Topologically Engineered Thermal Energy Storage for Carnot Batteries

Dr Adriano Sciacovelli

Associate Professor,

University of Birmingham, Birmingham, UK,

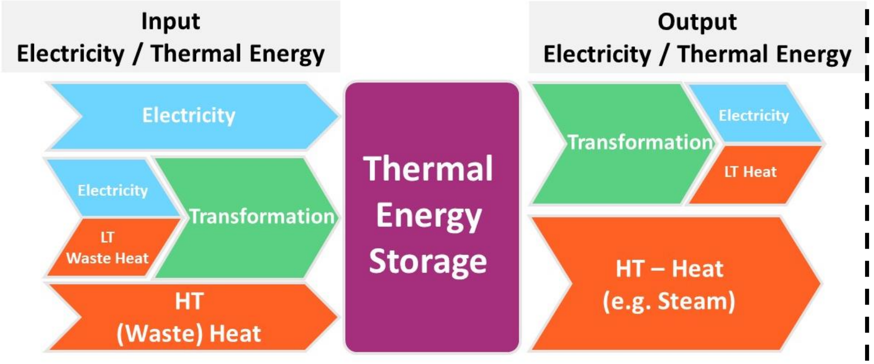
School of Chemical Engineering, Birmingham Energy Institute

a.sciacovelli@bham.ac.uk

Mix – MoXes

Carnot Battery

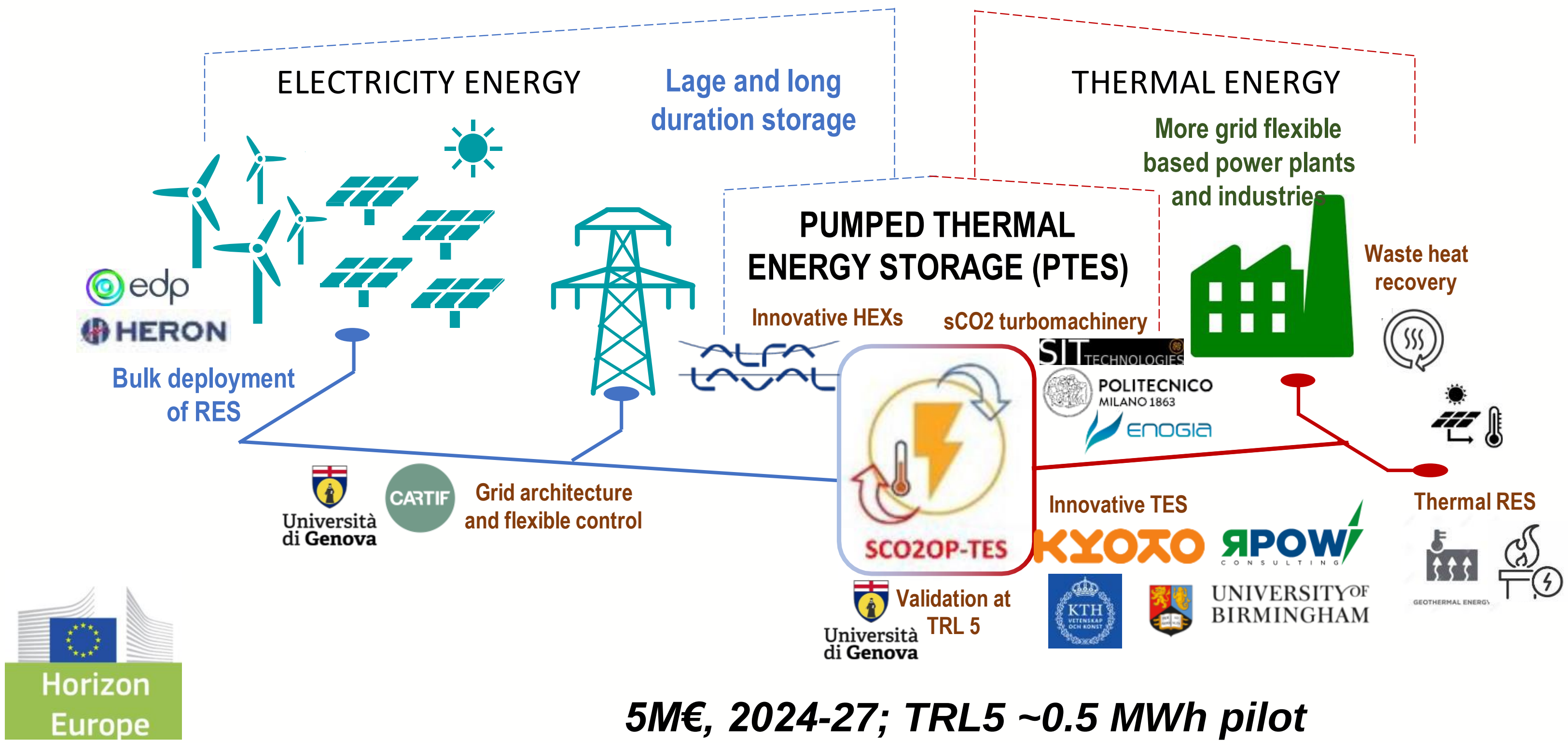
- **A “Multi-energy Hub” beyond Electricity-to-Electricity storage**
- For **industrial decarbonization**, energy districts, and grid storage



Technology Collaboration Programme

by iea *Task 44 Heat Integrated Carnot Batteries [2024-26]*

sCO_2 Operating Pumped Thermal Energy Storage for grid/industry cooperation

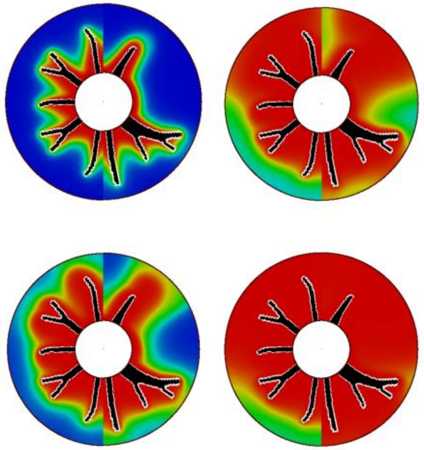


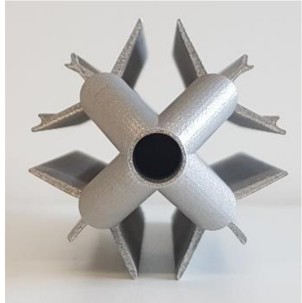
5M€, 2024-27; TRL5 ~0.5 MWh pilot

Thermal Energy Storage – Key component of Carnot Batteries

- **Growing evidence that "unconventional" TES configurations are beneficial/needed for CBs**
  - Use of advanced TES materials (PCMs, TCS); Strong coupling with operation fluid-machines (e.g. HP, ORCs, etc);

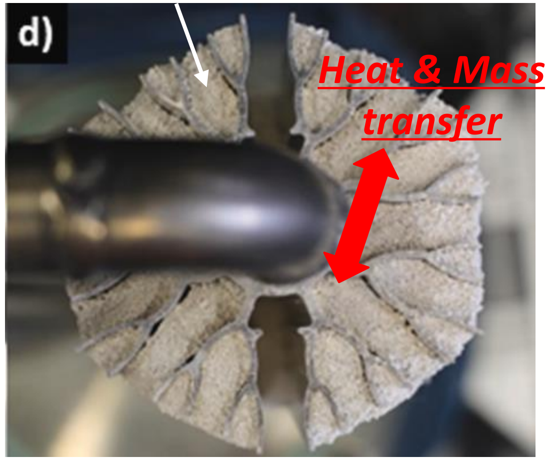
Thermal Energy Storage





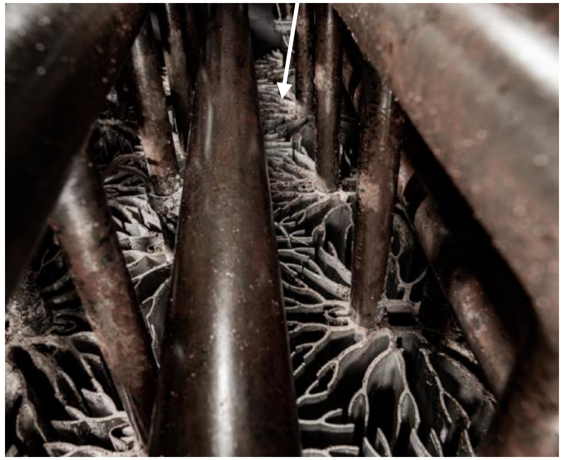
Ge R, [...], **Sciacovelli**, A, Appl Therm Eng. 2020 & 2023 5;180:11

Thermochemical storage materials



Stengler J, et al, J of H&M Transfer,, 2021

Phase changing material

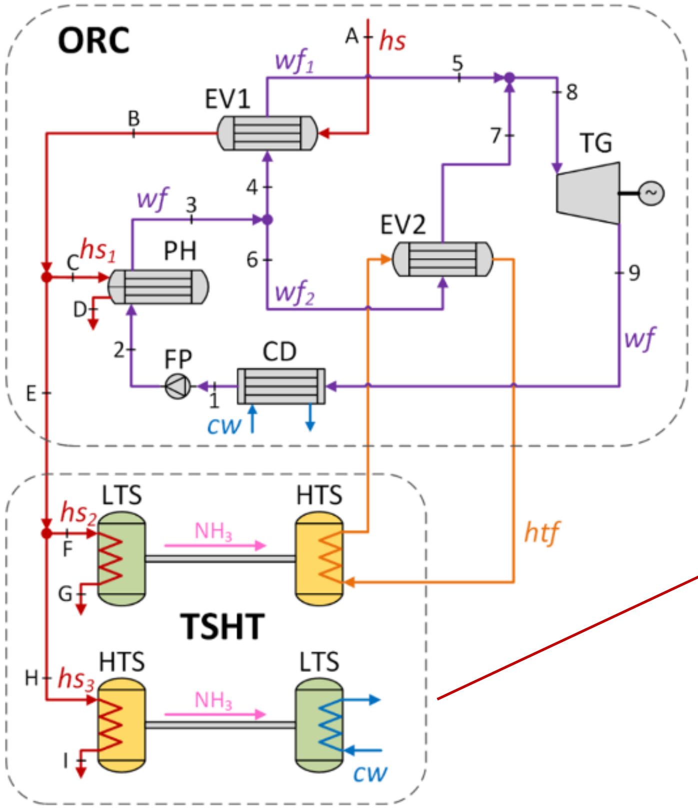


Johnson M, et al, DLR, 'Carnot Battery workshop', DLR, Stuttgart, 2022

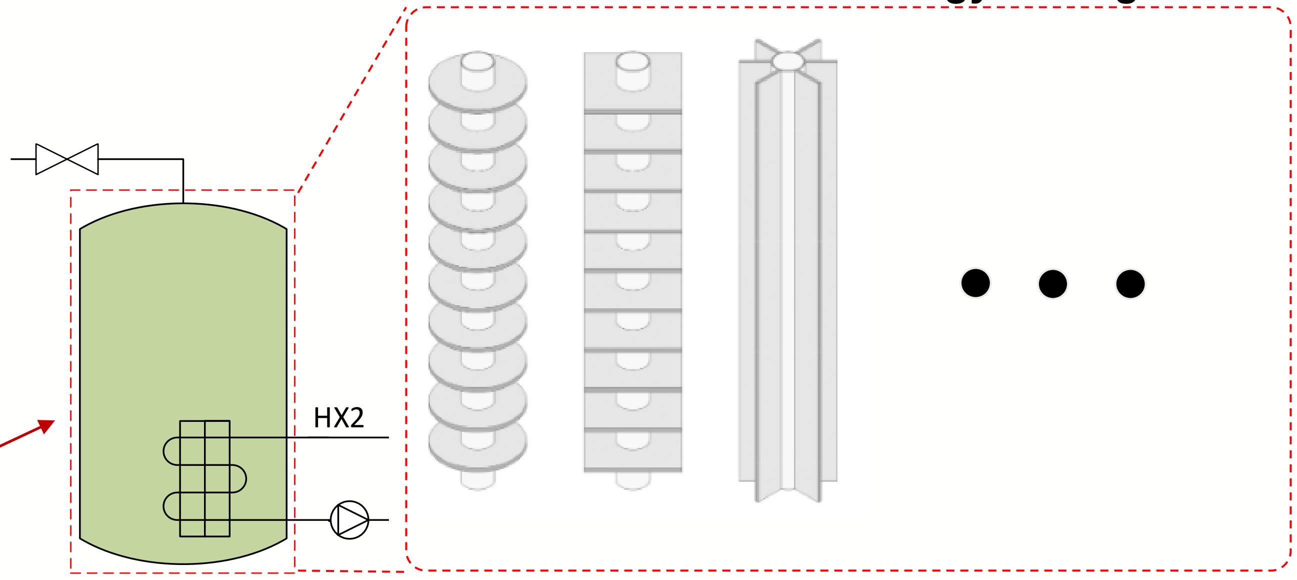
Topological Engineered Thermochemical Energy Storage (I)

- **At fundamental level transient heat and mass transfer govern the performance** ; (λ_{bed} ~ 0.2-1 W/m/K) ; (K_{bed} ~ 1E-10 - 1E-14 m^2)
- Theoretical performance of TCS systems are thermodynamic-path dependent

Carnot Battery



Thermo-chemical Energy Storage



$$A + B \leftrightarrow A \cdot B + \Delta H_r^0$$

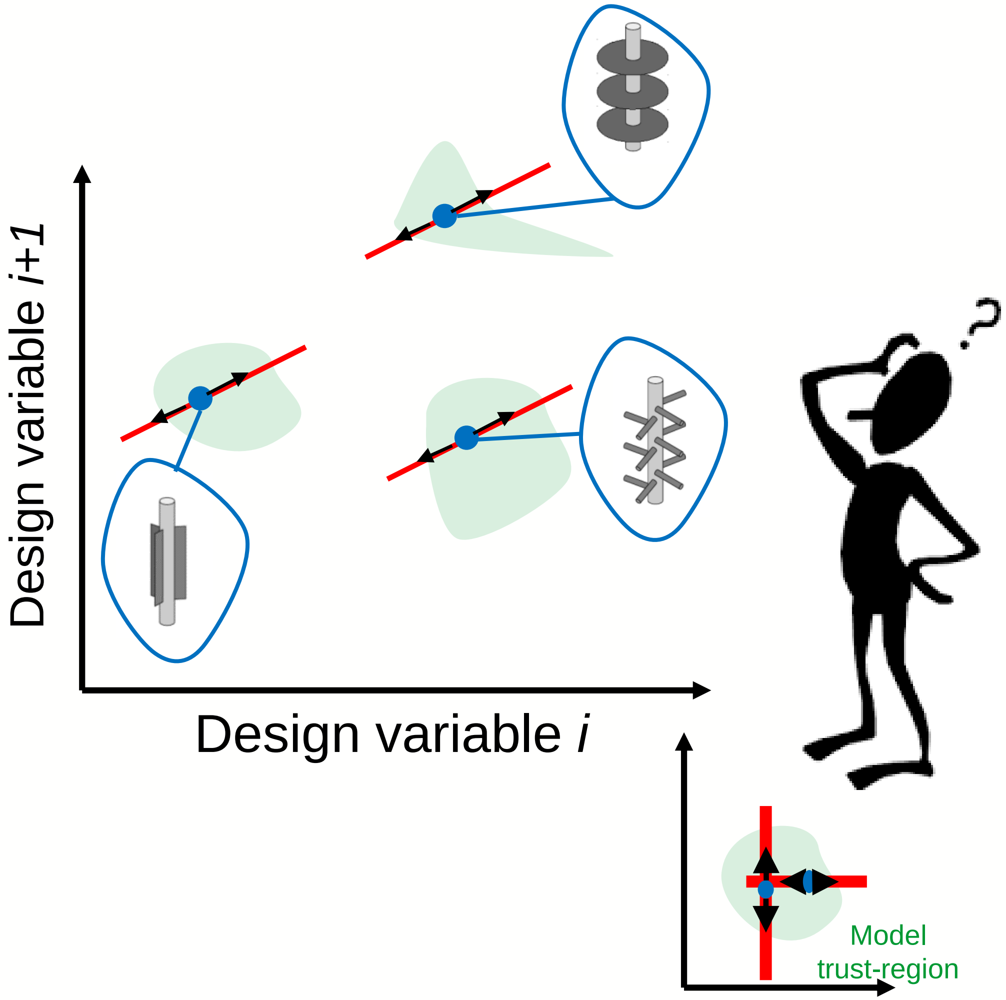
Sorbent : Hydrates salts, Ammoniate Salts

Sorbate: NH_3, $H_2O_{(g)}$, …

Refs: Manente G, […], **Sciacovelli A,** *Applied Energy* 2021, 15;304:117980. Humbert G, Ding Y, **Sciacovelli A**. *Applied Energy*. 2022 1;311:118633.

Traditional approach to TES development vs Top. Optimization

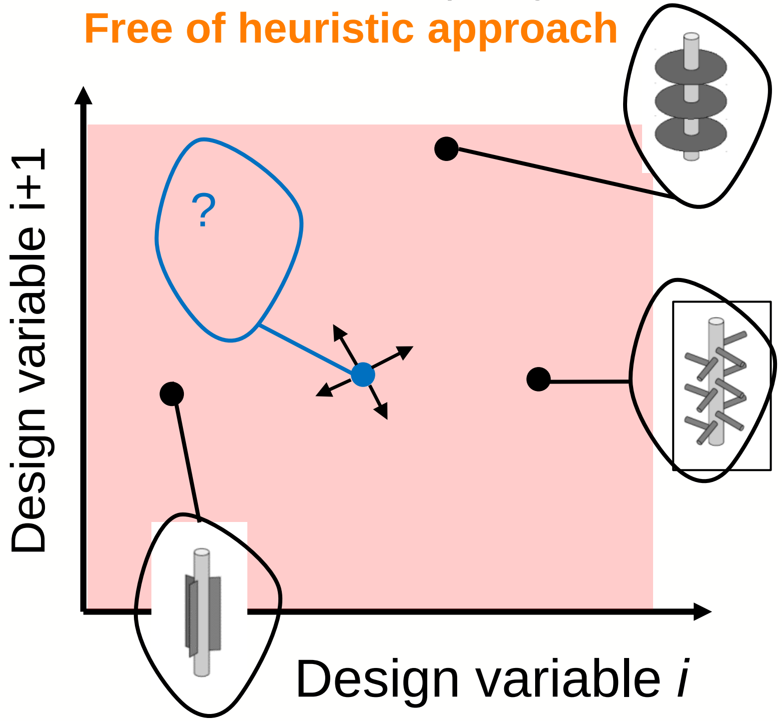
«Parallel» parametrizations



Topology optimization

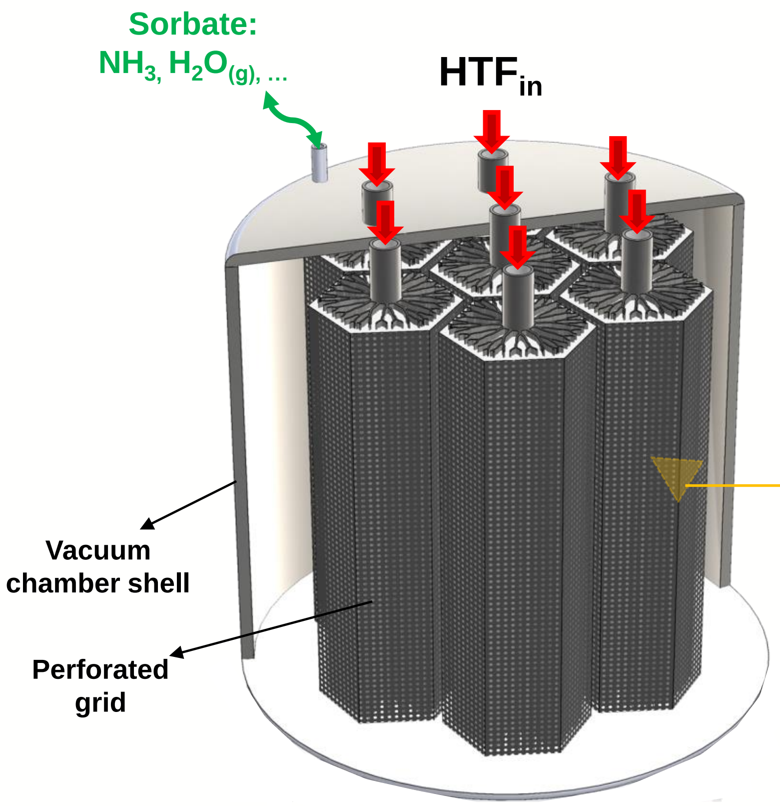
Continuous morphing

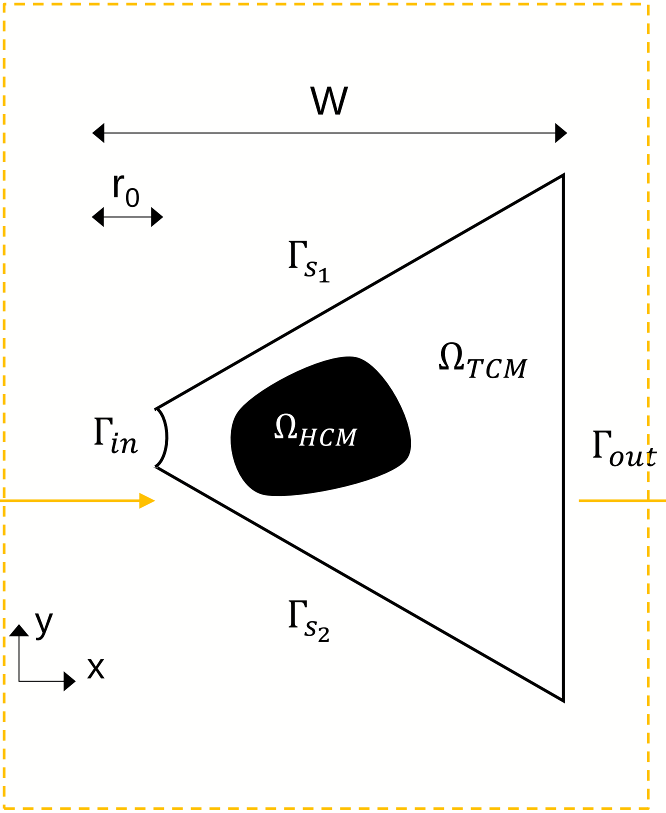
Free of heuristic approach

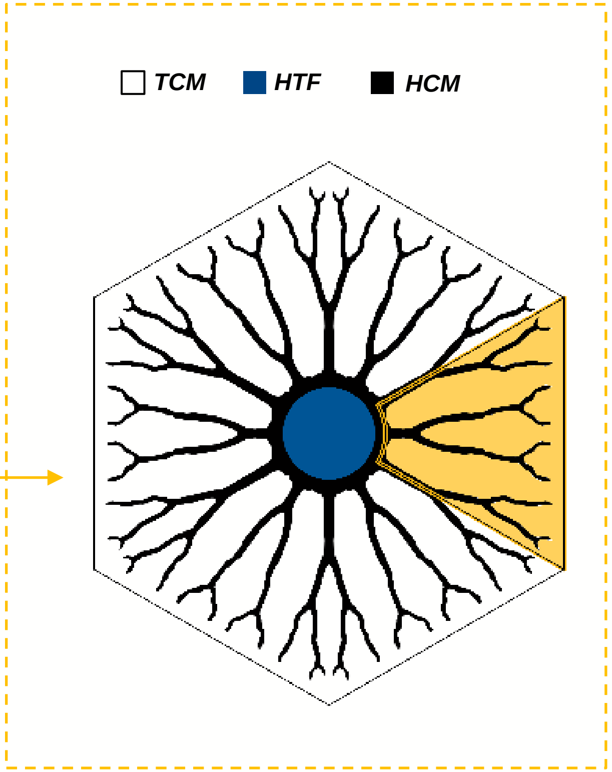


Topological Engineered Thermochemical Energy Storage (II)

- fundamental answer to: *what is the best conceivable TCS Reactor designs?*
- It also offer a novel approach to develop and optimize TCS reactors







The material distribution is the design variable

Humbert G, **Sciacovelli A**, *Journal of Energy Storage* 2023;64:107132.; Humbert G, Ding Y, **Sciacovelli A.** Applied Energy. 2022 1;311:118633; Pizzolato A, […], **Sciacovelli A**, *Energy* 2020 ;203:114797.

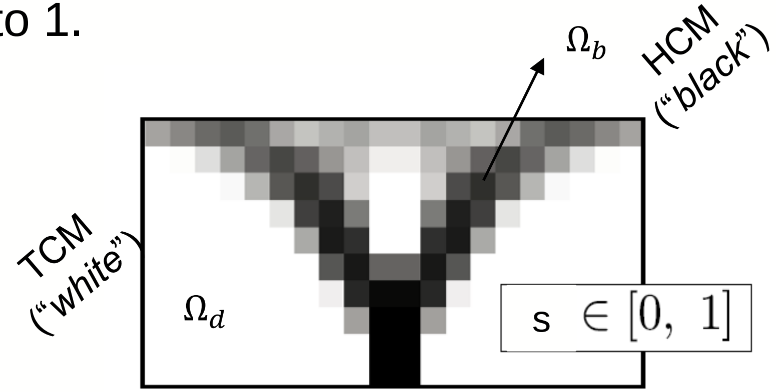
How to describe topology? Material distribution

- Material is described as a continuous scalar variable from 0 to 1.

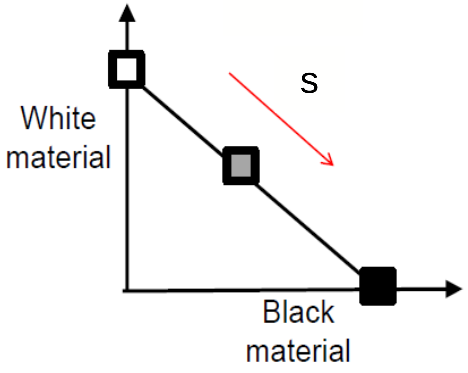
Density Approach [1]

$$s = \begin{cases} 1 & \forall\, x \in \Omega_b \\ 0 & \forall\, x \in \Omega_d / \Omega_b \end{cases}$$

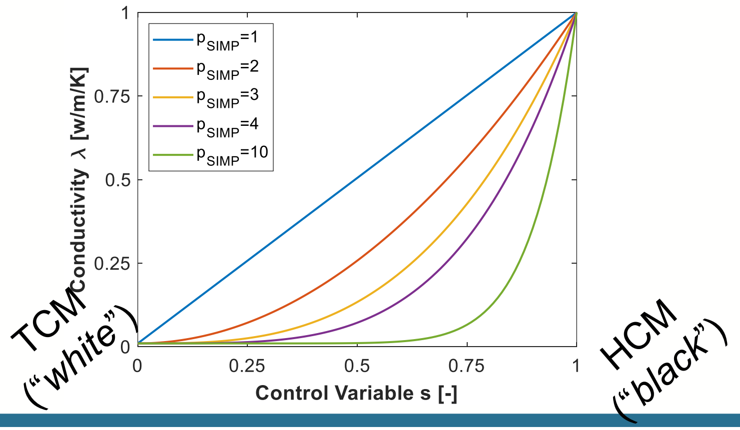
Smoothing description



- The use of a continuous variable allows for gradient-based optimizers, which are computationally robust. However, artificial laws need to be adopted for intermediate material properties:



Material interpolation



Pizzolato A, […], **Sciacovelli A**, *Energy* 2020 ;203:114797. Humbert G, **Sciacovelli A**, *Journal of Energy Storage* 2023;64:107132;
[1] M.P. Bendsoe, O Sigmund, 2002

The local physics of the problem → now it is design-dependent

- The description of material distribution is fully embedded into the physical description of the problem

Design-dependent Diffusivity

Design-dependent Reaction rate

Mass conservation

$$\varepsilon\,(s)\frac{\partial(c)}{\partial t}+\mathbf{u}\nabla c=\dot{m}(\alpha(\dot{s}))$$

Design-dependent Permeability

Darcy law

$$\mathbf{u}=-\frac{K(s)}{\mu}\nabla p$$

Design-dependent Thermal diffusivity

Design-dependent Thermal conductivity

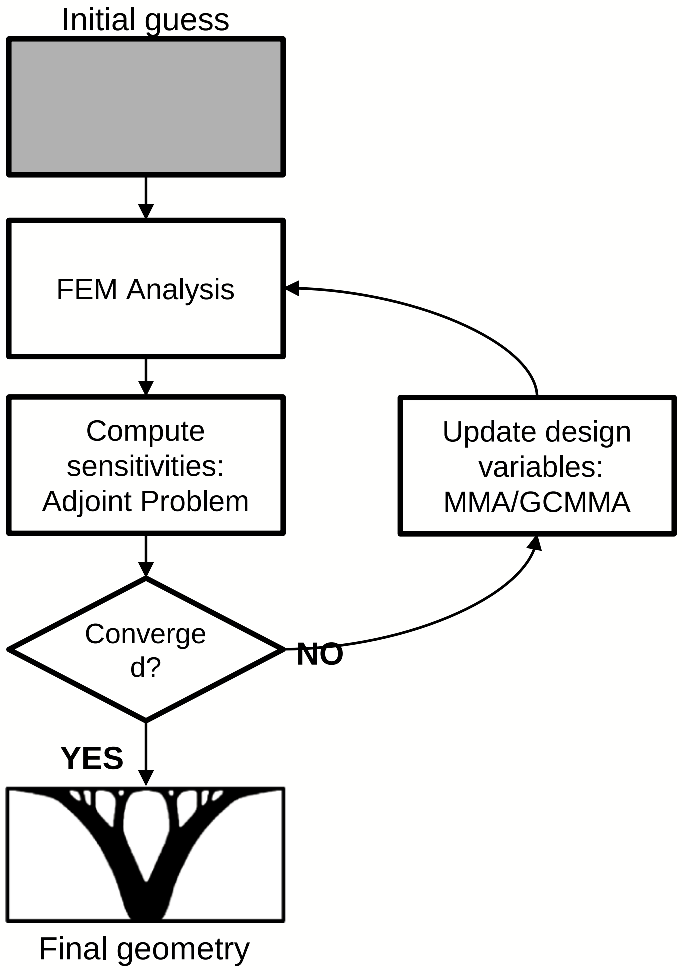
Energy Equation

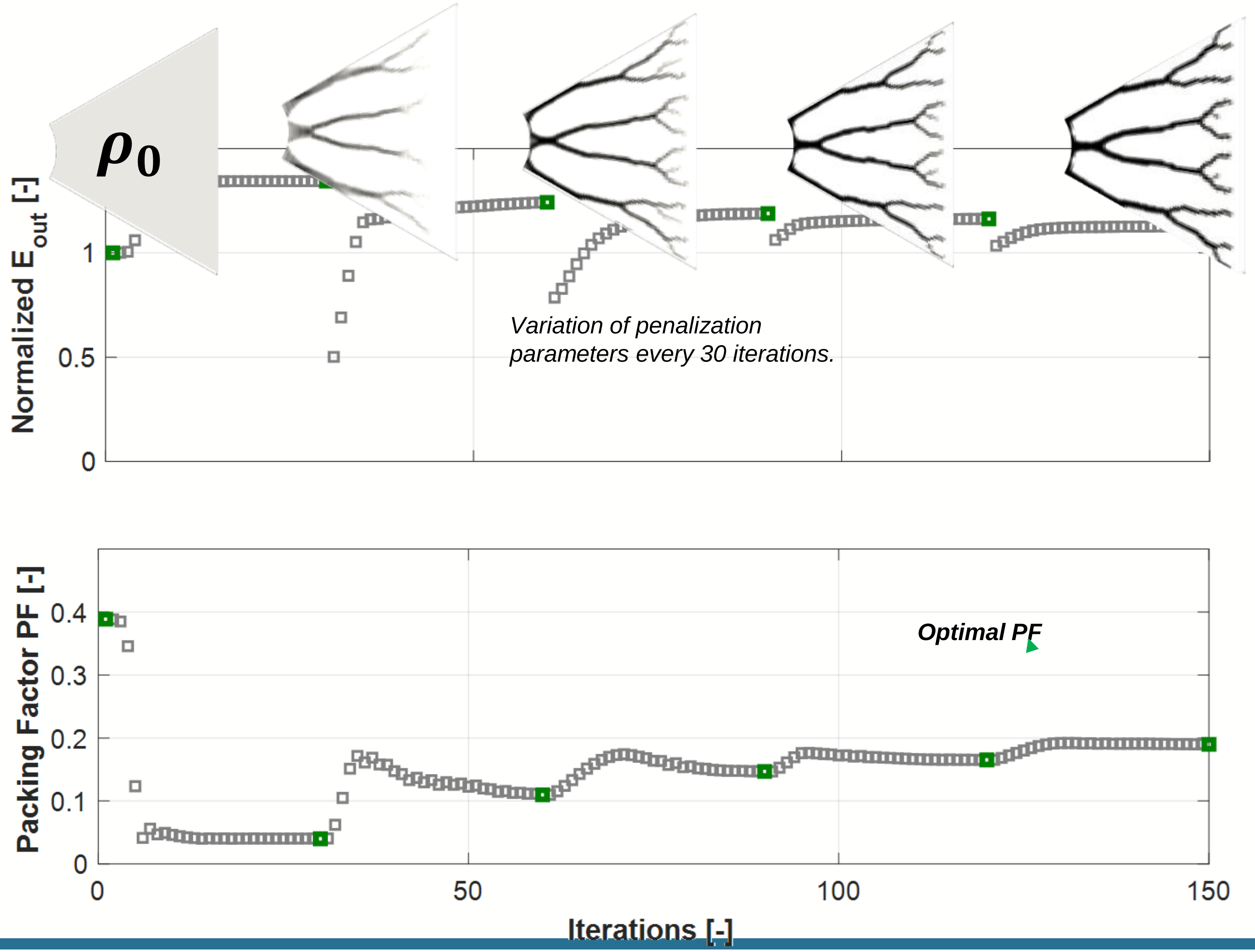
$$\mathrm{C(s)}\frac{\partial \mathrm{T}}{\partial t}+\nabla\cdot(\lambda(\mathrm{s})\nabla T)=\dot{\mathrm{q}}(\alpha(\dot{s}))$$

Reaction kinetics

$$\dot{\alpha}=k_{cin}\,(1-\alpha)\left(T_{eq,hydr}(p)[K]-T\,[K]\right)^{1.79}g(s)$$

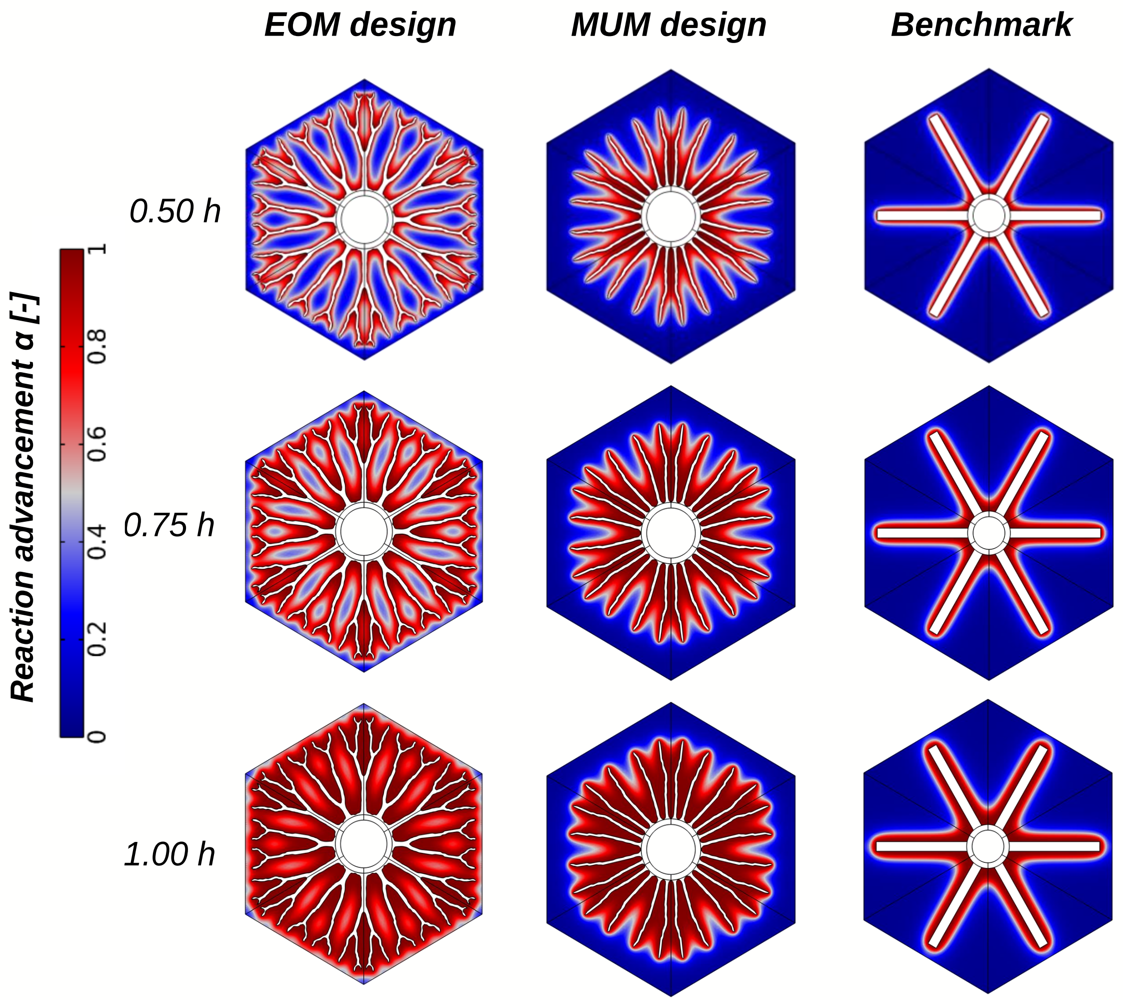
Putting everything together into suitable optimization algorithm: Design evolves freely – no initial guess

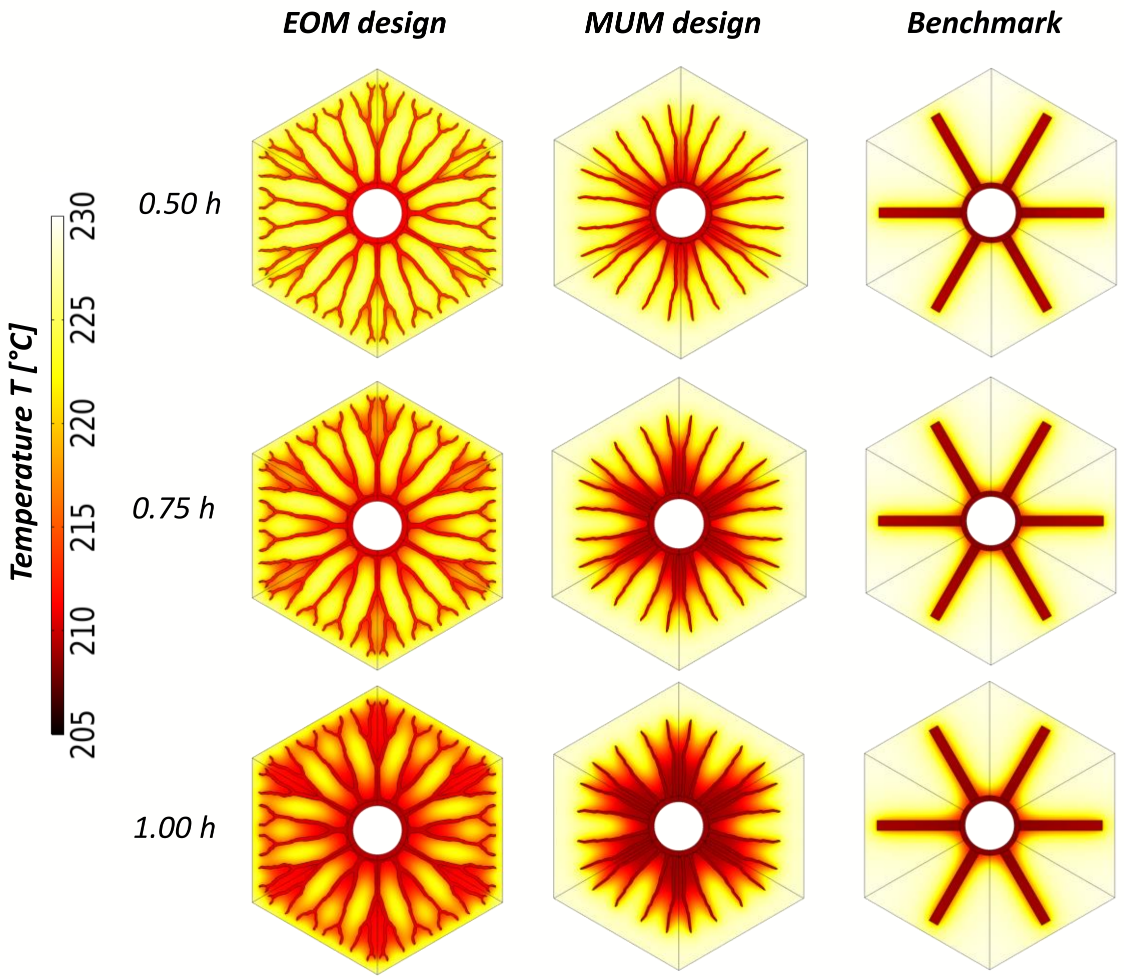




Topological Designs outperform traditional configurations (I)

For the MUM problem: Packing factor is 10% (as benchmark). The EOM problem generated a packing factor of 18%.

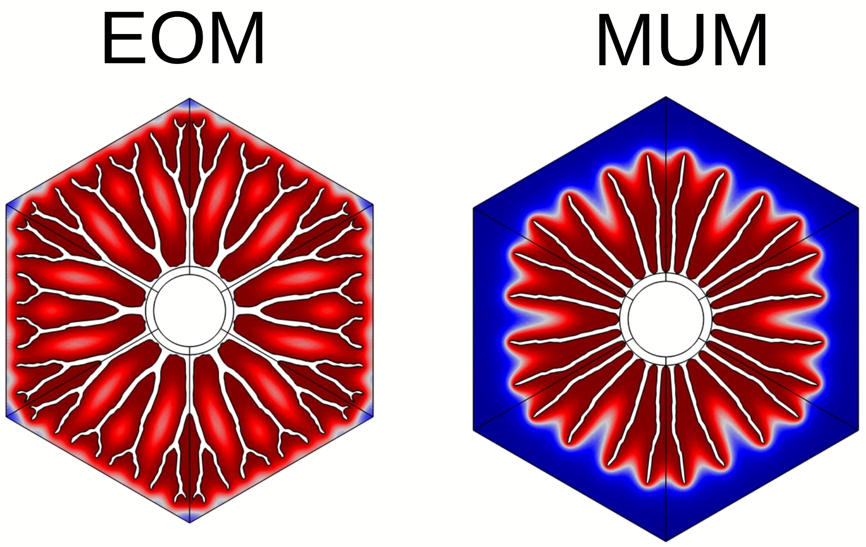




Humbert G, **Sciacovelli A**, *Journal of Energy Storage* 2023;64:107132. Ge R, [..], **Sciacovelli A**, *Applied Thermal Engineering,* 2020;180:115878; Pizzolato A, […], **Sciacovelli A**, *Energy* 2020 ;203:114797.

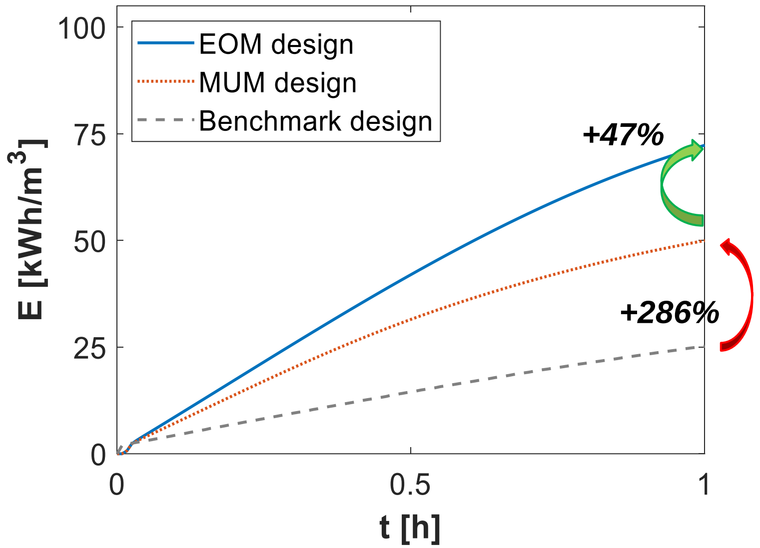
Larger amount of material for heat Exchanger improves effective energy storage density

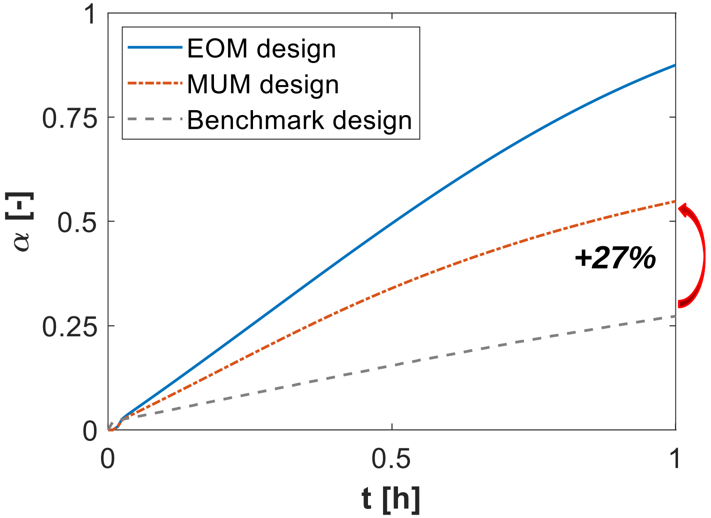
EOM allows higher effective energy storage density even if the amount of HEX material is higher (i.e. less thermochemical storage material)



(a) $\Omega_{HCM} = 18\%$ (optimal)

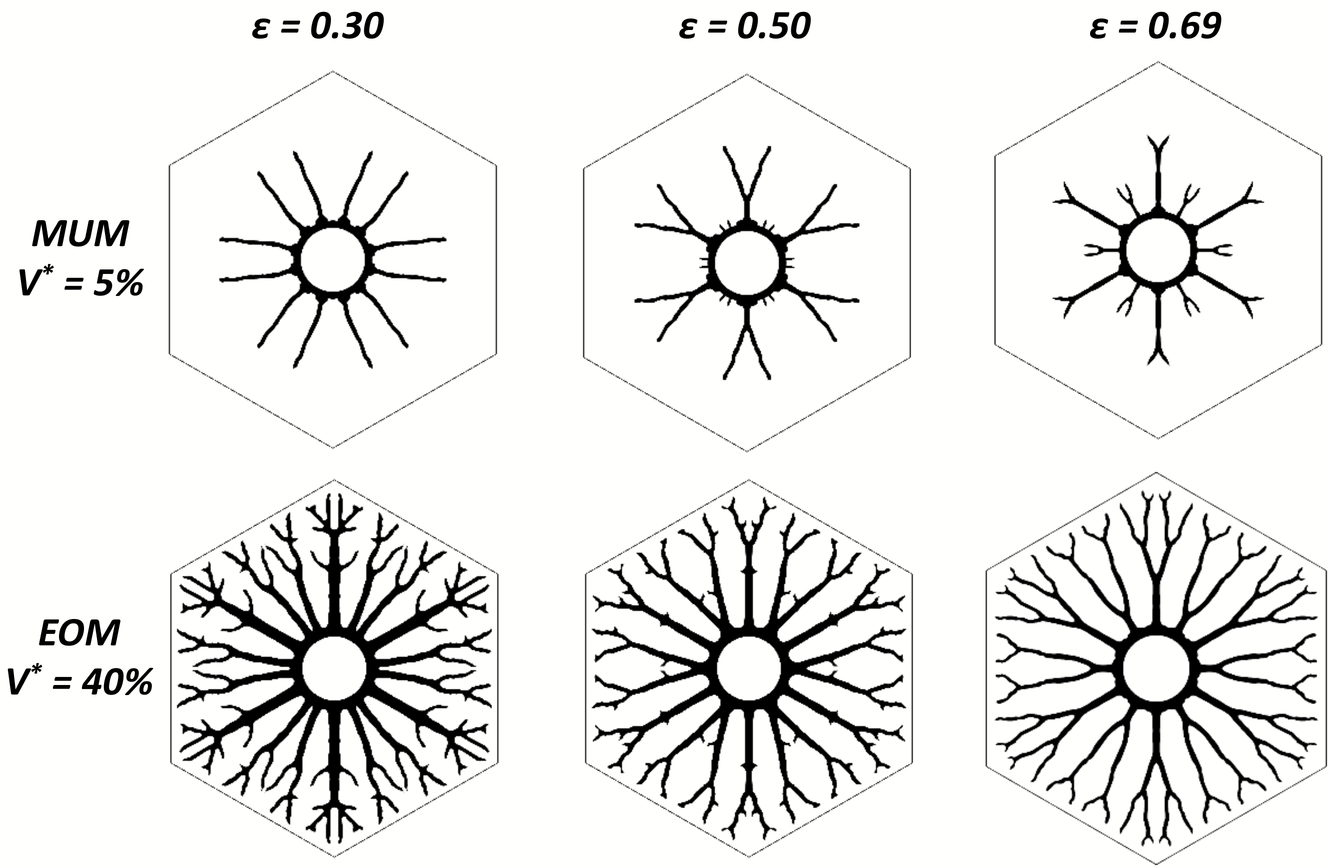
(b) $\Omega_{HCM} = 10\%$ (prescribed)

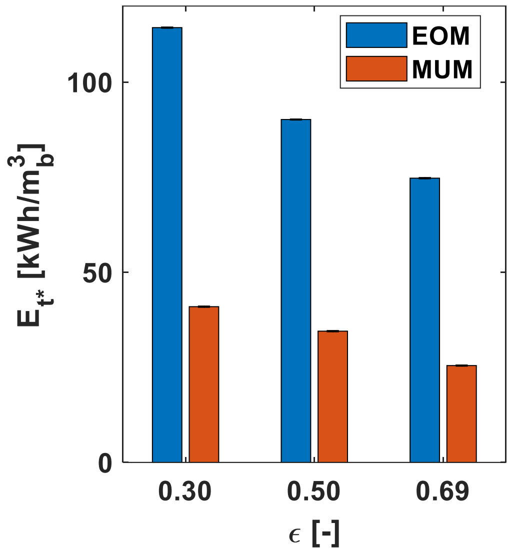




Influence of design factors is automatically accounted → example: Effect of material porosity on topology

- Lower amount of HEX material and thicker fins are preferrable for less packed materials (lower porosity).



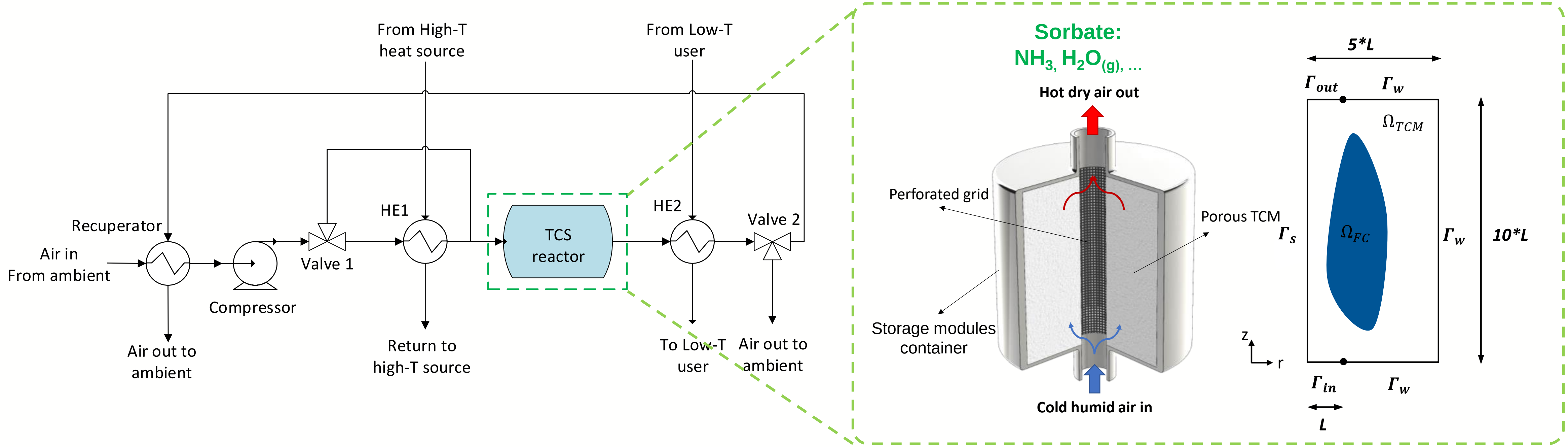


	EOM		
ε [-]	0.30	0.50	0.70
Ω_{HEX} [%]	0.27	0.21	0.18

Humbert G, **Sciacovelli A**, *Journal of Energy Storage* 2023;64:107132. Humbert G, **Sciacovelli A**, *ECOS 2022 Conference Proceedings*

Topological engineering for thermo-fluid problems: Generality

- TO generality: **discovery of designs for whole class of thermo-fluid problems**
  - **Example:** open TCS reactors



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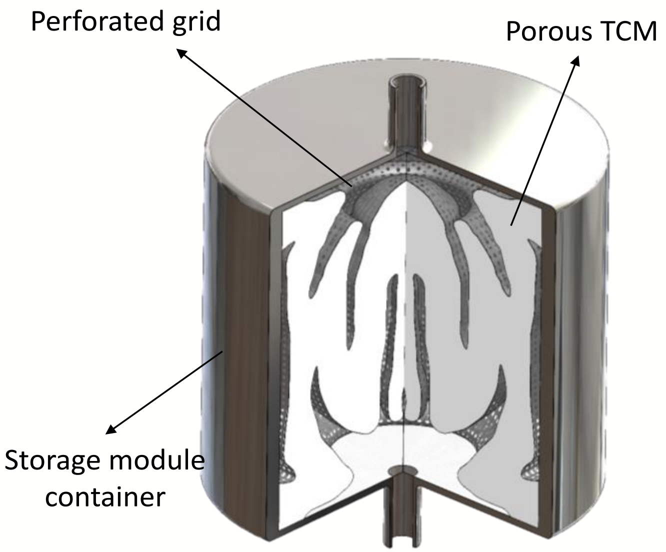
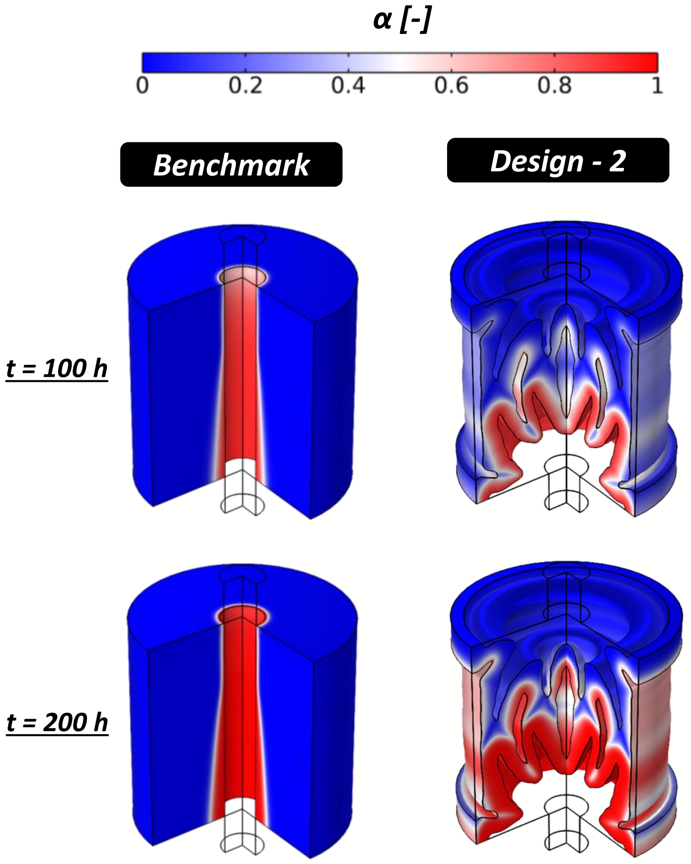
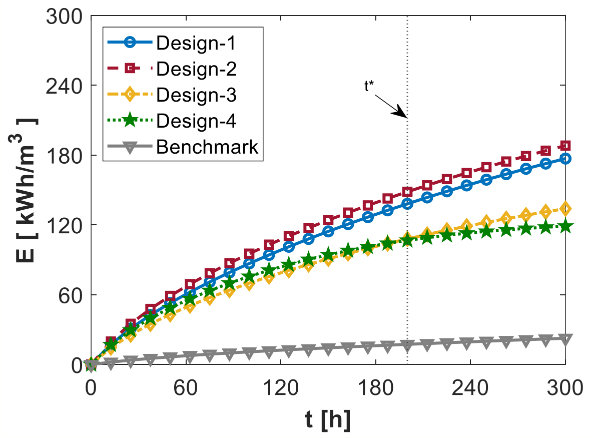
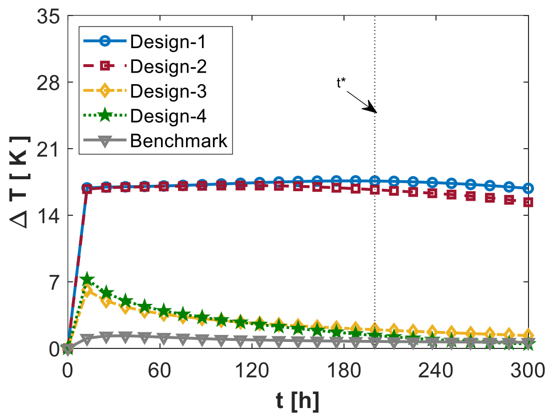
Topological Designs outperform traditional configurations (I)









$$\eta_{ex} \rightarrow +210\%$$

Humbert G, **Sciacovelli A**, *Journal of Energy Storage* 2023;64:107132.

Wrap up - Contributions

- Offers a novel approach to find optimal TES configurations *It demonstrated that configurations found outperform traditional devices by ~50 – 250%*

- Provides new insight on what fundamentally governs optimal performance, and demonstrated that some ‘established’ general guidelines are NOT true in general

- Demonstrate that advancements at component-scale (HEXs, reactor) are essential and that there are ample margins to gain

Dr Adriano Sciacovelli

University of Birmingham, Birmingham, UK,
a.sciacovelli@bham.ac.uk

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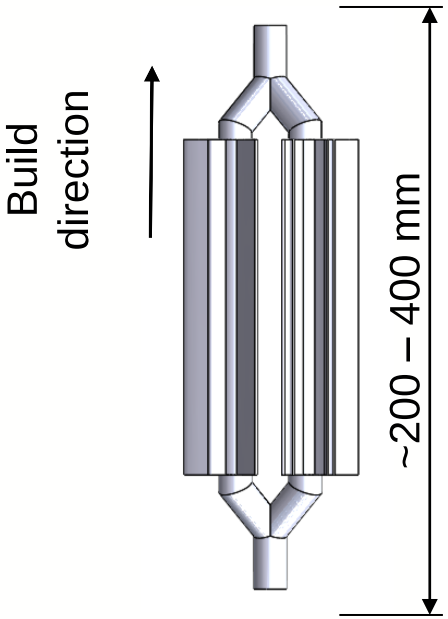
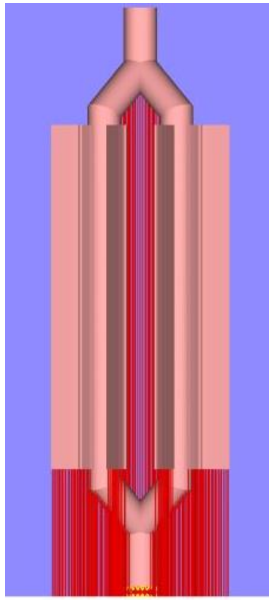
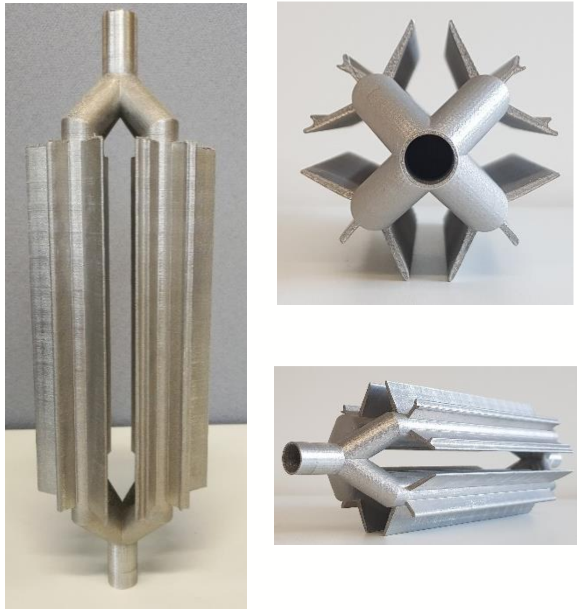
Topology optimization & Additive manufacturing

- AM HX will be bigger and bigger & faster and faster
  - ‘Old’ 3D printers (2018): X-Line (US), MetalFab (Netherlands), TS500 (China): ~ 500 x 500 x 500 mm^3
  - New 3D (2023): Sapphire/Velo 3D (US), NXG XII (DE), M1250: 1200 x 1200 x 1200 mm^3 & 12 lasers

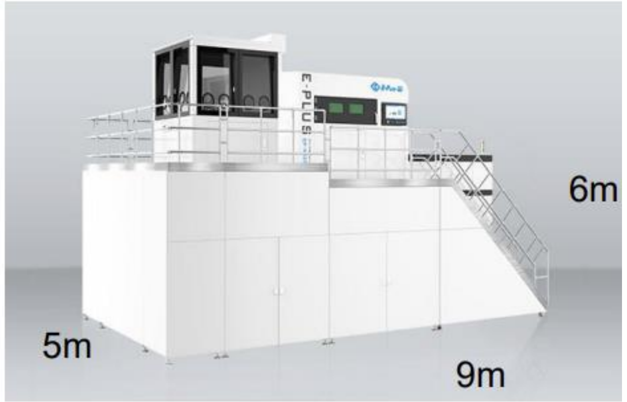




Support generation



Finished part



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