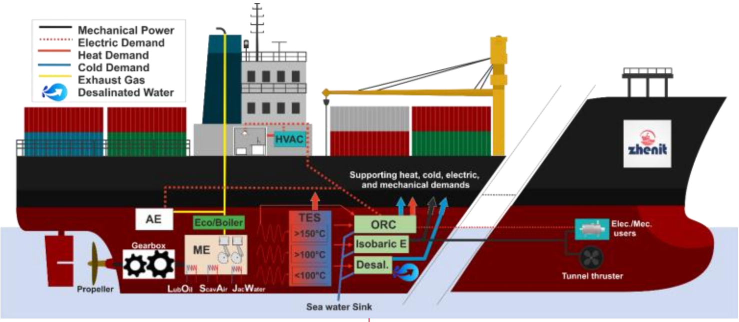
28 | 02 | 2025

On-board waste heat

Relevant secondary resource - currently and under fuel switching scenarios



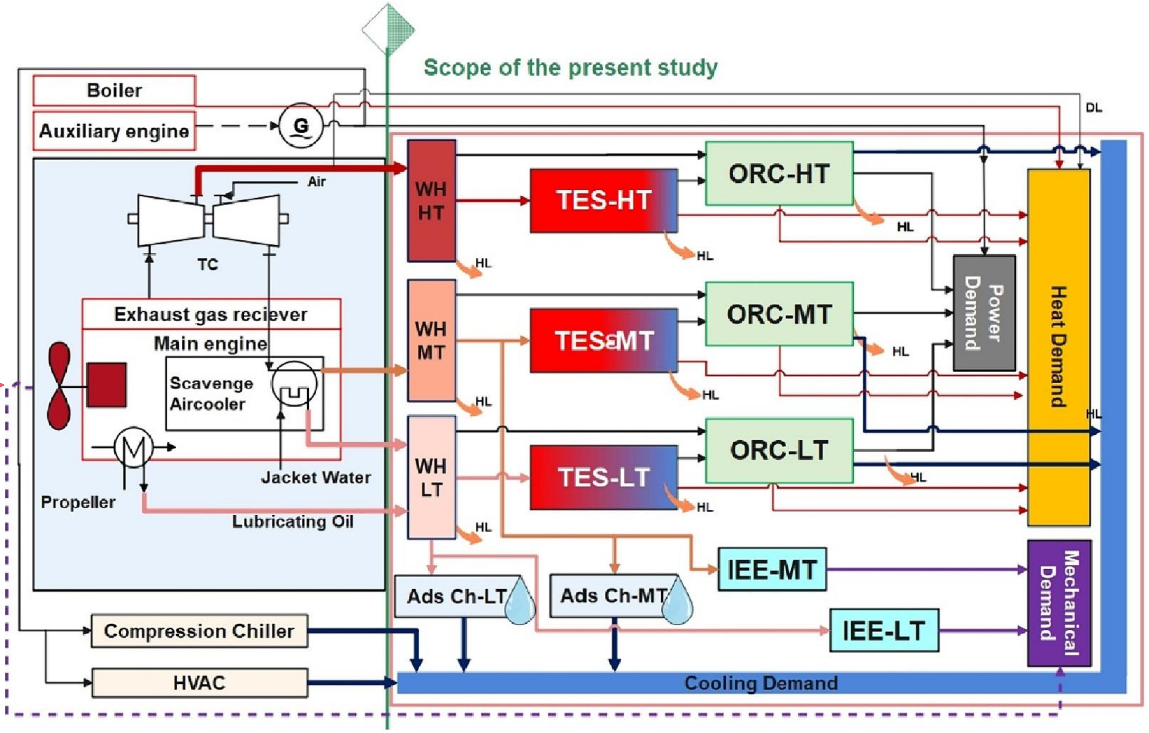


Fig. 6. Simplified Schematic of the onboard energy system with WHR technology.

From ours Publications: **Applied Energy** 366 (2024) 123298; **ECOS** Proceedings (2023)

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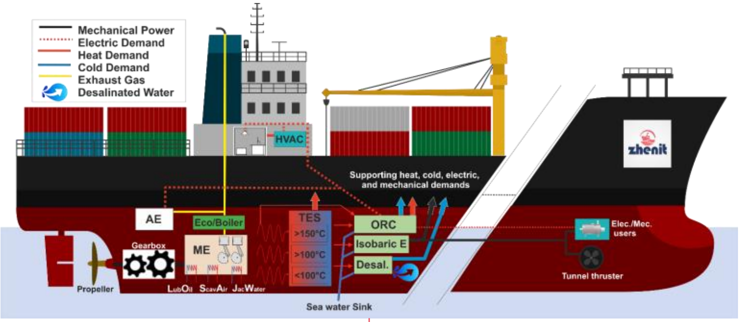

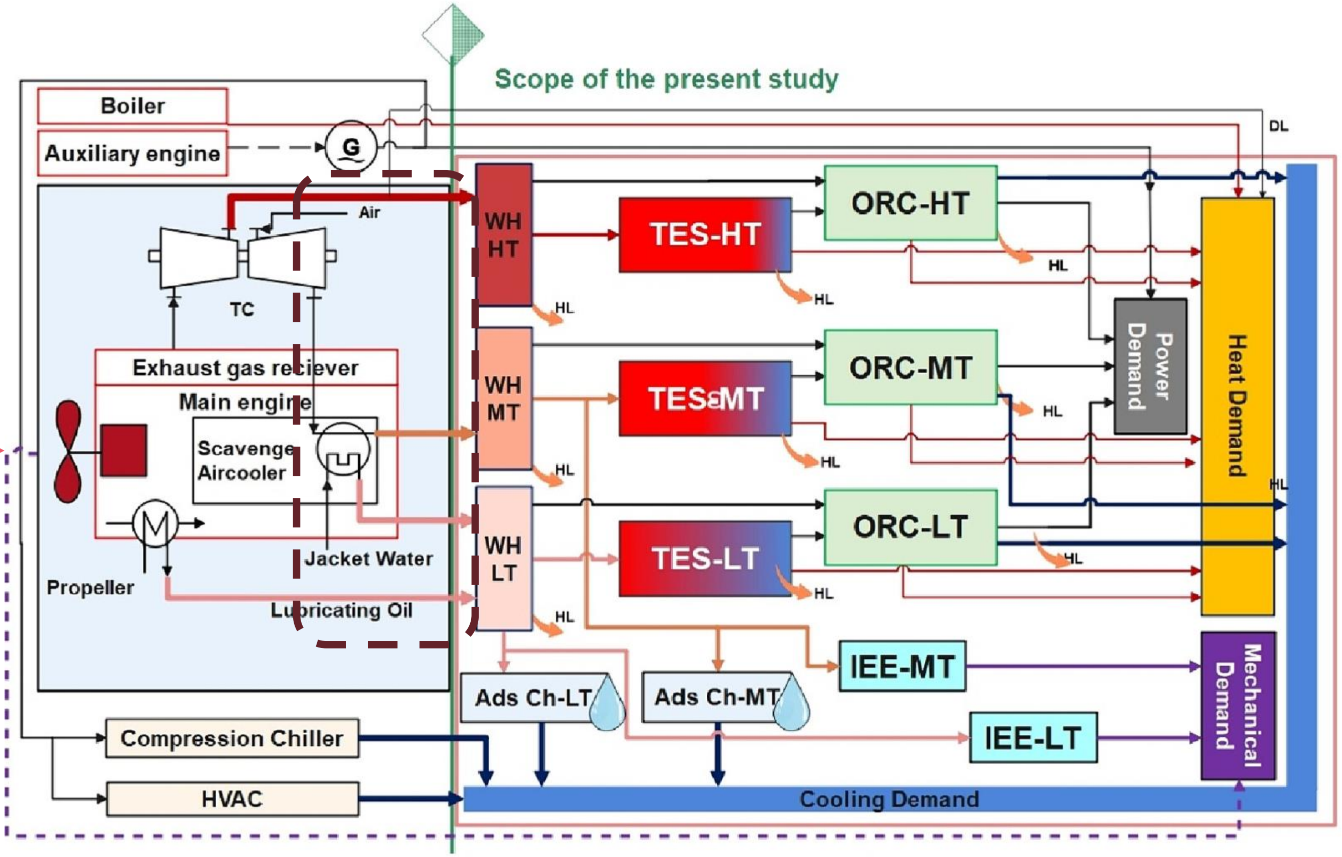

Fig. 6. Simplified Schematic of the onboard energy system with WHR technology.

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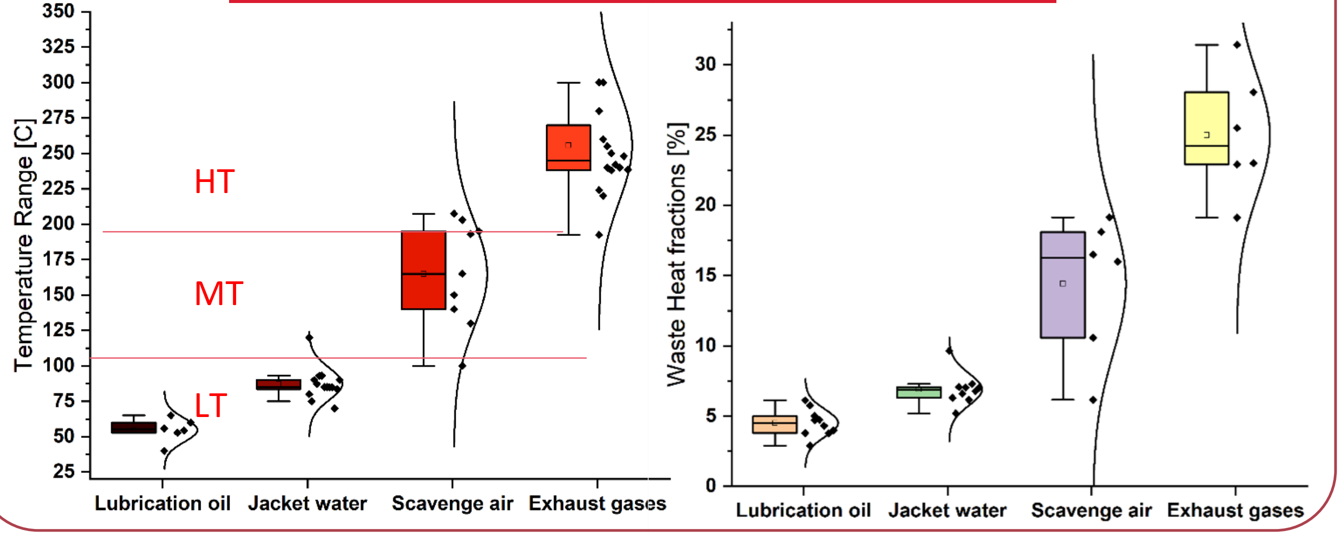
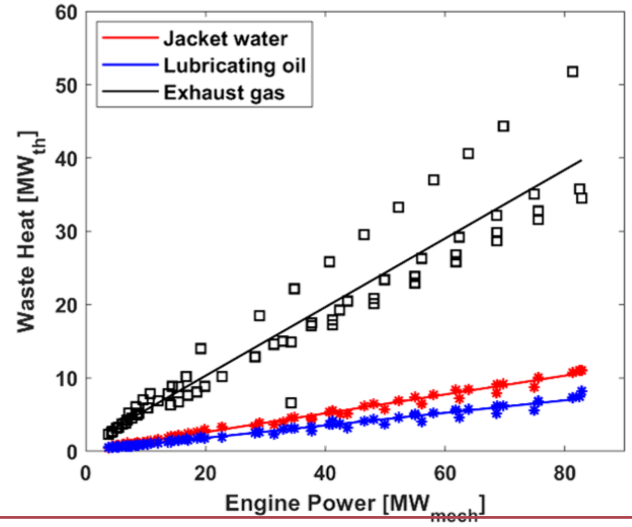
On-board waste heat (II)

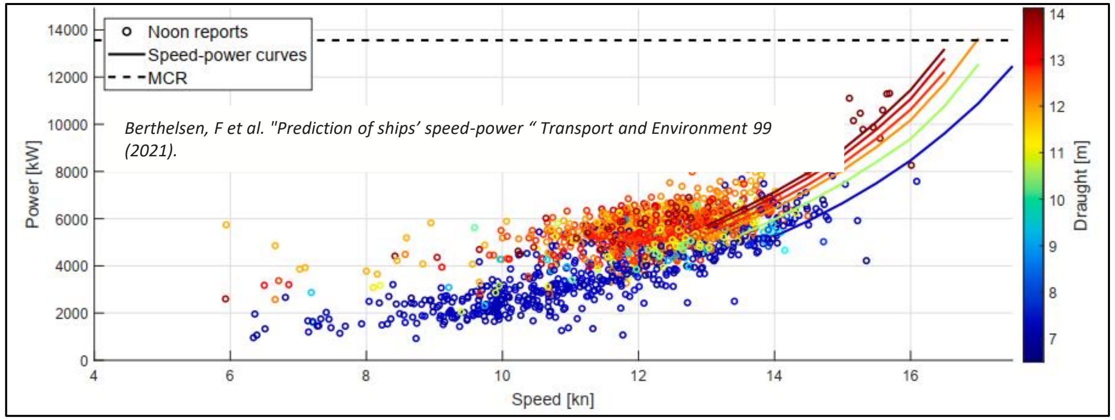
From engine data and partial load analysis

Averaging of literature data on WH distributions



Waste heat fraction





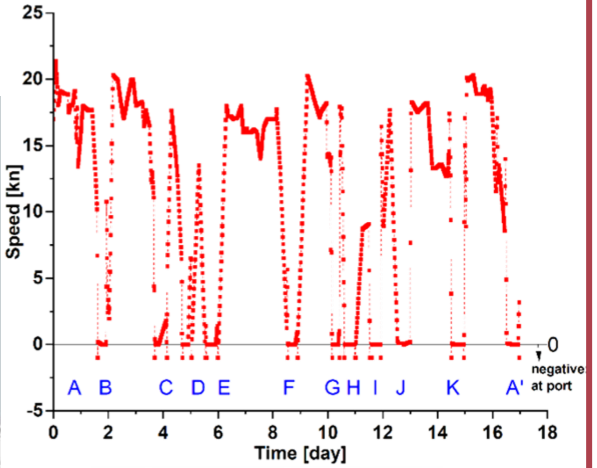
Engine load correlations

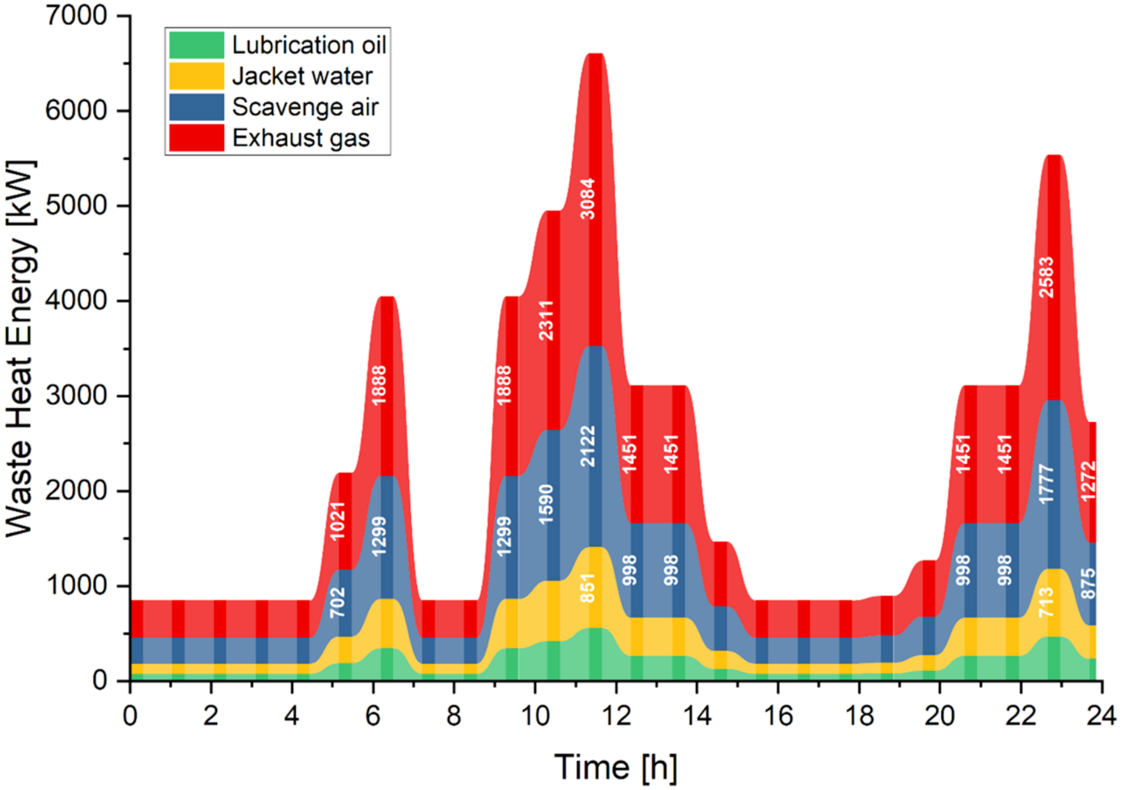
From ours Publications: **Applied Thermal Engineering**, (2024), 253, 123740 **Applied Energy** 366 (2024) 123298; **ZHENIT Deliverables** (Open access)

Waste heat dynamics – a voyage dependent resource

From engine data and partial load analysis

- **Multiple stops**, highlighting tourist destinations and leisure activities
- **Variable speeds**, may increase to meet tight schedules for tourists' comfort





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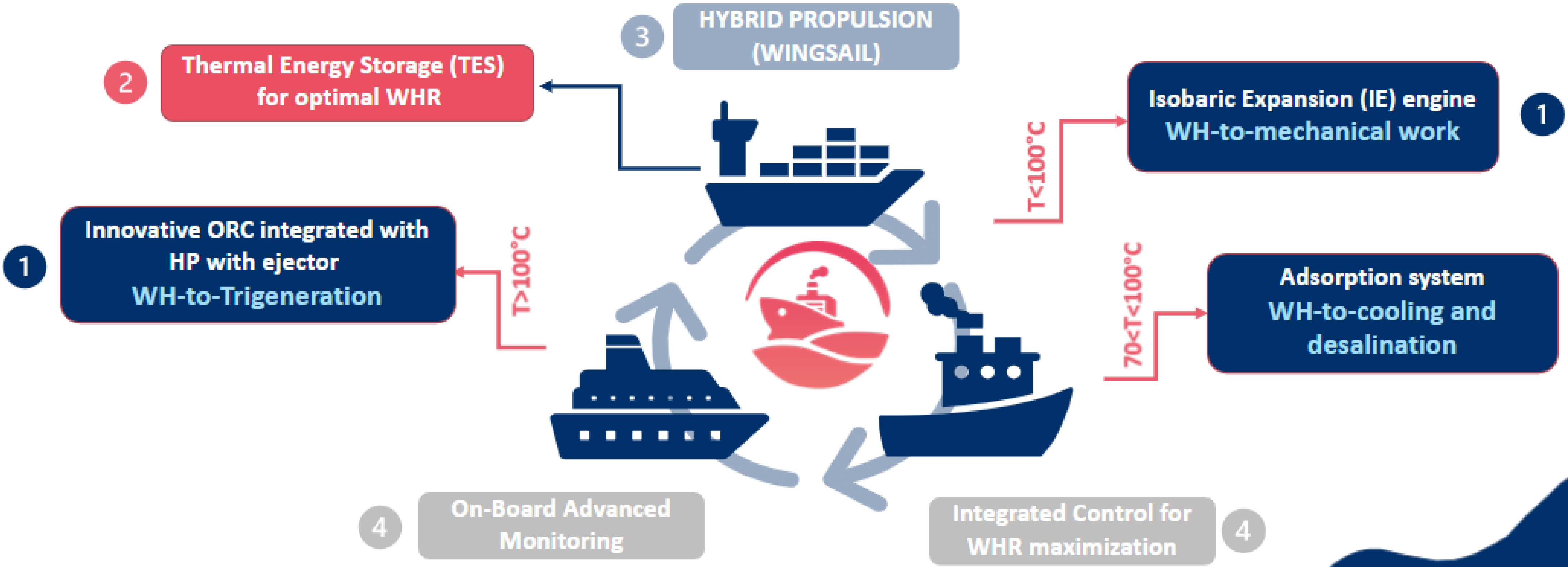
- **ZHENIT learnings on**:

  - On-board waste heat & decarbonization of the maritime sector
  - <u>*Optimized Waste Heat Recovery by integrated technologies*</u>
  - Advanced thermal energy storage

- Final remarks:

Multi-energy system analysis and optimization

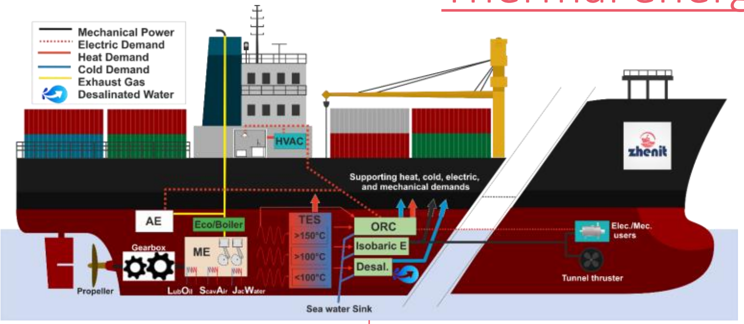
Combined Investment and operational optimization



Multi-energy system analysis and optimization (II)

Integrated conversion technologies → valorization

Thermal energy storage → management of dynamics AND more valorization



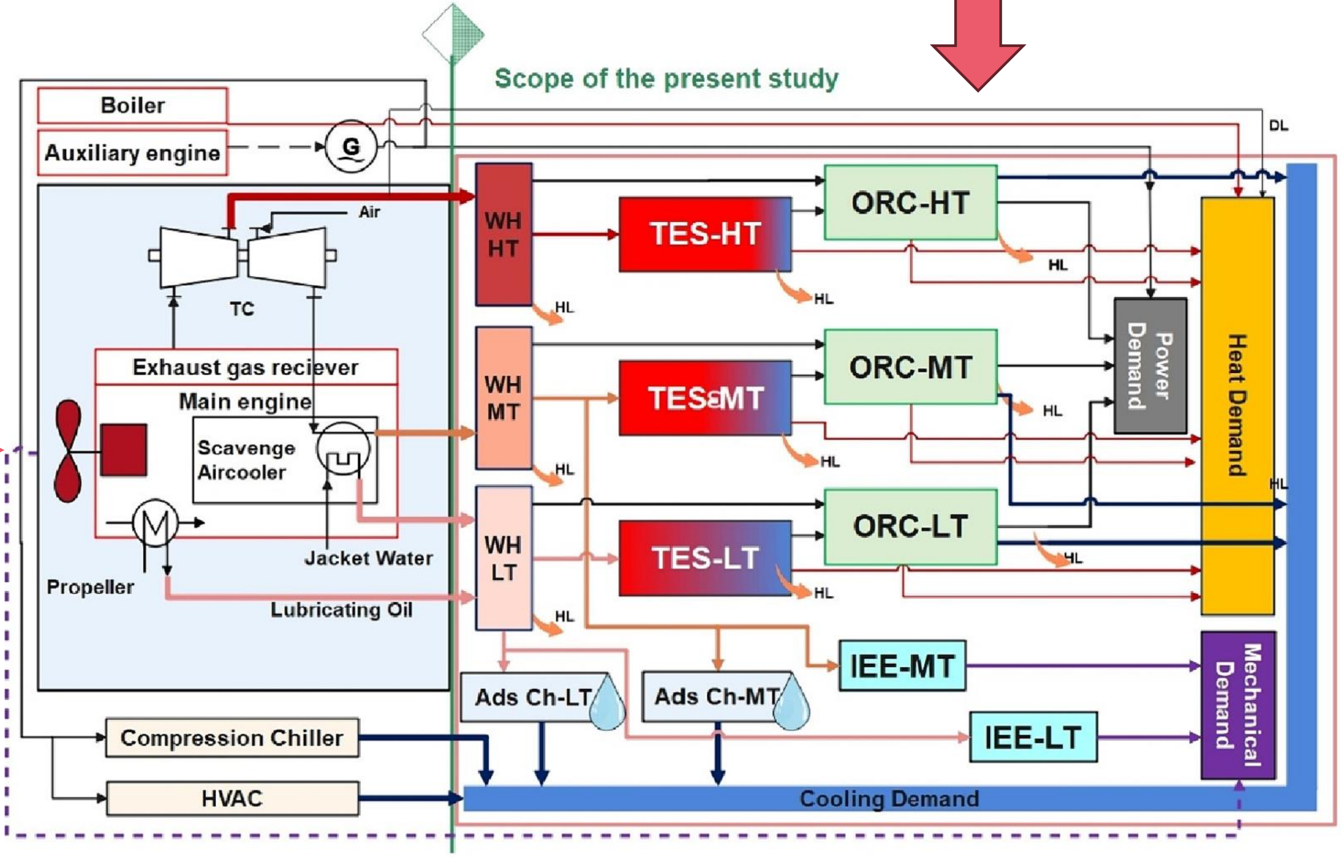


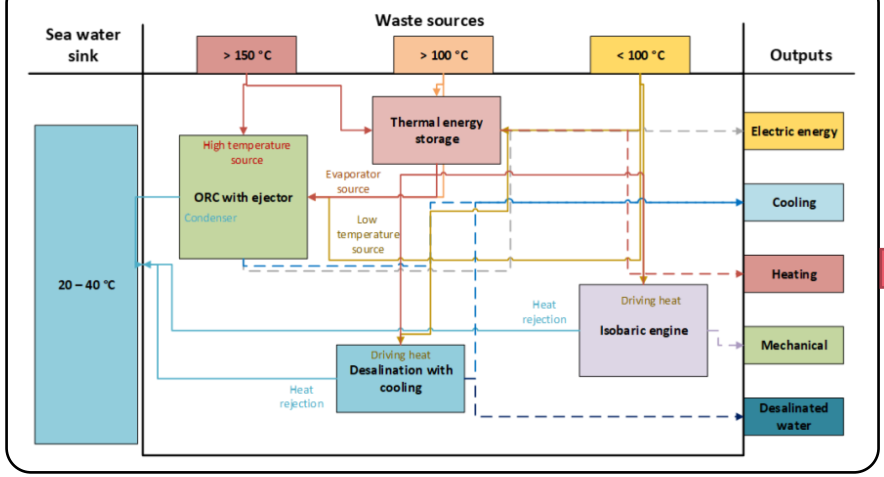
Fig. 6. Simplified Schematic of the onboard energy system with WHR technology.

Multi-energy system analysis and optimization (III)

Combined Investment and operational optimization

Input

Supply (available WH) and **D**emand profiles



-Key **boundaries** and **ranges**
-Additional ones is required in terms of compatibility, dynamic operation & timing. Some boundaries are forced by the upstream/downstream Technology.

Constraints Type 1: Scenarios & case studies
Constraints Type 2: thermodynamics
i.e. WHR technology can't withdraw more heat than demand.

Solver

$$\underbrace{\begin{array}{cccc} Q_t^S & Q_{t+1}^S & \cdots & Q_{t+N}^S \\ Q_t^D & Q_{t+1}^D & \cdots & Q_{t+N}^D \\ C_t^D & C_{t+1}^D & \cdots & C_{t+N}^D \end{array}}$$

Time frame of optimisation

Linear equations

Linearised model of WHR Techs, i.e.

ORC : $Q_{ORC}^{in} = \frac{1}{\eta} W_{ORC}^{out}$

Inequality constraints

Equality constraints

$$\min_{t=1\ldots n}(Obj)$$

$$\overbrace{f(CAPEX) + g(OPEX)}$$

Energy balance

MILP solver

Output

Answer to the question of how to get the most from WHR technology to minimise the waste heat at time step i^{th} (or time frame of $i^{th} \ldots i^{th+10}$).

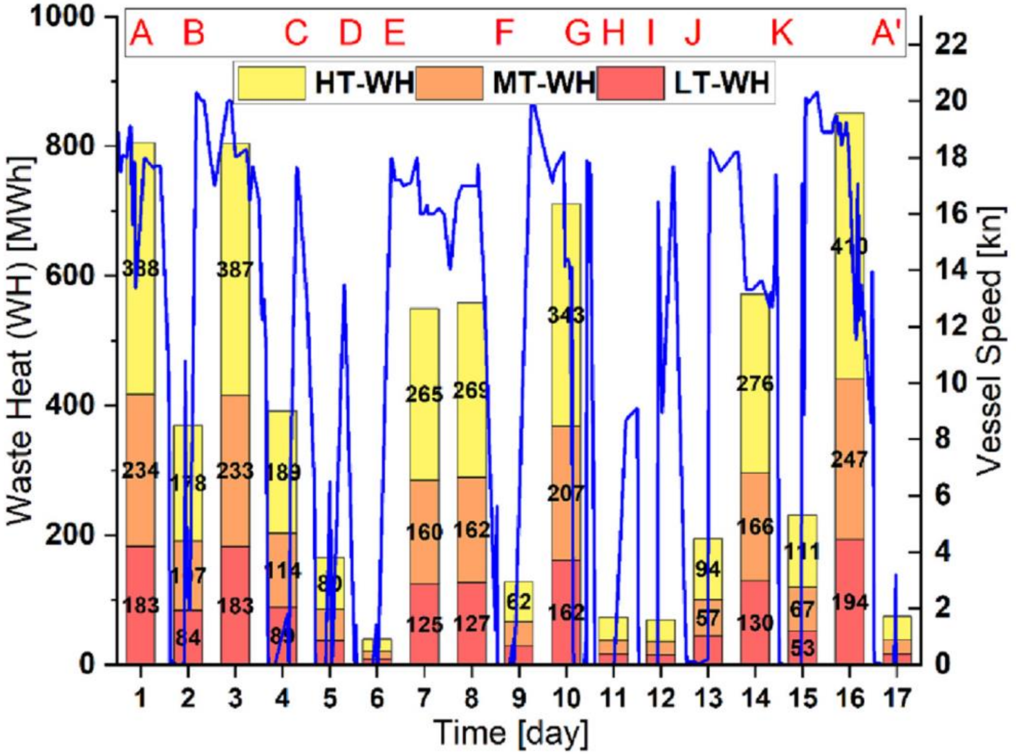
i.e.

	ORC	IEE	AC&D	TES-ORC	TES-AC&D
i^{th}	0	1	1	0	1
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
i^{th+n}	1	1	0	1	0

Optimised for OpEx and Capex contributions with weighted sum approach

Results – Exemplar case (I)

Waste heat dynamics and dynamic operation of ZHENIT technologies



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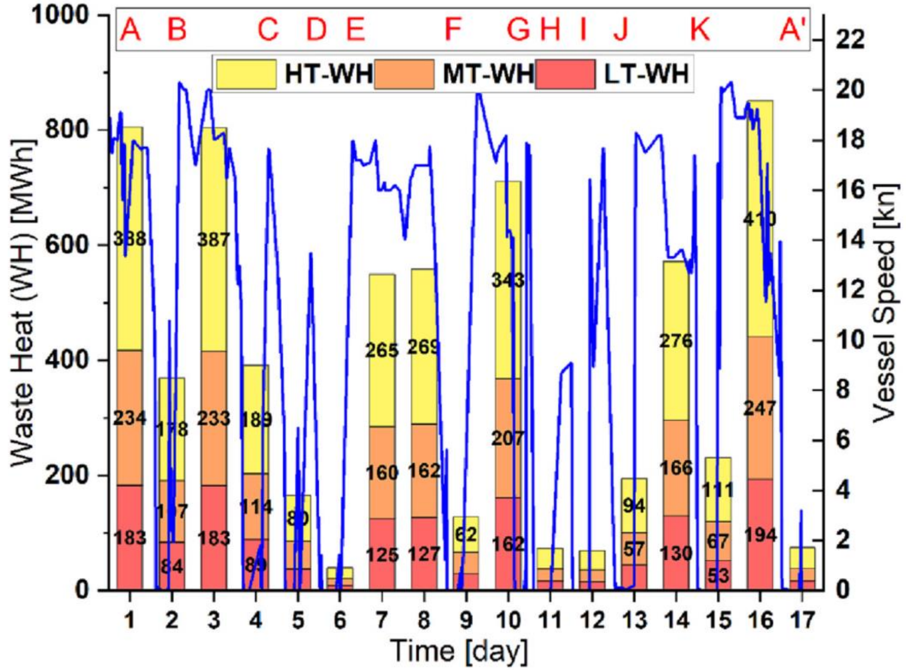
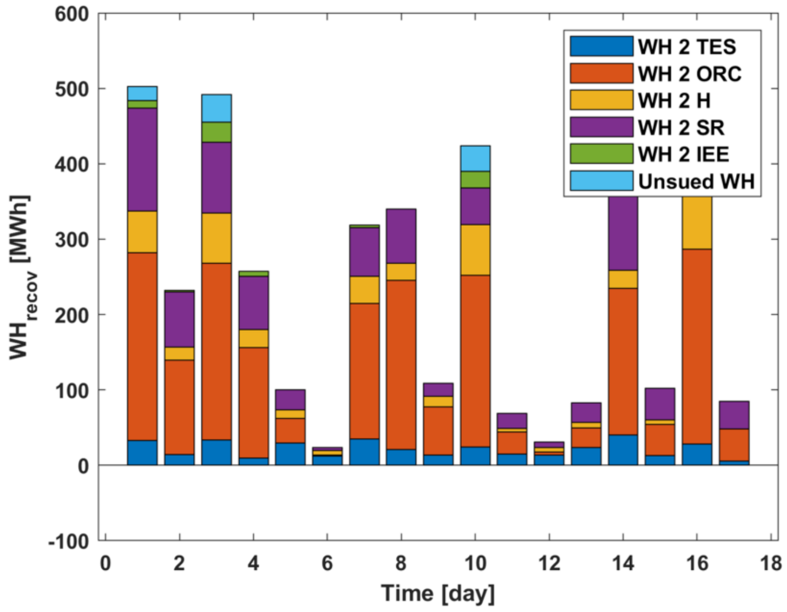
Techno-Economic Results – Exemplar case (II)

Waste heat dynamics and dynamic operation of ZHENIT technologies





- Thermal Energy Storage
- Organic Rankine Cycle (with/without cooling production)
- Adsorption cooling – desalination
- Advanced thermal energy storage
- Isobaric expansion engine

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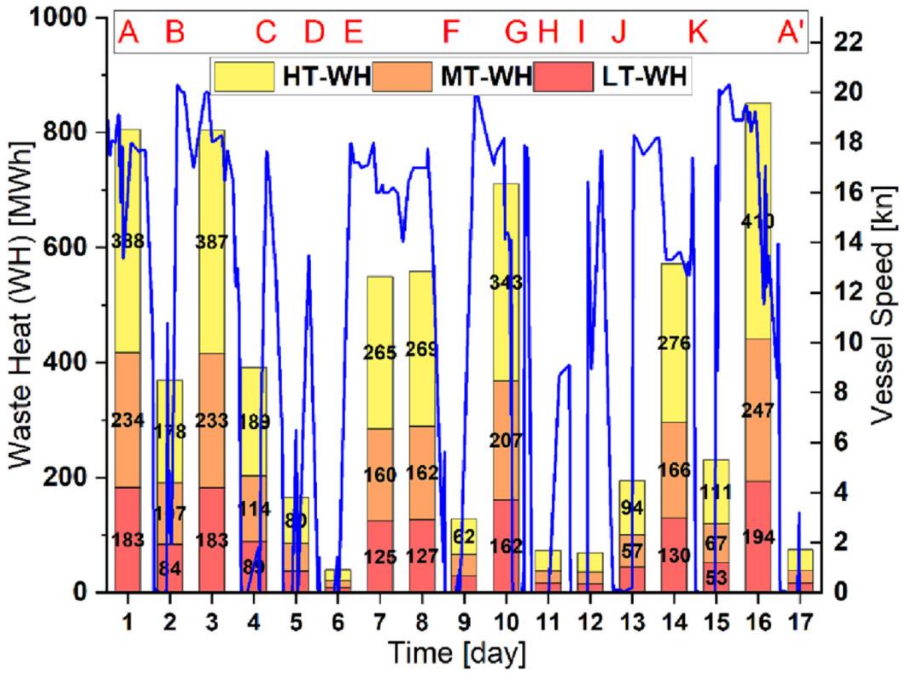

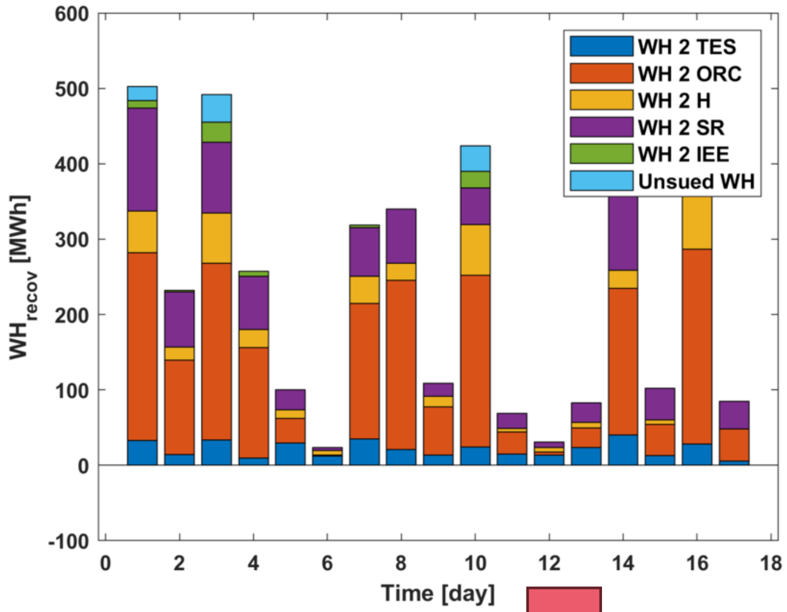

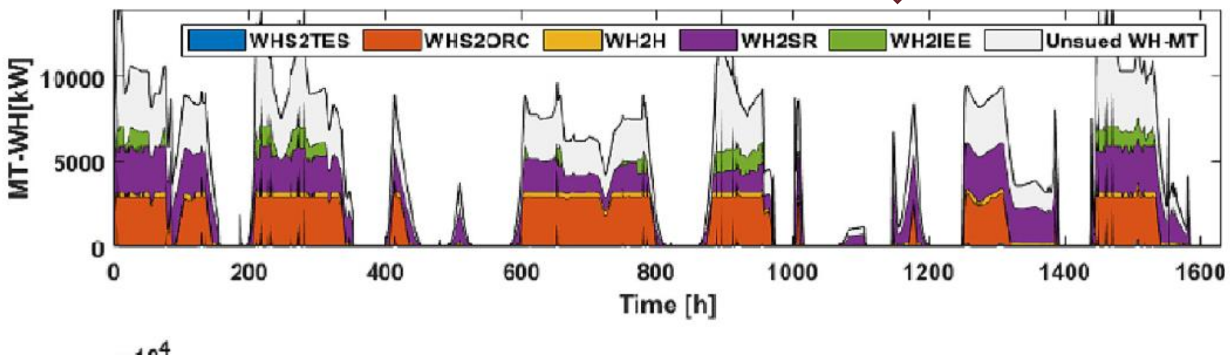

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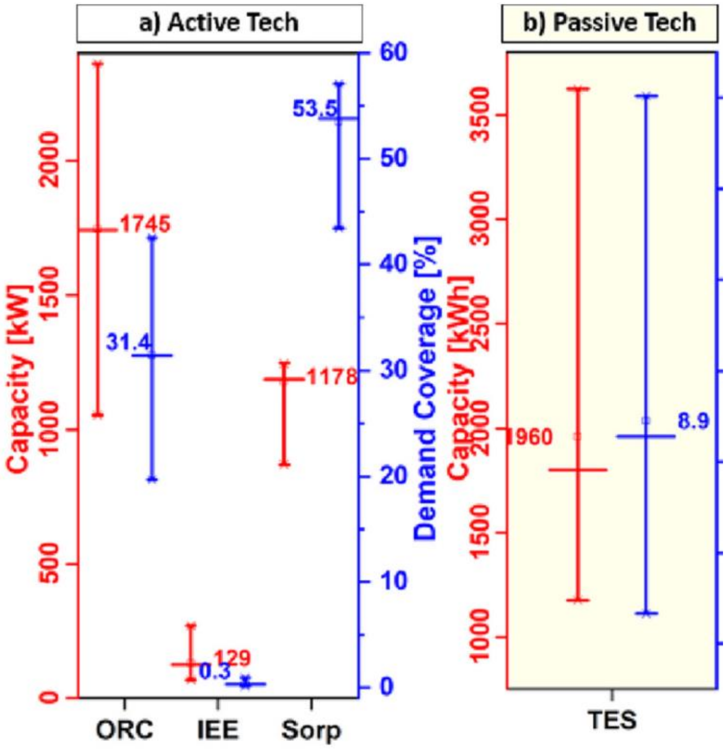

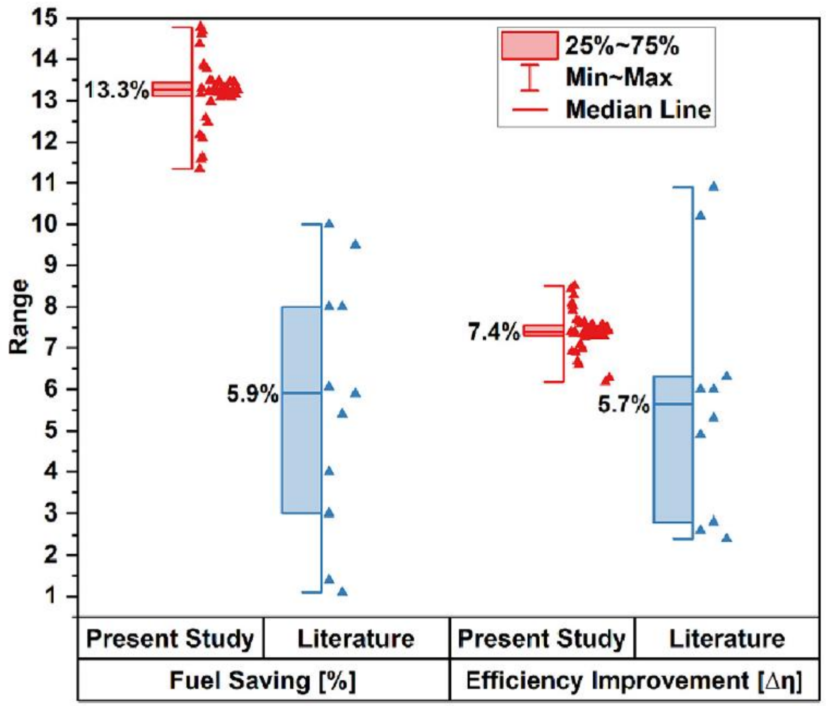

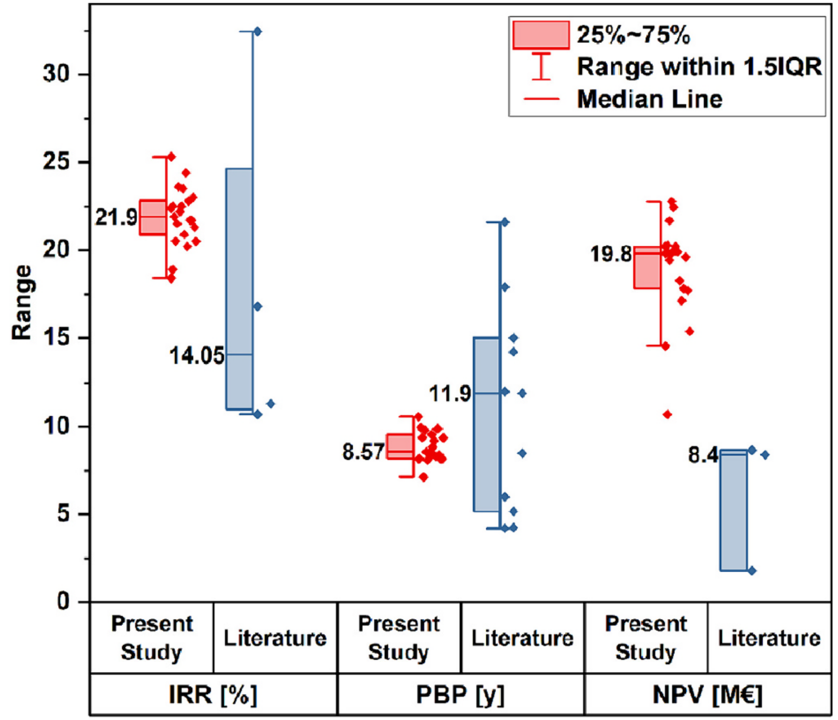

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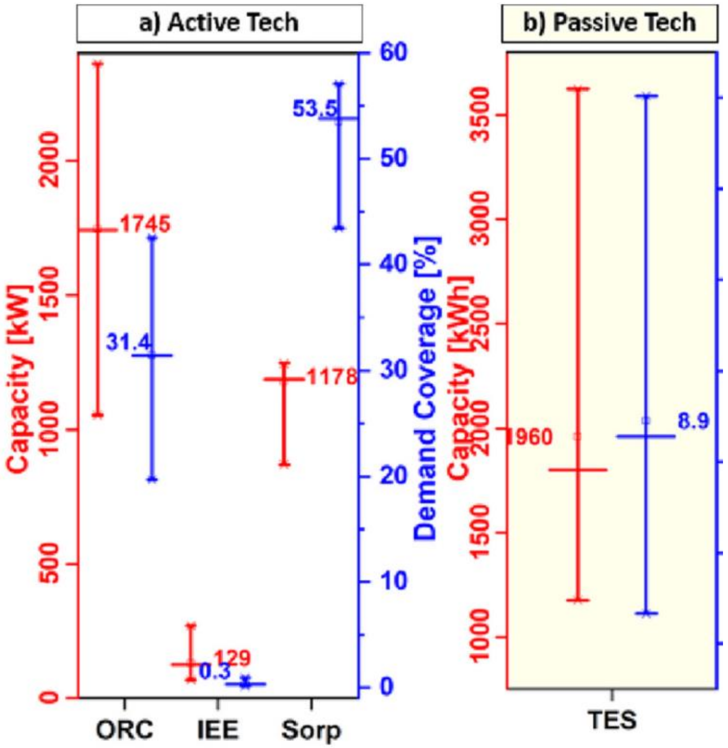
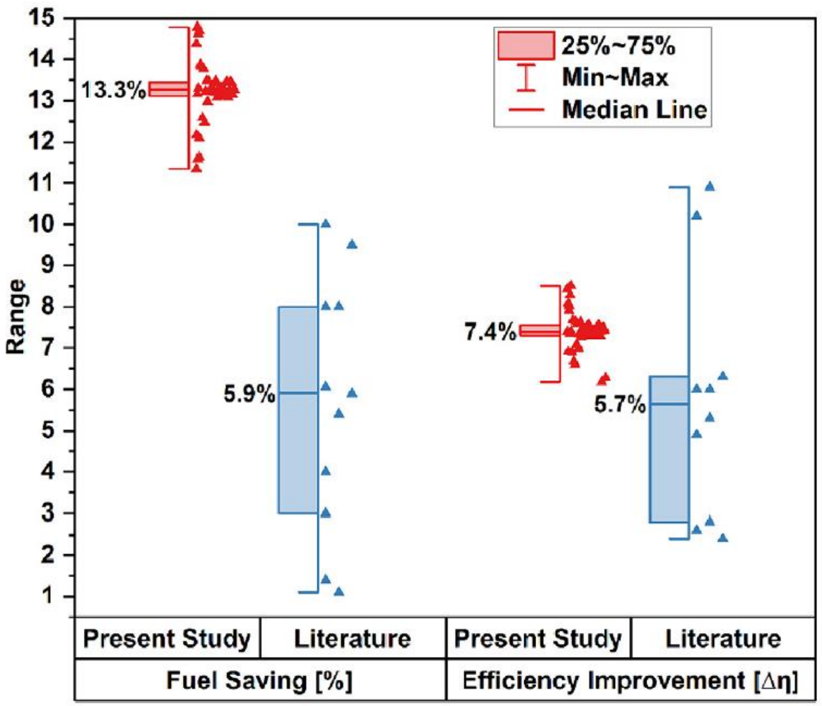
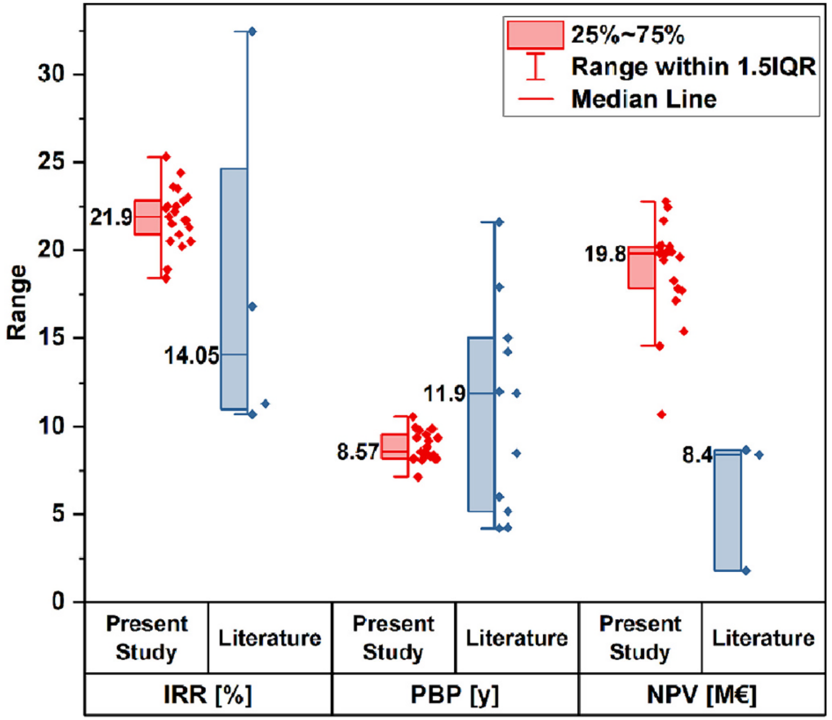
Remarks & Learnings







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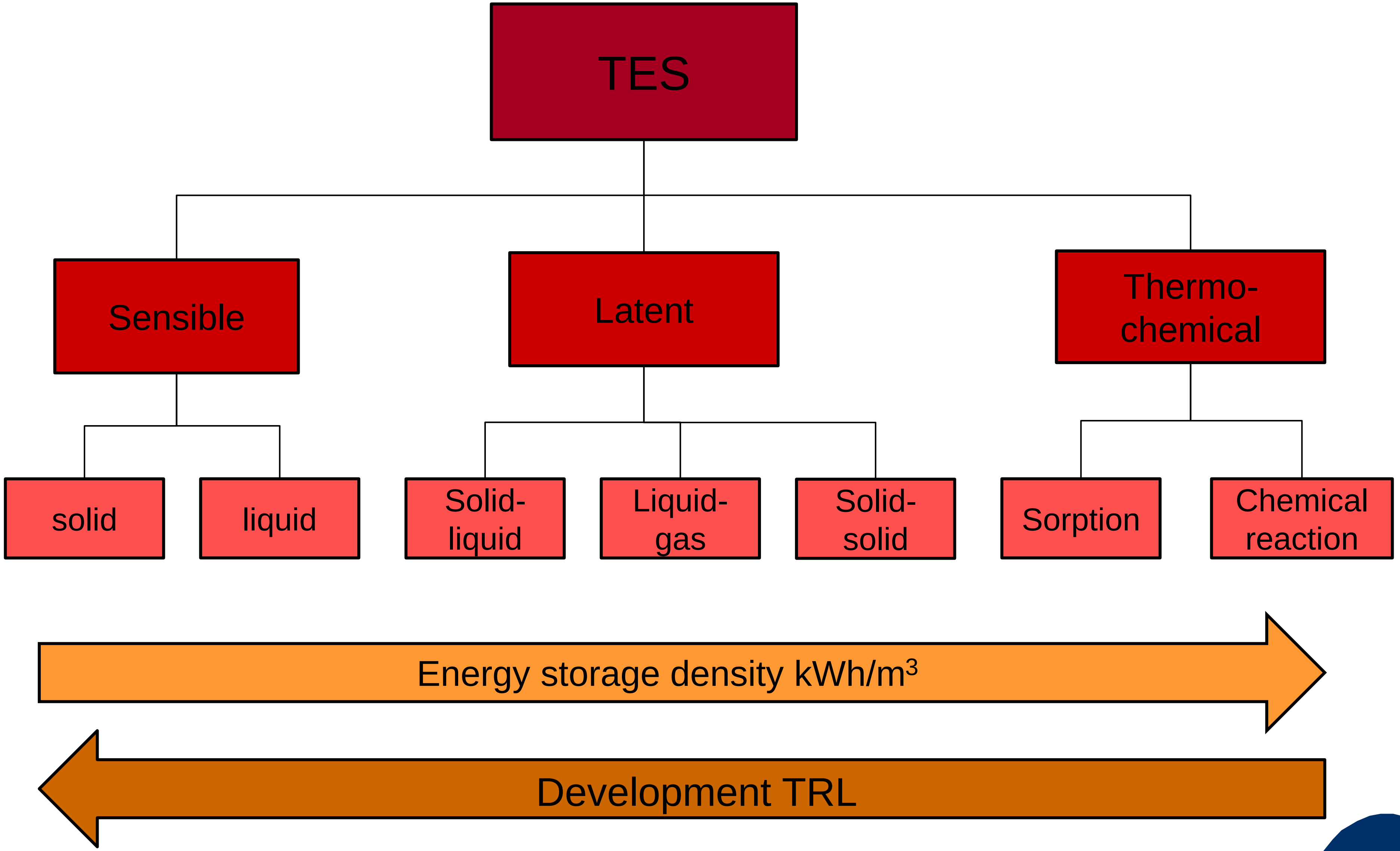
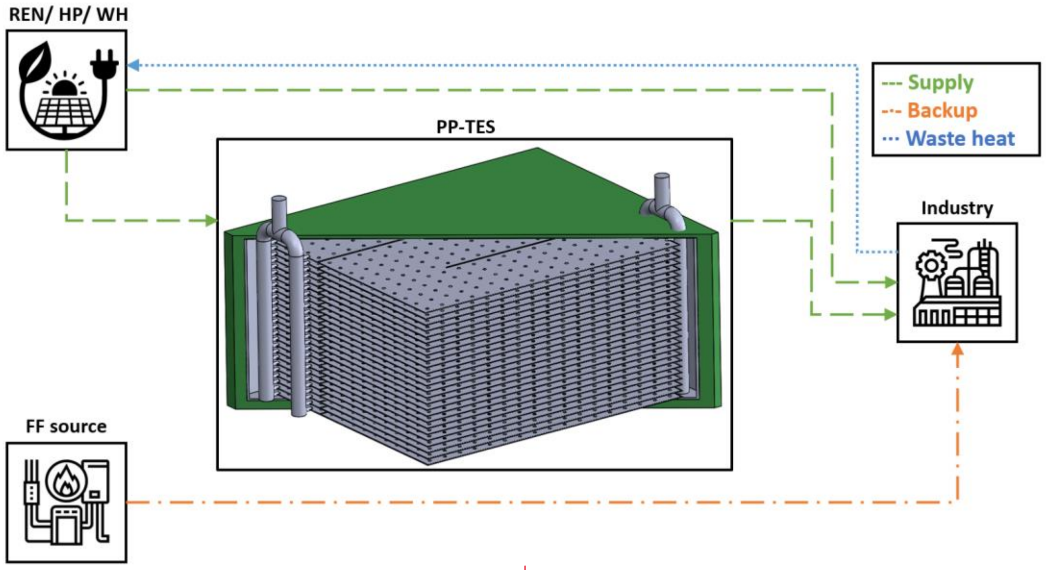
Advanced thermal energy storage



Latent heat thermal energy storage

- Compactness → positive for space-limited applications
- Multi-temperature → matching with different heat sources



Other applications

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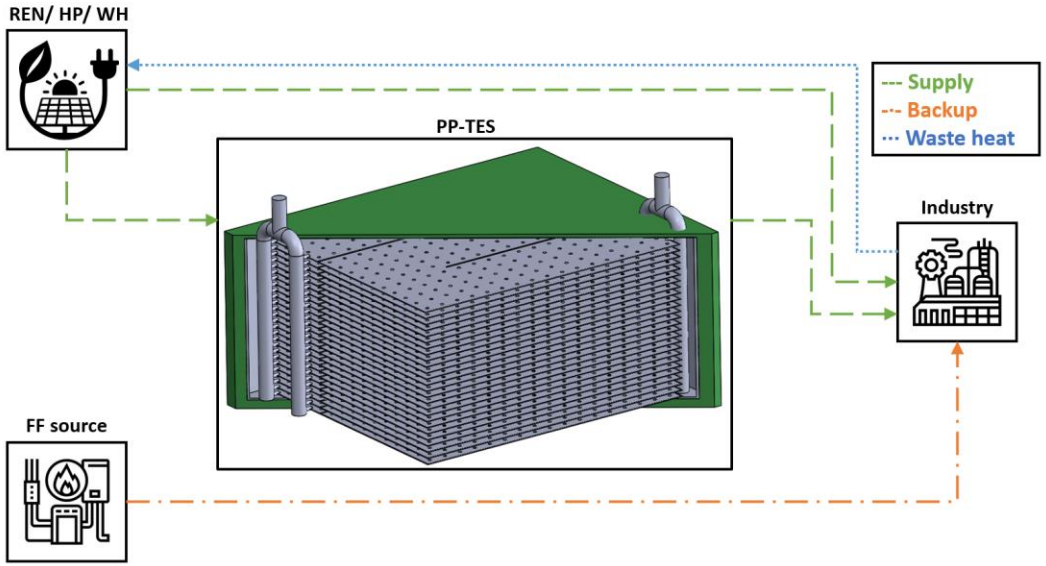
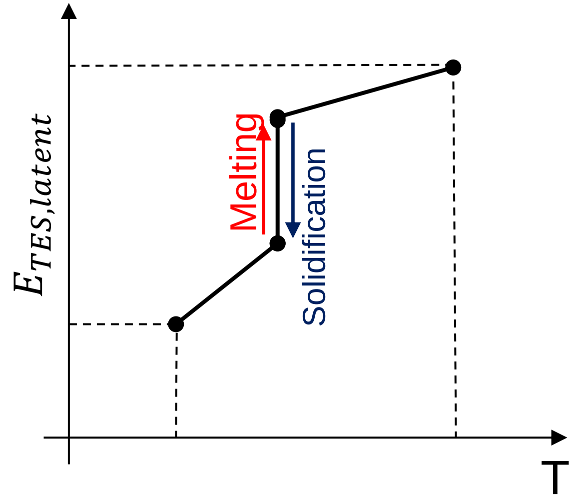
Latent heat thermal energy storage (LHTES)

- Compactness → positive for space-limited applications
- Multi-temperature → matching with different heat sources





Phase change materials (PCMs)

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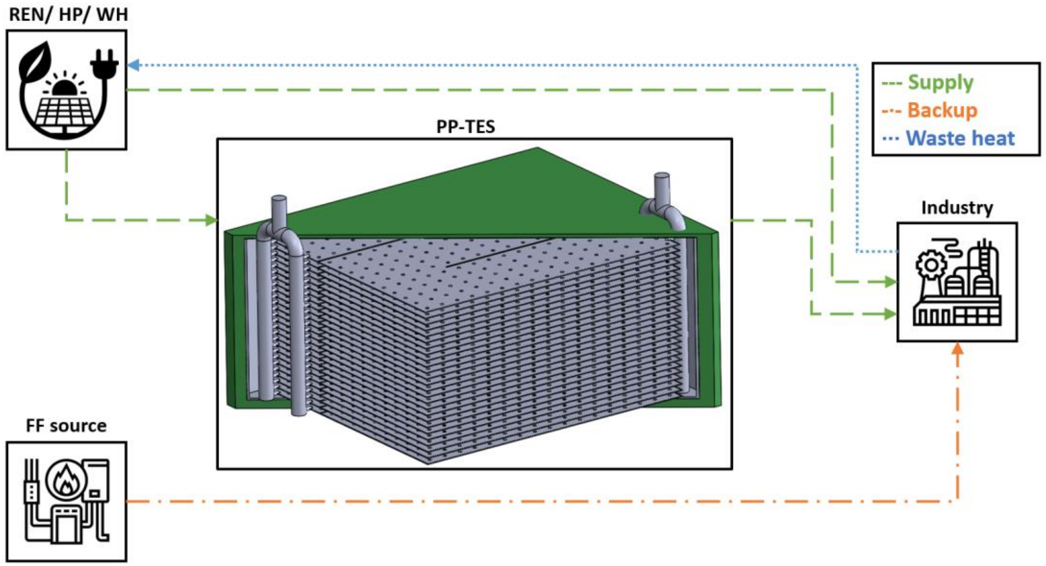
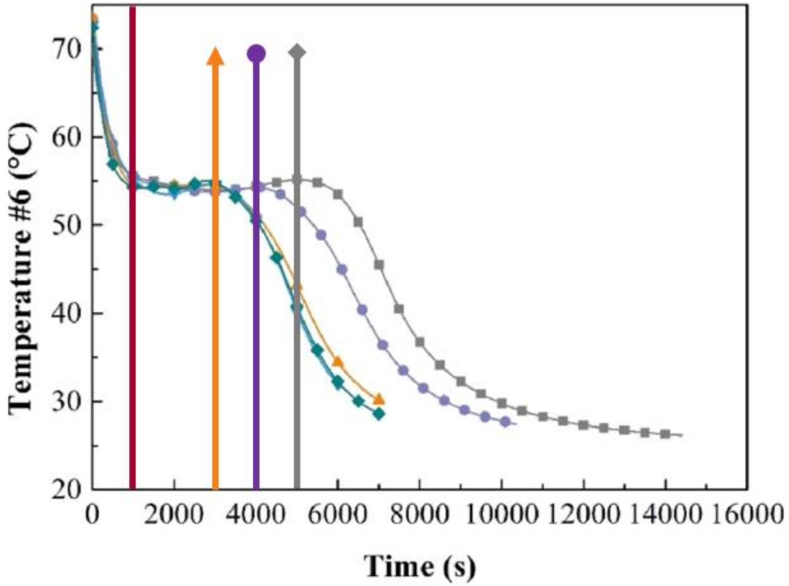


Typical Tout in Discharge



Charge/discharge rate [kW], Storage capacity [kWh], Costs [€/kWh], more…

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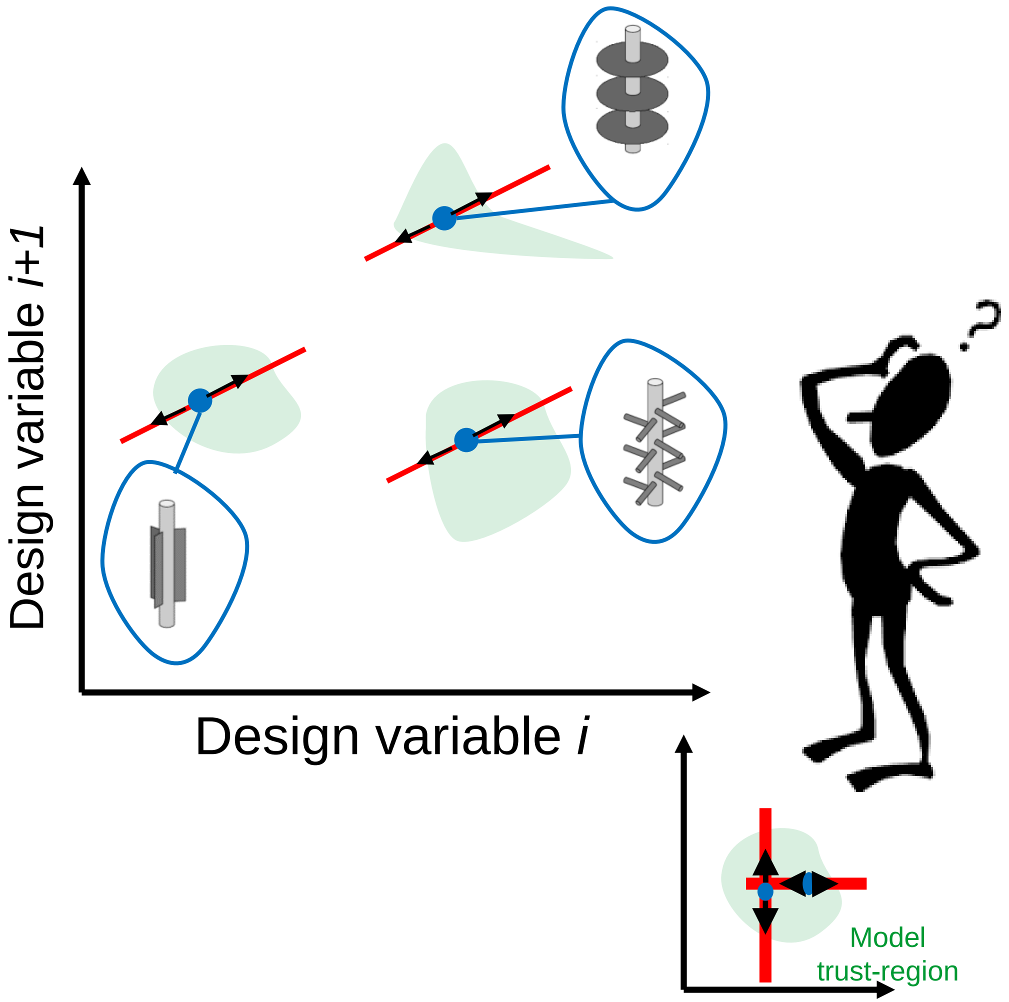
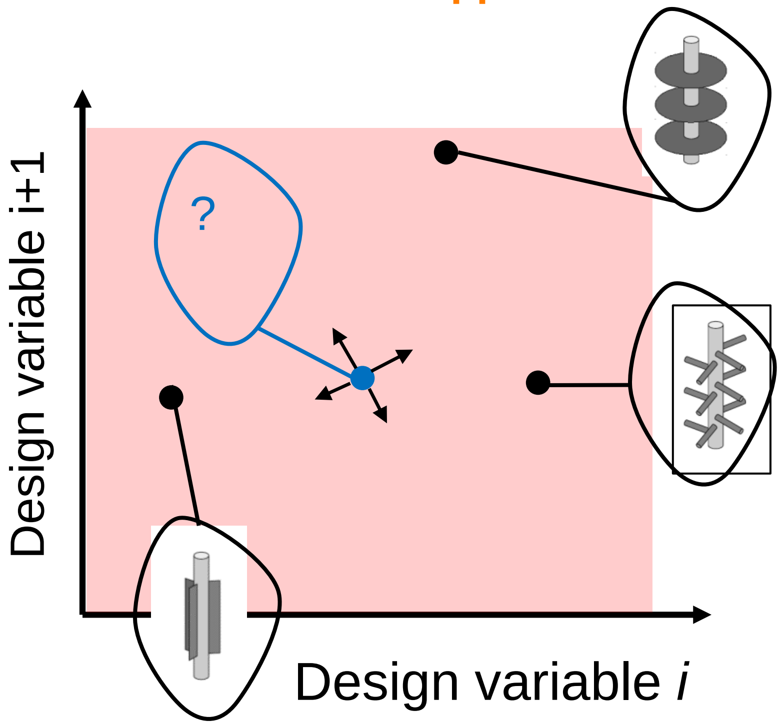
Conventional development vs non-parametric approach to LHTES

«Parallel» parametrizations

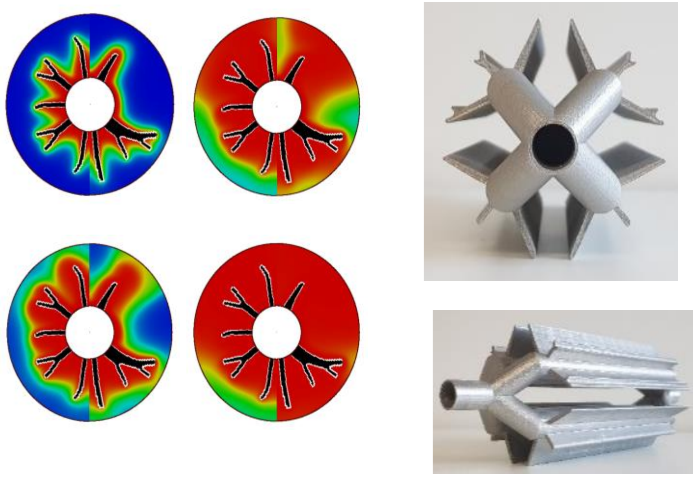


Continuous morphing optimization
Free of heuristic approach



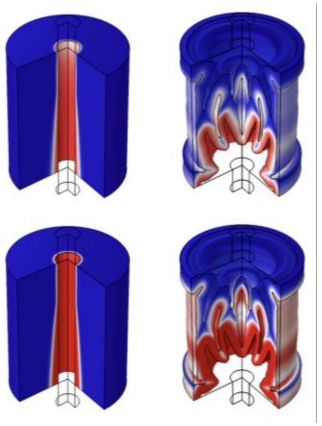
Conventional development vs non-parametric approach to LHTES

Phase changing material



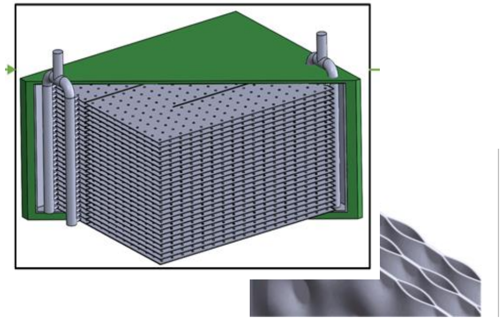
Ge R, […], **Sciacovelli**, A, Appl Therm Eng. 2020 & 2023 5;180:11

Thermochemical storage materials



Humbert G, **Sciacovelli**, A J Energy Storage 2024

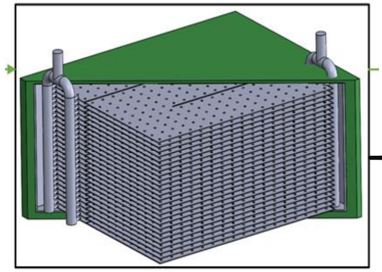
Phase changing material

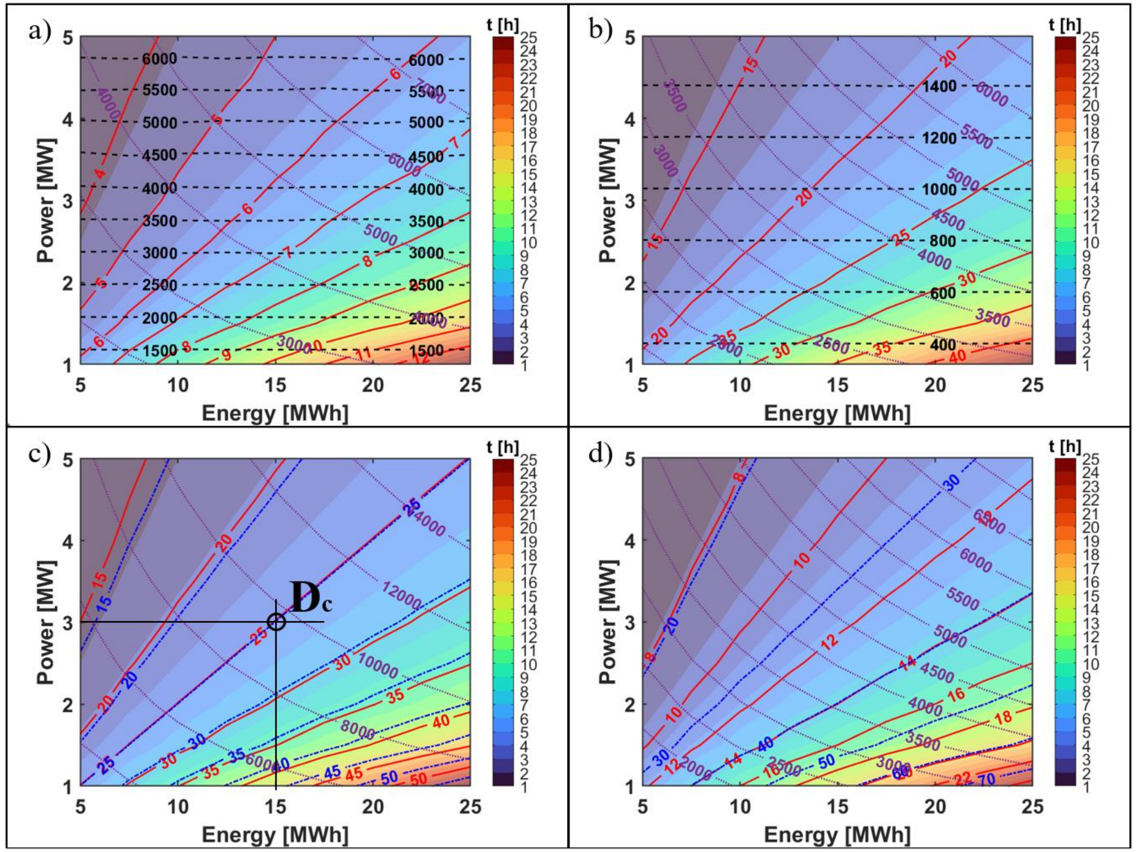


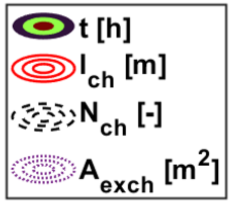
Niknam P, Ciappi L, **Sciacovelli** A, Appl Therm Eng 2024

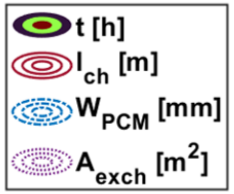
Conventional development vs non-parametric approach to LHTES

Systematic exploration of design space







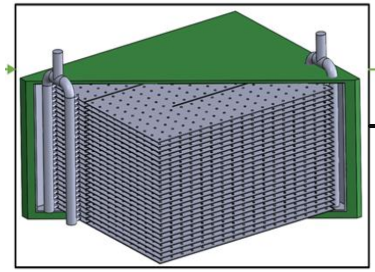


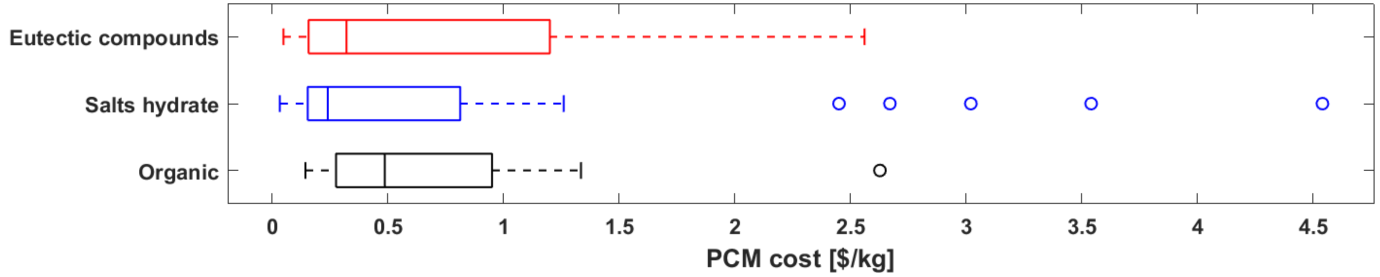
Discharge time
Channel length
Number of channels
Total heat transfer area
Spacing

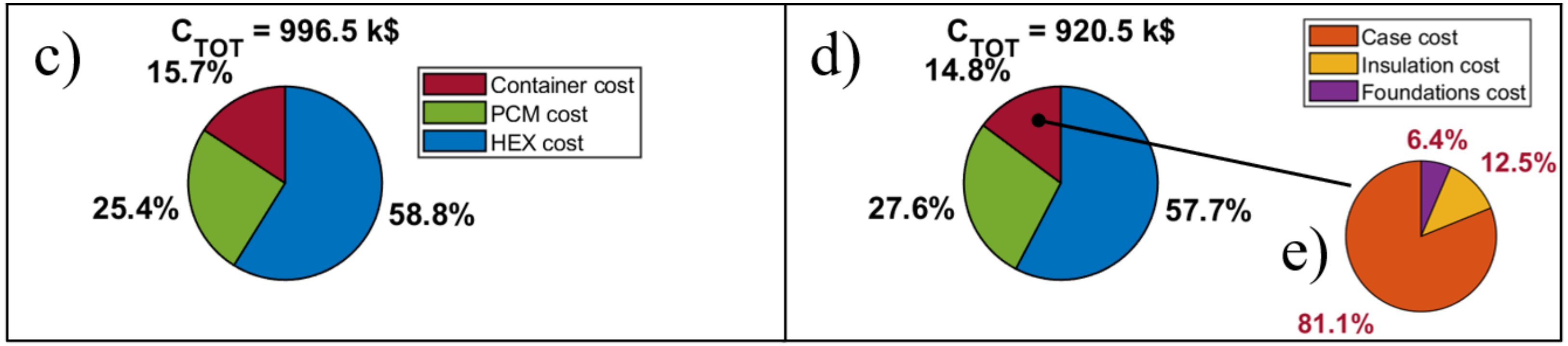
Figure 8: Thermal design maps. a) Eutectic compound PCM, ΔT=5°C, Tmelt=183°C. b) Eutectic compound PCM, ΔT=20°C, Tmelt=183°C. c) Organic PCM, ΔT=10°C, Tmelt=165°C, k_{PCM} = 0.19 W/m/K. d) Eutectic compound PCM, ΔT=10°C, Tmelt=183°C, k_{PCM}= 0.59 W/m/K.

Conventional development vs non-parametric approach to LHTES

Systematic exploration of the cost space







Costs breakdown

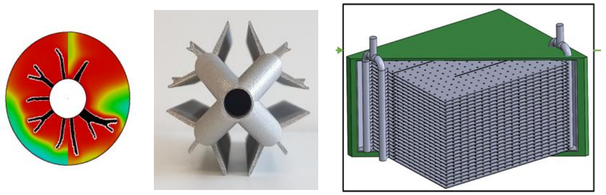
Cost competitiveness:

- Specialized thermo-dynamic conditions
- No easy alternatives (e.g. temperature level, safety, compactness, pinch-points)

Final remarks

Key to address:

- The physics of the challenge → understand and take advantage thermal processes
    - E.g. Latent heat for thermal energy storage



- The system point of view of the challenge
    - E.g. dynamic interactions between technologies and processes

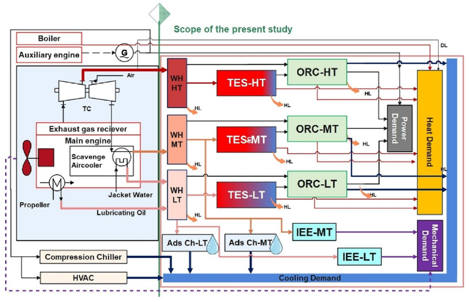
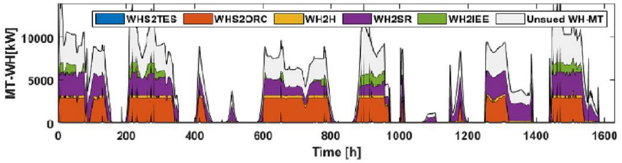


Fig. 6. Simplified Schematic of the onboard energy system with WHR technology.

- The thermo-economics of the challenge
    - E.g. rational and economic use of energy resources



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