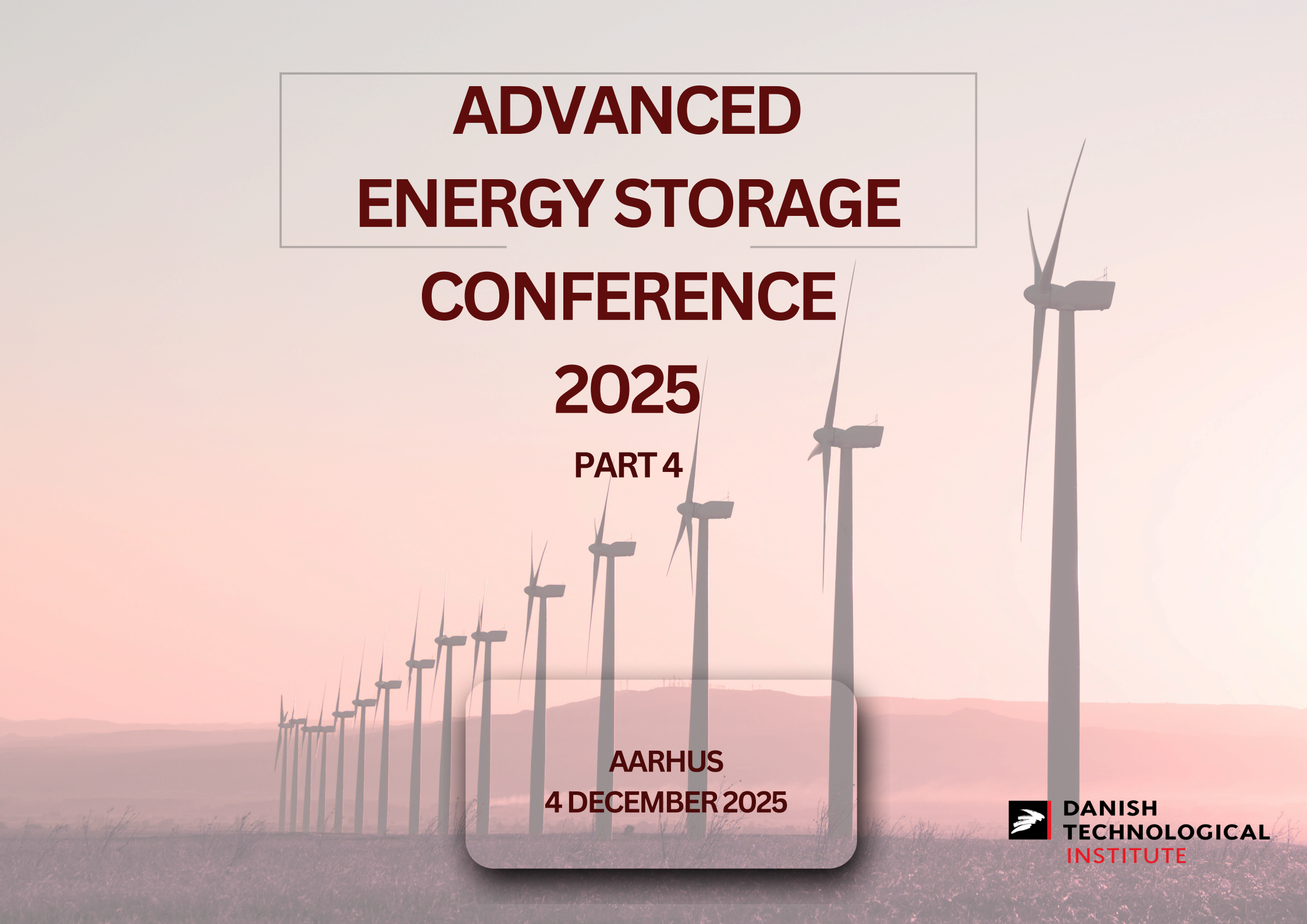
ADVANCED ENERGY STORAGE CONFERENCE 2025

PART 4

AARHUS
4 DECEMBER 2025



DANISH TECHNOLOGICAL INSTITUTE

THE CONFERENCE IS SUPPORTED BY

The conference is supported by the Danish Agency for Higher Education and Science under the Ministry of Higher Education and Science.

Ministry of Higher Education and Science Denmark

The conference is also supported by Danish Center for Energy Storage (DaCES)

DaCES Danish Center for Energy Storage

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DANISH TECHNOLOGICAL INSTITUTE

ADVANCED ENERGY STORAGE CONFERENCE 2025

Coupling Steam Production and Thermal Storage for the Process Industry

Kurt Engelbrecht, Danish Technological Institute

Coupling steam production and thermal storage for the process industry

Advanced Energy Storage Conference

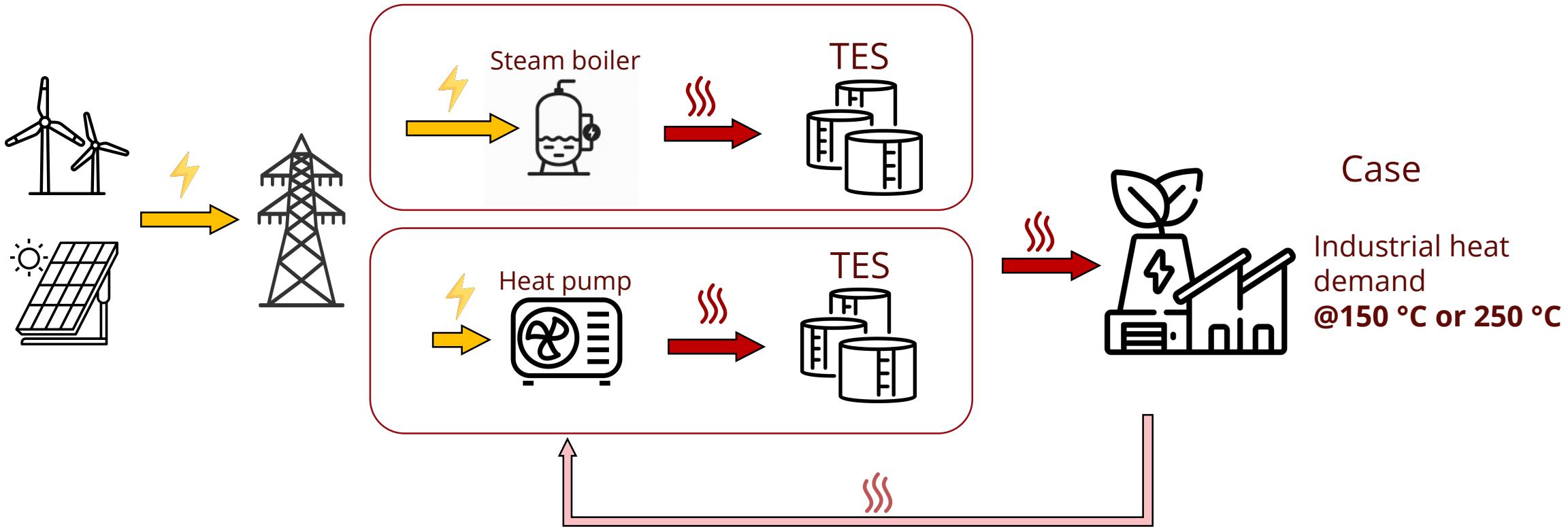
4 December, 2025

Kurt Engelbrecht

Francesco D’Ettorre

CHASE project foundation

Options investigated in this study as part of the CHASE project:



Case

Industrial heat demand
@150 °C or 250 °C

CHASE partners

TEKNOLOGISK INSTITUT

novo nordisk®

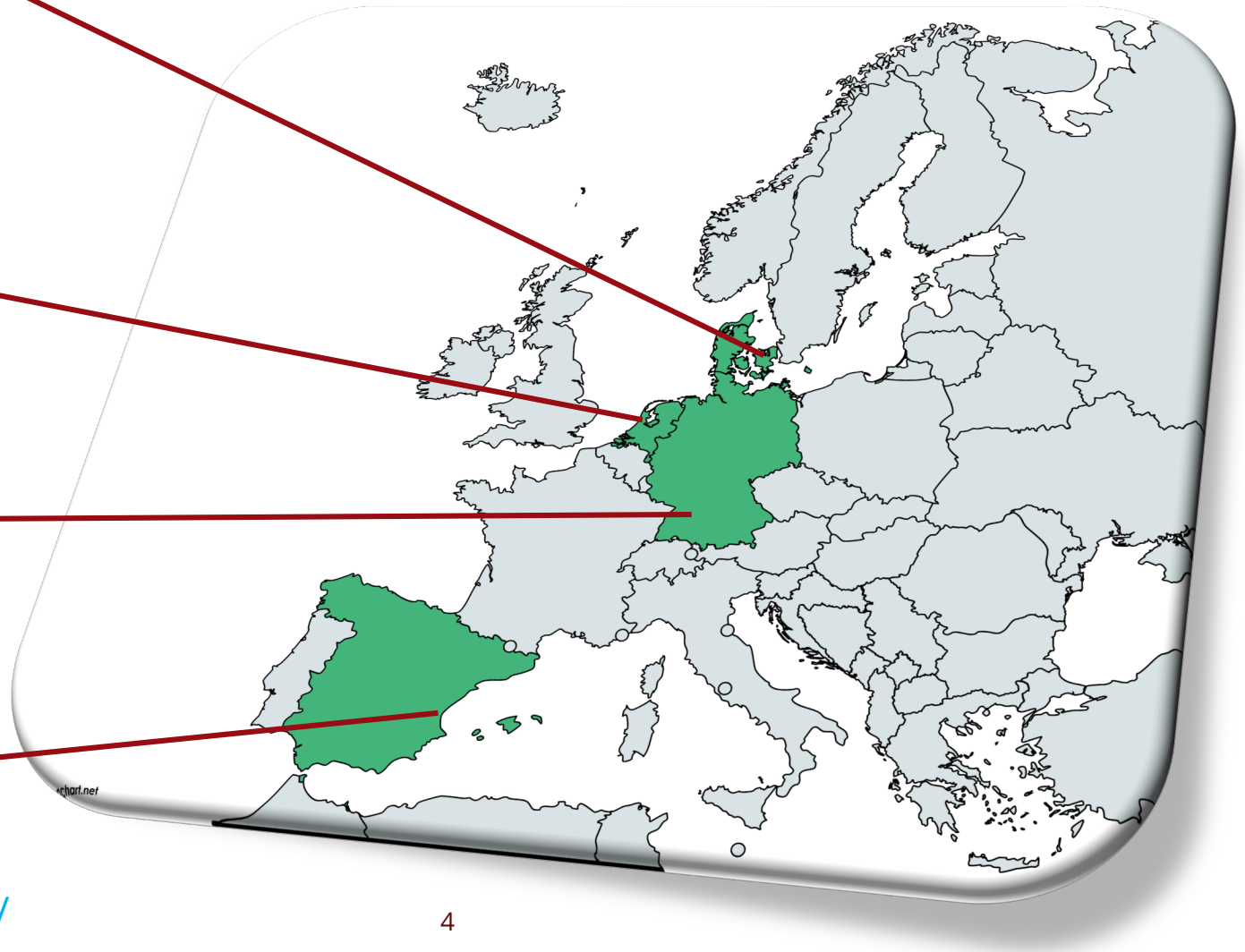
TNO

Standard Fasel

TRESPA

DLR

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

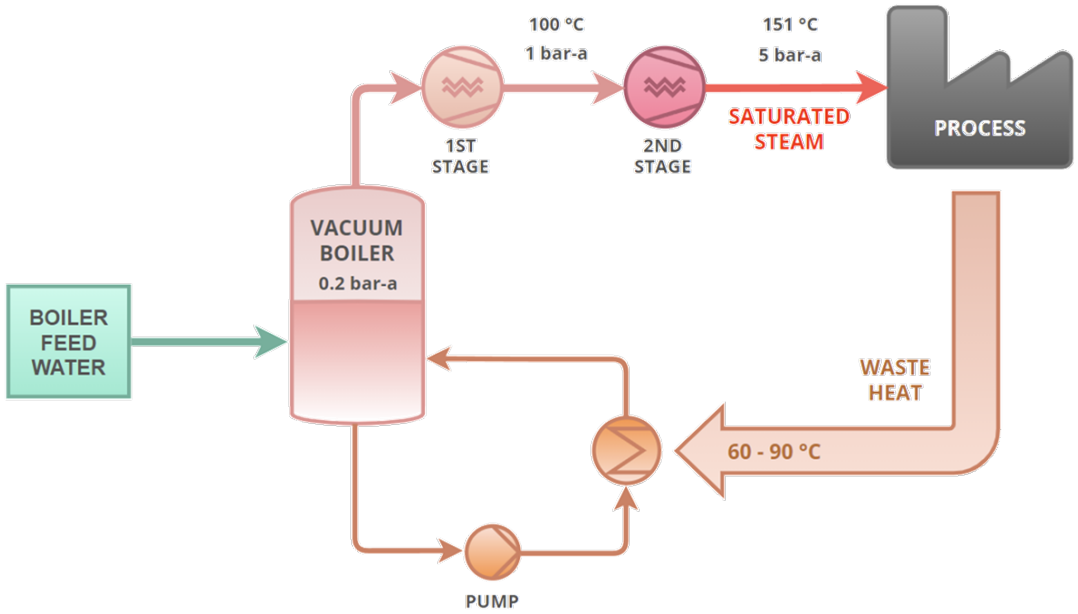


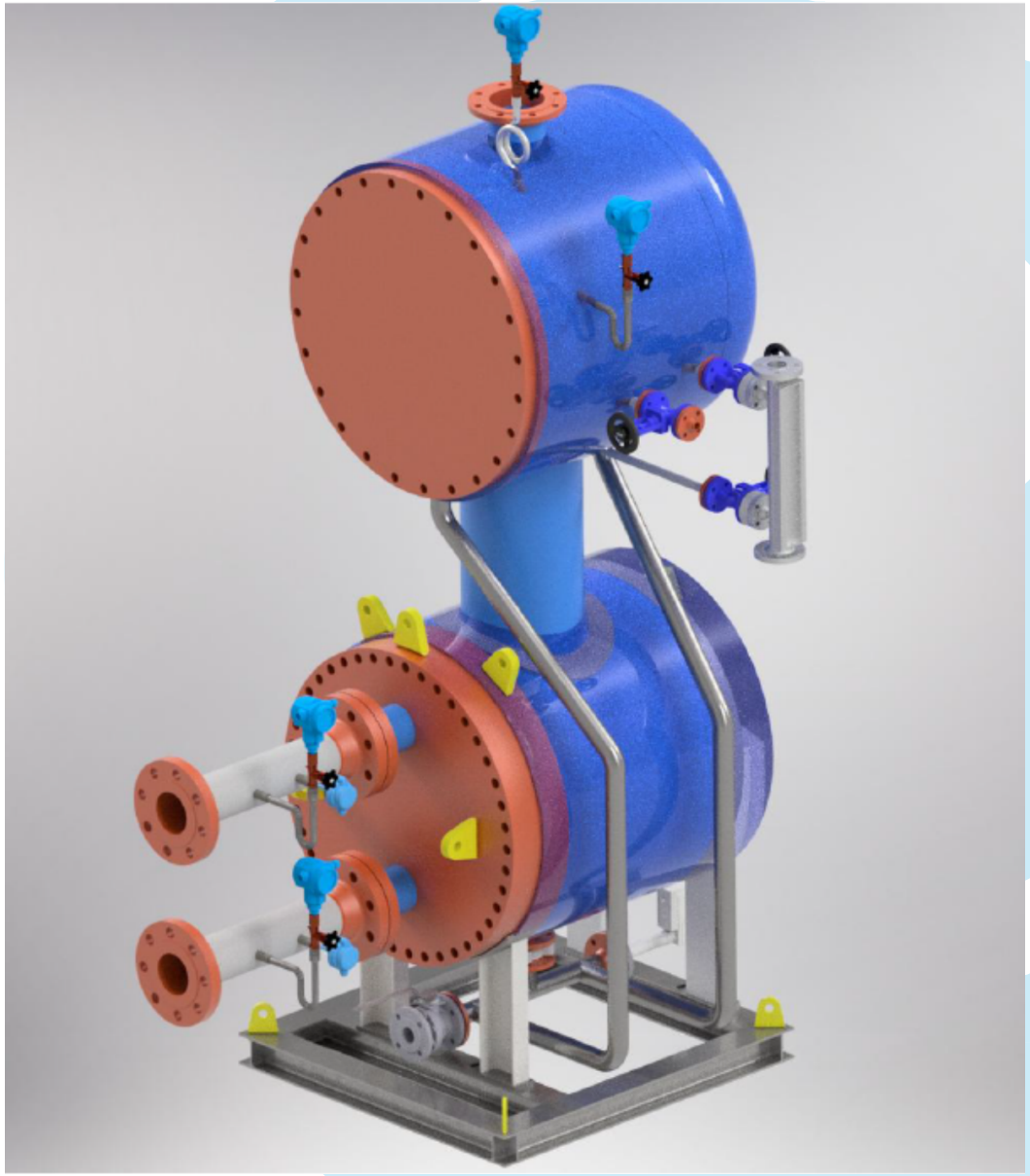
https://chase4heat.eu/

Standard Fasel

Vacuum Boiler 2.0

- Produces 5 bar(a) steam
- Water as the refrigerant
- Shell & plate heat evaporator
- Controlled circulation ratio to handle boiling suppression
- Water/vapor separation by top drum





Babcock Wanson Group

Standard Fasel

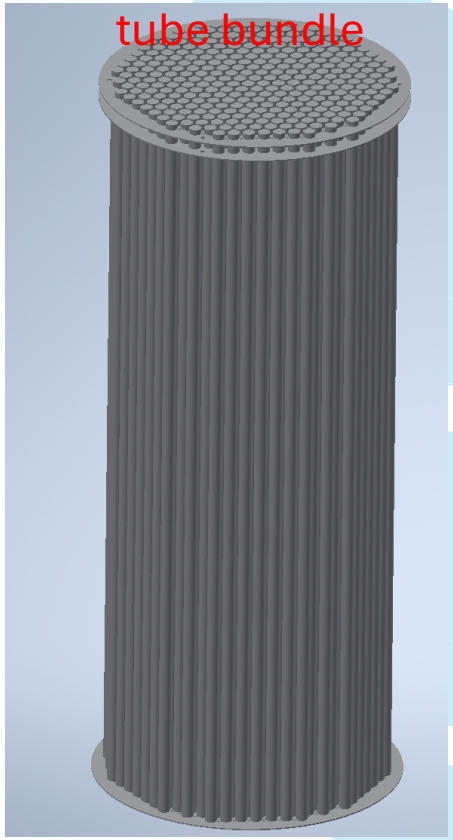
3D concept Flexsteam XXL

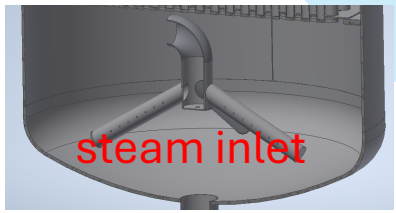
Design

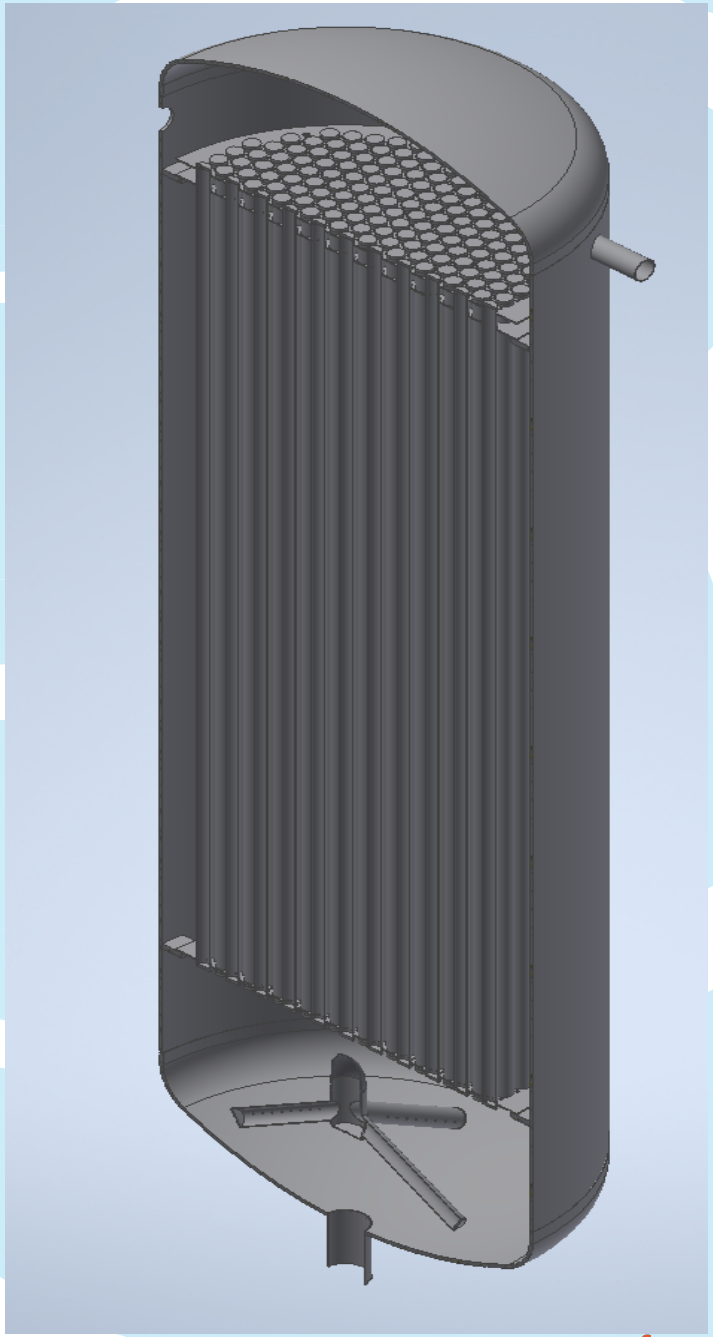
- 100kWh latent heat storage
- 3m long tubes filled with a phase change materials (adipic acid and graphite)
- Steam inlet at bottom of pressure vessel
- Steam outlet at top of pressure vessel

Performance

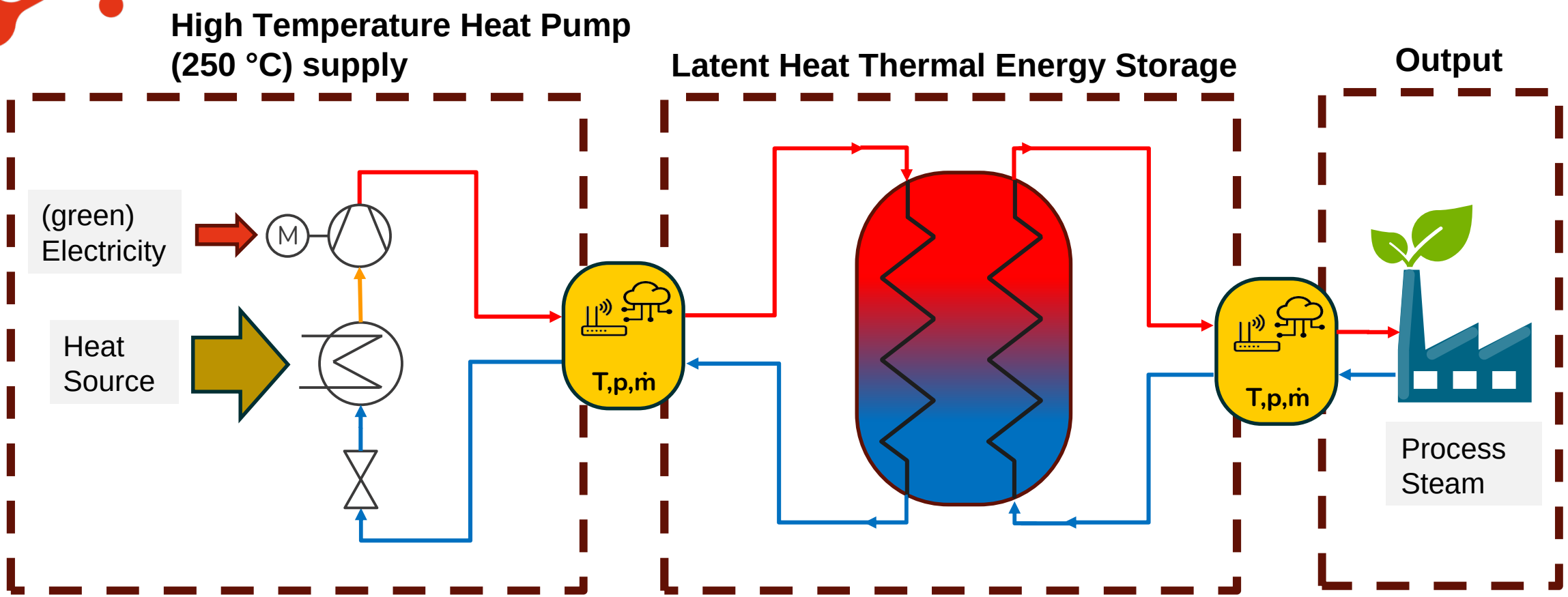
- Can be operated filled with water or steam
- Expected (dis)charging times <30 minutes using 10K driving force (0-100% or 100-0%)
- Cooperate together with SCHP (max. 300 kW_{th}) to either provide peak steam demand or to charge LH-TES



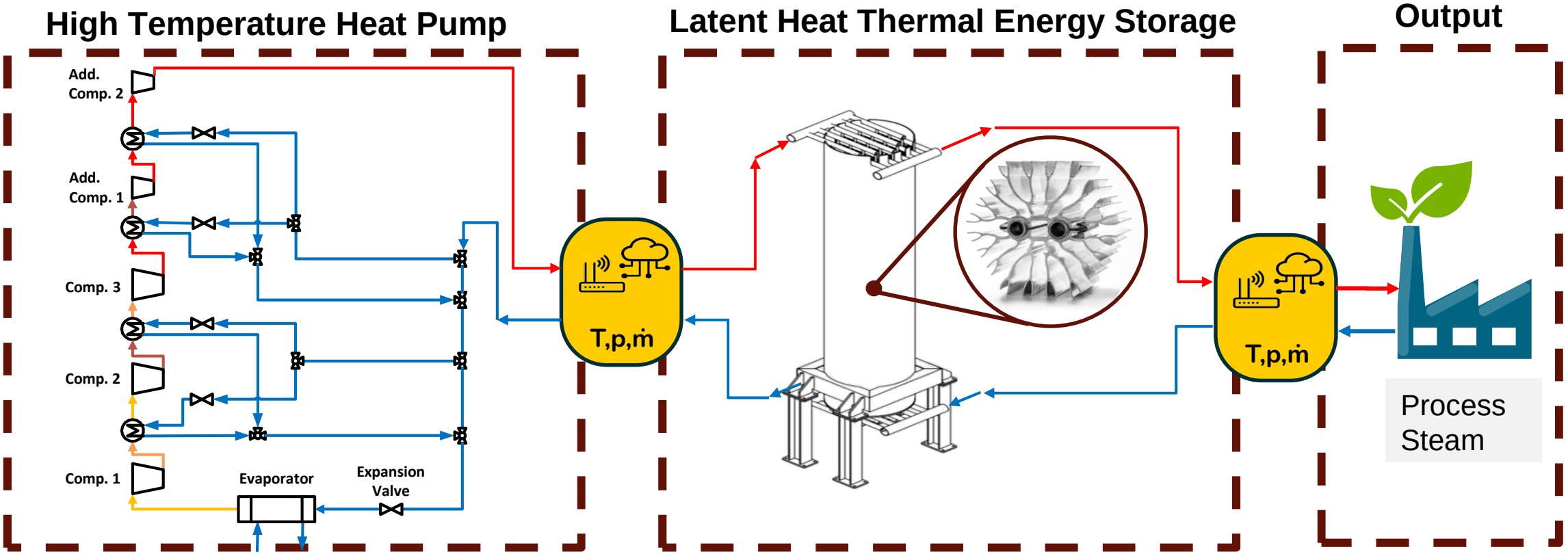




(Digital) Coupling of HTHP2 and LHTES2 to CS2



(Digital) Coupling of HTHP2 and LHTES2 to CS2



(Digital) Coupling of HTHP2 and LHTES2 to CS2

High Temperature Heat Pump

- Steam compression heat pump
- 5-stage turbo compression design
- Outlet of 5th stage: 250 °C/39.8 bar
- Direct driven geared at 120 k rpm

Project CHASE:

- Physical implementation of 4th stage, simulative implementation of 5th stage

T,p,ṁ

Latent Heat Thermal Energy Storage

- 1.6 tons of NaNO3/KNO3 (eu) as PCM, melting point: 222 °C
- Use of 19 dual-tube aluminum fins
- Charging and discharging with temperature difference <10 K
- Flexible steam up to 20 bar
- Heat storage capacity ≈ 60 kWh
- Experimental characterization of the storage within laboratory

T,p,ṁ

Output

- Provided by DTI
- Simulative coupling
- Tailored to industrial require-ments

Industrial case background

- Hourly steam consumption data from a relevant industrial steam user
- Reducing cost of heat is an important objective
- Variation in load can be detrimental to some equipment in the steam production

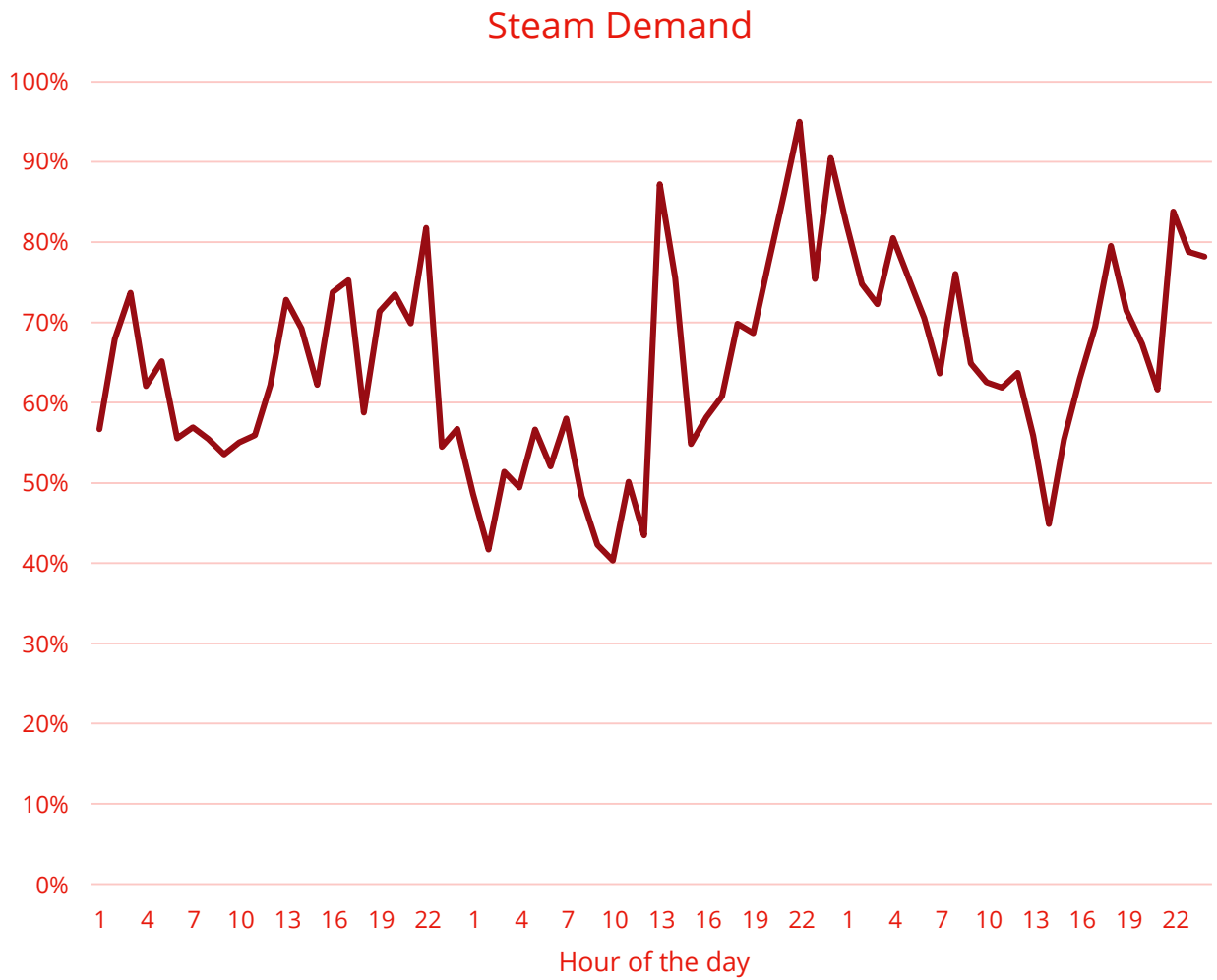
Optimization cases

We have considered full year operation for a representative steam load. The data foundation is:

- 2024 electricity spot price, DSO and TSO tariffs
- Equipment CAPEX estimates

Two cases are considered:

- Heat pump coupled to a thermal storage
  - Heat pump (+ backup) used to charge the thermal storage
  - Equipment payback time is minimized
- Thermal storage only
  - Storage charges from existing steam system
  - Variation in load on existing steam production is minimized



Optimization approach

Case 1

System configuration:
HP and TES replacing existing steam generation.
Existing generation used for peak loads

Objective function:

Minimize OPEX (Maximize net present value)

Optimization approach

Nested optimization
- Inner problem: operational optimization (MILP)
- Outer problem: exhaustive search over system sizes (HP, TES)

Case 2

System configuration:

Storage charged from existing steam system.

Objective function:

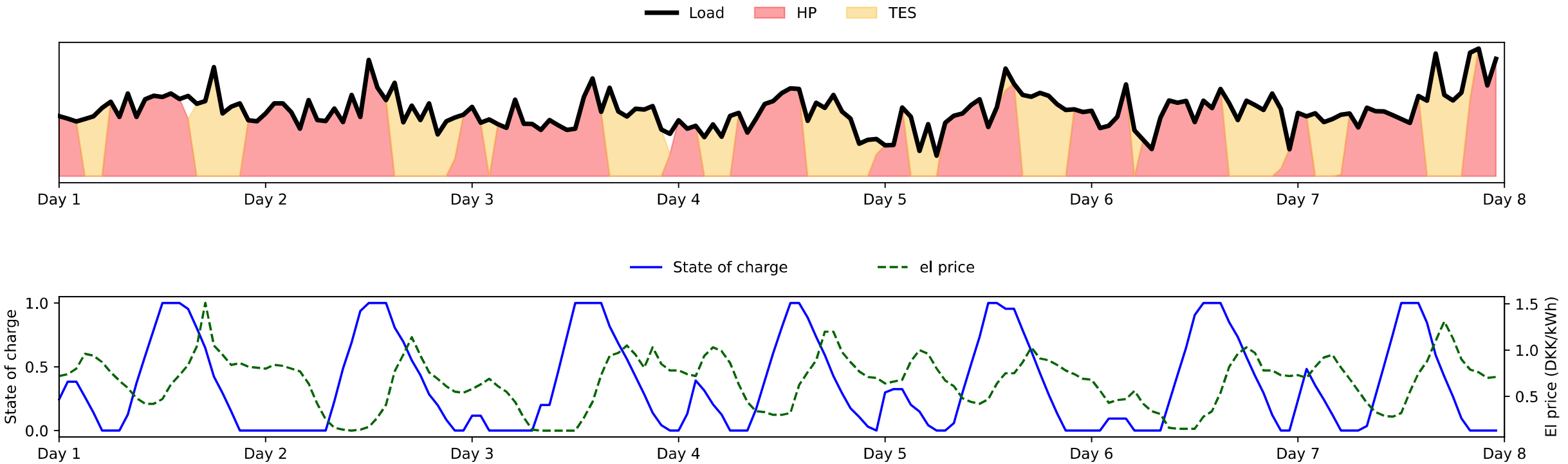
Minimize load variation on steam production.

Optimization approach

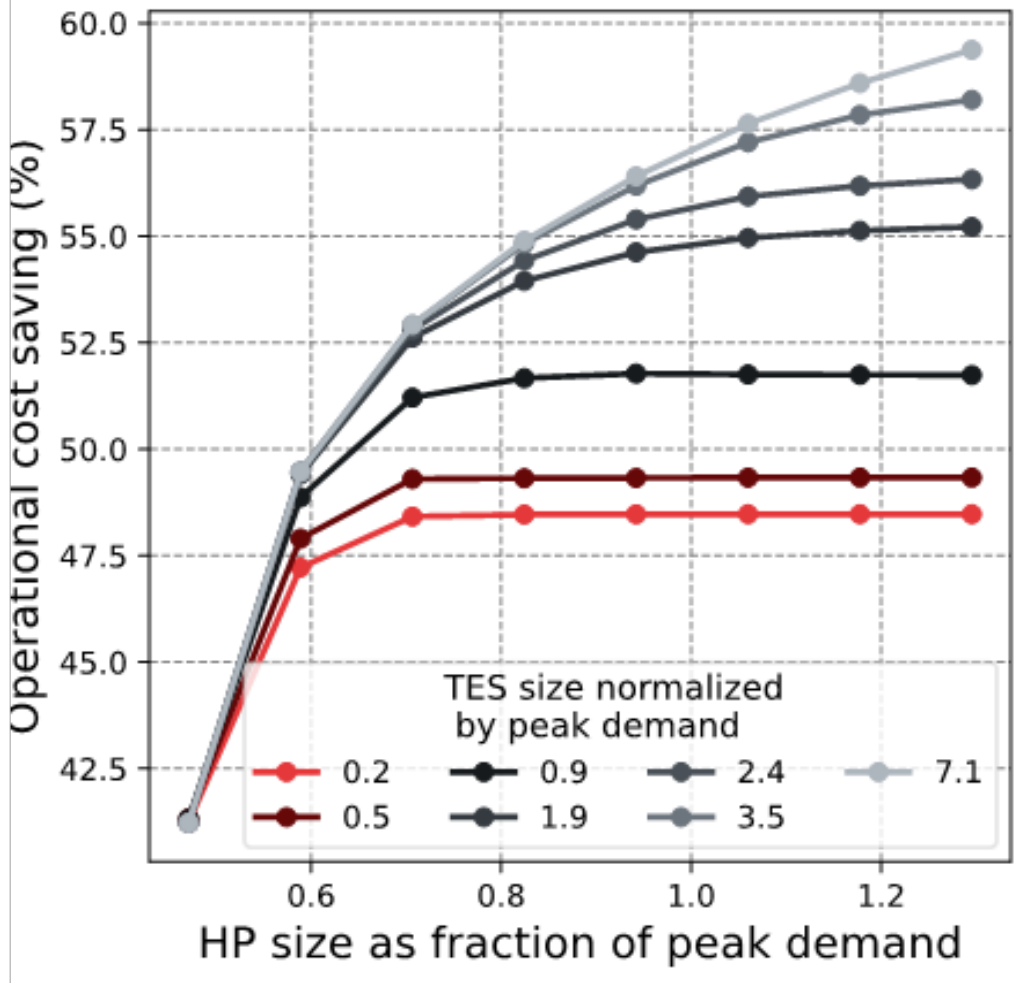
Mixed-Integer Linear Programming (MILP)

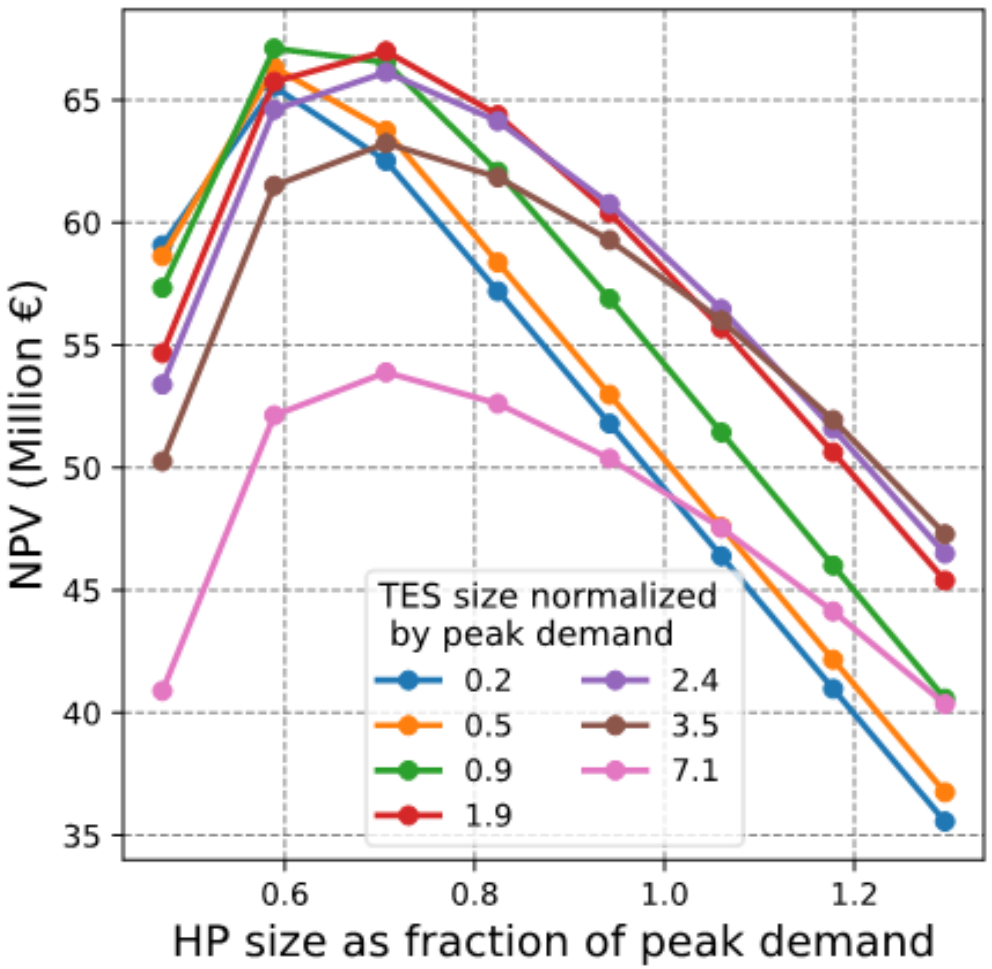
OPEX minimization result (HP + TES)

Heat pump power is 0.75x max load, TES can supply max load for 1.9 h

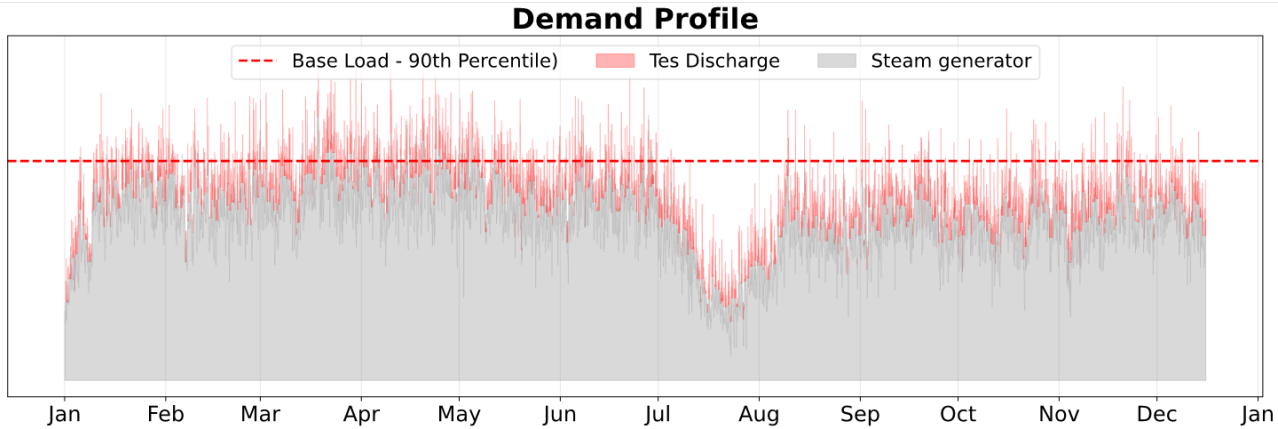


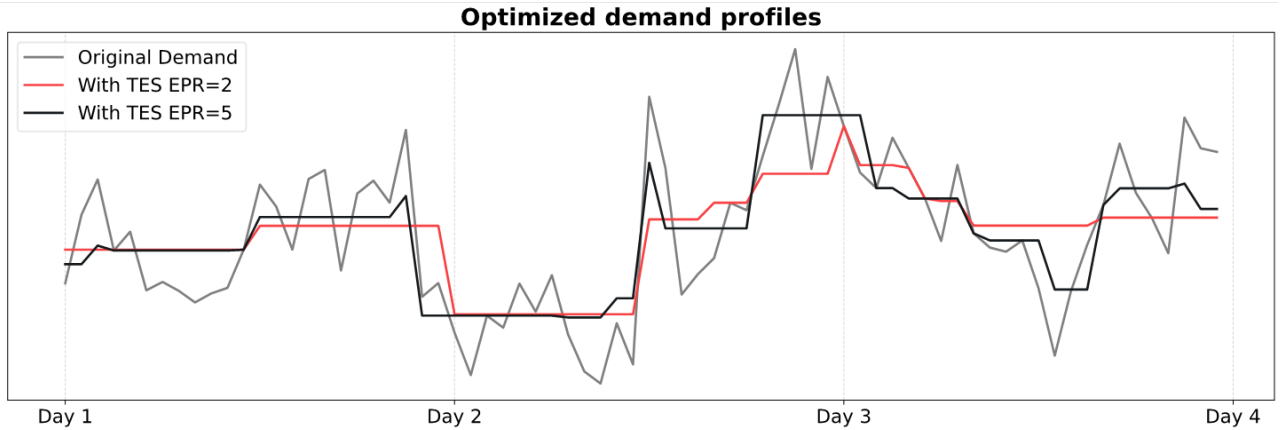
Equipment payback minimization

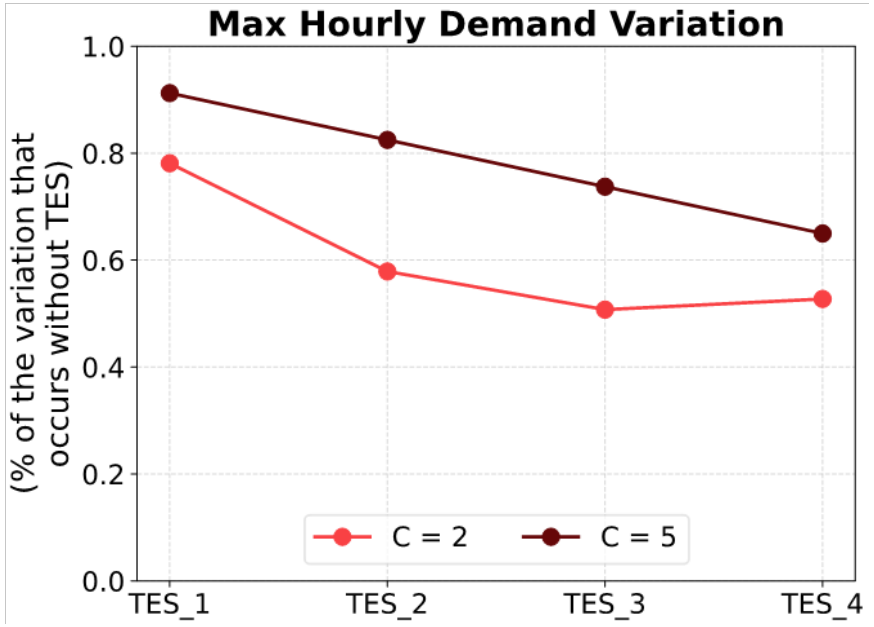




Load variation minimization (TES only)







Summary and conclusions

- The CHASE project aims to demonstrate heat pumps operating at 150 °C and 250 °C coupled to latent heat thermal energy storages
- System optimization was performed with two objectives: reducing heating costs and smoothing operation of steam producing equipment
  - It was shown that TES can help cover peak steam demand and the required heat pump size to deliver an overall lower cost system
  - A heat pump that can deliver 75% of peak demand coupled to a TES that can deliver 2 hours of peak demand heat gives the lowest cost of heat
  - Sizing of the TES and heat pump depend on electricity pricing and demand curve
- A TES can smooth out thermal demand variation and allow equipment to operate at a more constant level
  - This can avoid harmful operation for specific equipment
  - Peak shaving allows production to be scaled up using the existing steam production equipment

Thank you for your attention.

keng@teknologisk.dk

This study was funded by the European Union under Clean Energy Transition Partnership (CETP) program and Innovation Fund Denmark under the project title “CHASE – Combined Heat Pump and Thermal Storage for Energy Efficient Industry

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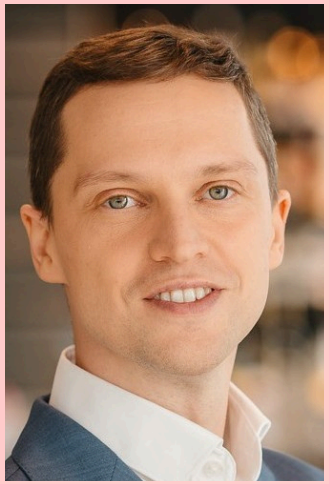

Rondo Heat Battery for Reducing Industrial Heat Costs (and for Decarbonization)

Janis Bethers, Rondo Energy

RONDO




Can a **brick** solve **heat decarbonization challenge?**

Rondo: ensuring industrial decarbonization supported by industry leaders

CLIMATE TECH INVESTORS

ENERGY IMPACT PARTNERS · Breakthrough Energy · JOHN DOERR · Speed & Scale

STRATEGIC INVESTORS

RioTinto · aramco · Microsoft · sabic · SCG · TITAN CEMENT GROUP · H&M

✓ *Mining & Minerals* ✓ *Energy* ✓ *Technology* ✓ *Chemicals* ✓ *Cement* ✓ *Textiles*

$250M USD
Equity raised

$175M+ USD
Project funding

EXECUTIVE LEADERSHIP

Eric Trusiewicz
CEO

John O'Donnell
CIO

Pete von Behrens
CTO

Karim Ibrik
COO

Tony Meneghetti
CFO

Paul Jones
CLO

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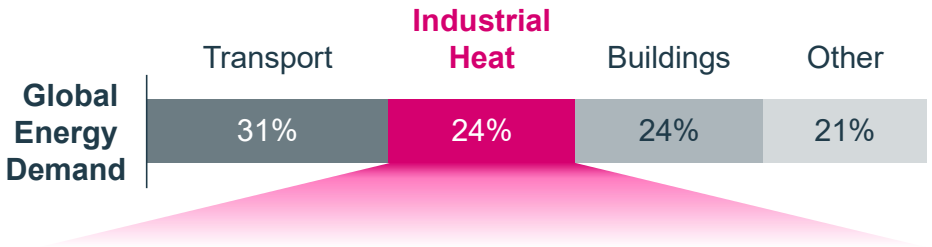
Industry has a **heat challenge**

INDUSTRIAL HEAT



- Food & Beverage
- Chemicals
- Paper
- Alumina refinement
- Mining (e.g., nickel, lithium)
- Textiles
- Refining, Bio-fuels, E-fuels
- Auto, Tires, EV batteries
- Other (CPG, Pharma, etc.)
- Steel
- Cement
- DAC & CCUS

THE CHALLENGE

Fossil fuels have <u>historically</u> been the best solution

- **Lowest cost** source of energy
- Deliver **continuous** heat, on demand

Yet there are problems with burning fossil fuels for heat

- **Risk of spikes** in fossil fuel prices; price on carbon is expected to **increase**
- Creates **25%** of global GHGs; **major scope 1 source** for industrials

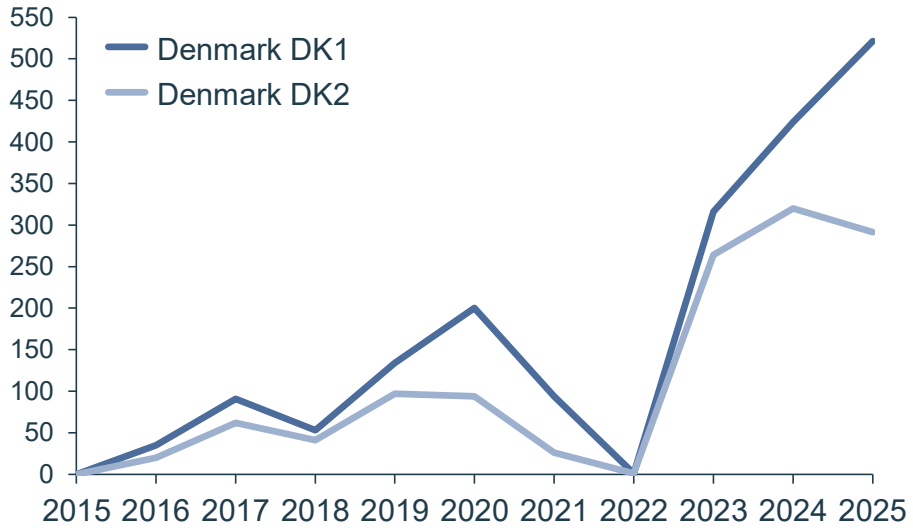
"I want to **save money** on heat and **drop the emissions!**"

RONDO

Intermittent electricity is **cheap**

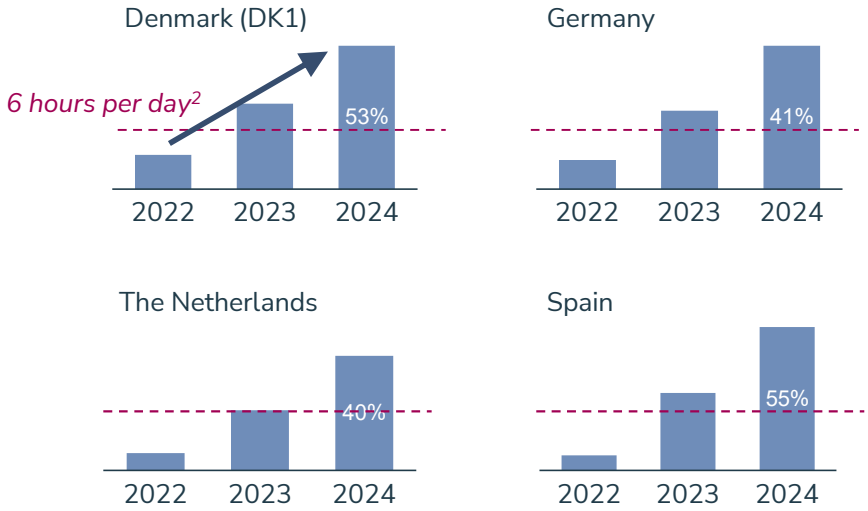
Negative prices on the rise

Number of hours per year with negative power prices[1]



Electricity < gas + carbon
for 25+% of hours (c.6 hours per day)

Share of hours with electricity prices below gas + CO_2 [%][3]

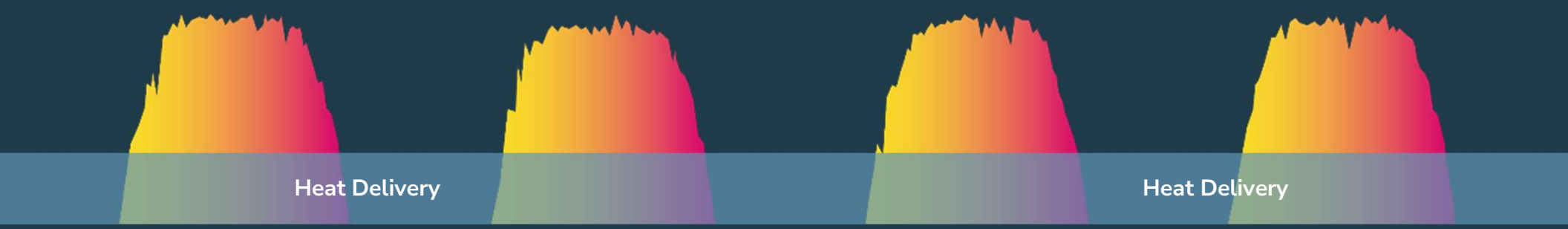


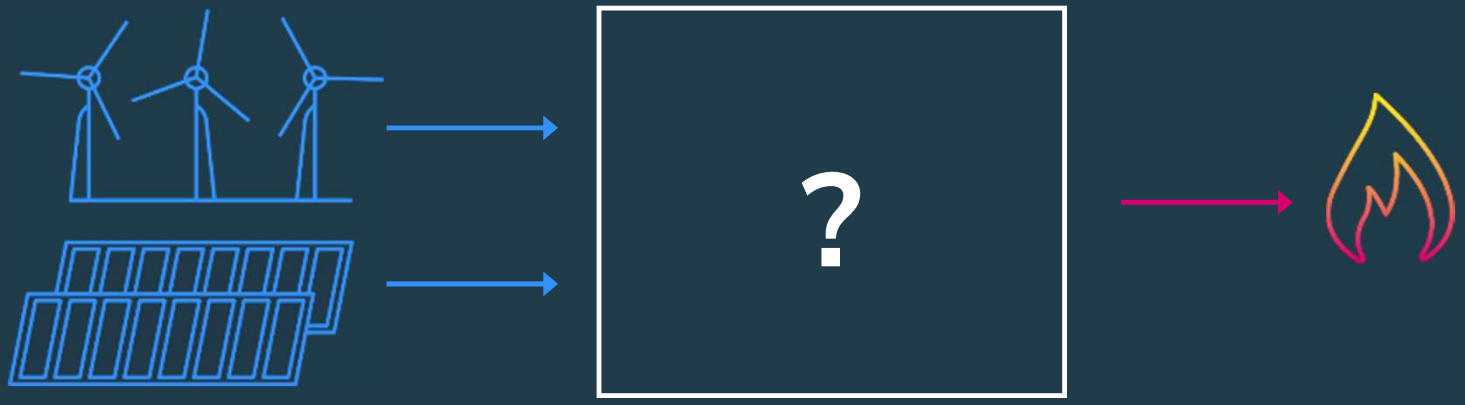
Rondo uses cheapest 6-8 hours per day to charge

[1] Based on wholesale electricity prices, 2025 prices till Dec-01, no negative prices in 2022 due to EU energy crisis [2] 6 hours per day = 25% of hours
[3] Average Gas + CO2 price of 60 €/MWh in Europe; Source: ENTSO-E

RONDO

We store cheap power as heat, and deliver heat on demand





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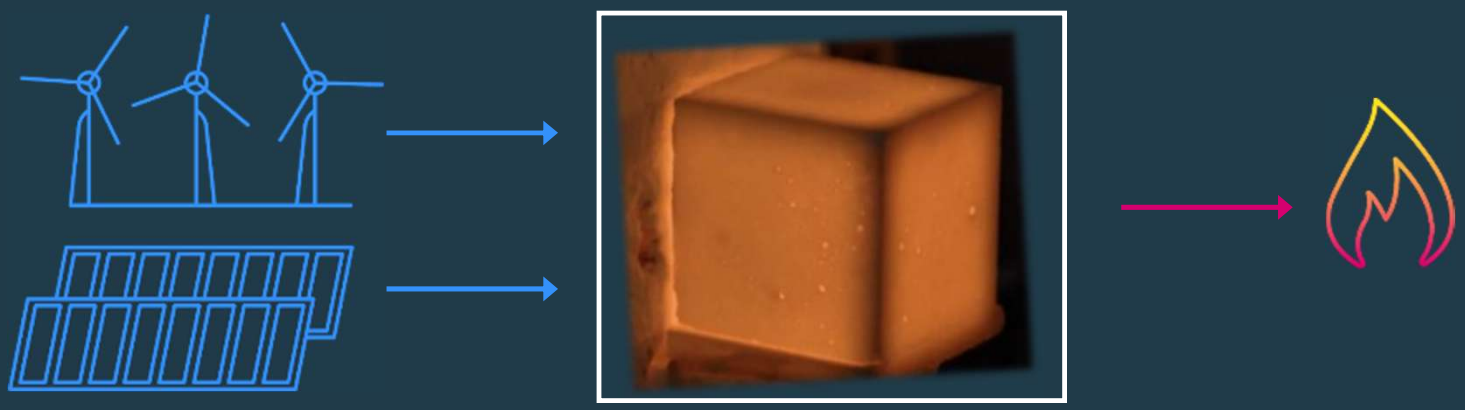
We store energy using **physics**, not chemistry

Intermittent Electricity

Heats Brick

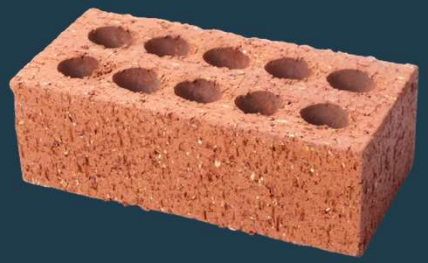
Hot Brick Delivers Heat



RONDO

Meet the Rondo Heat Battery

+



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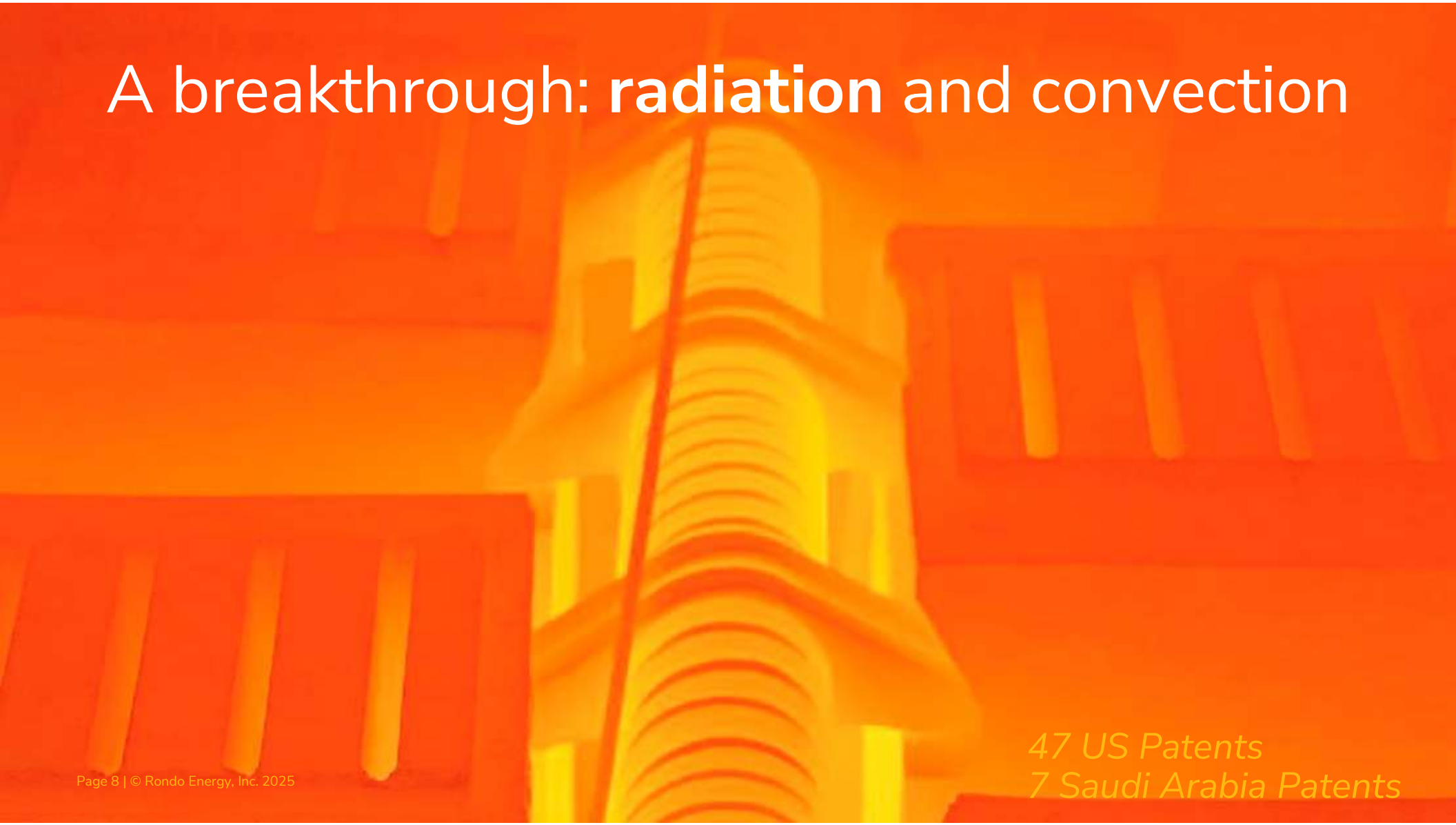
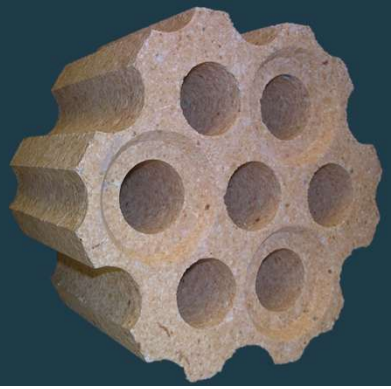
A breakthrough: **radiation** and convection

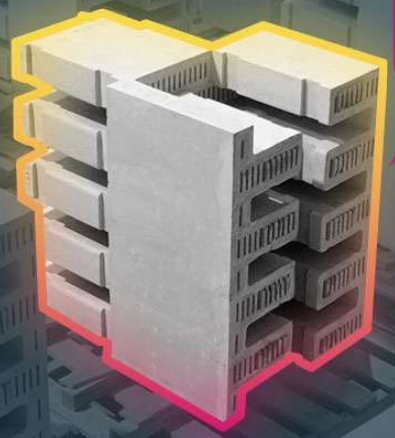


47 US Patents
7 Saudi Arabia Patents

Since 1860 Aluminosilcates **6MMt operating now**



Manufacturing capacity rising to **90 GWh/y**



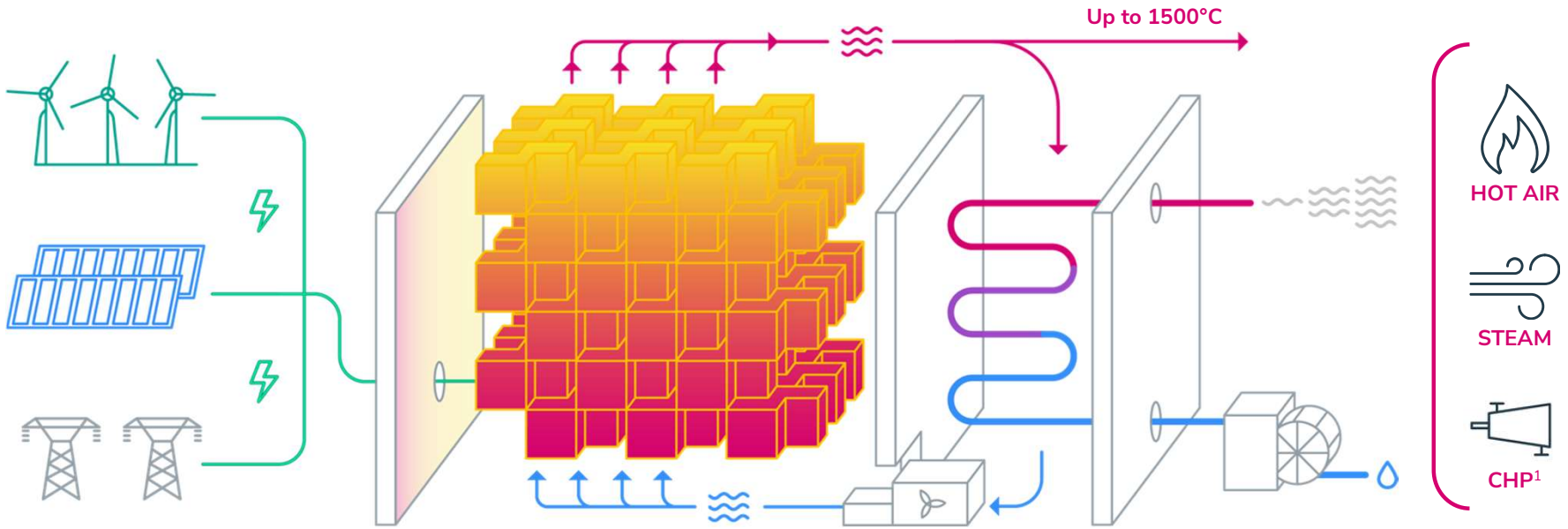
Internal electric heaters charge
from the power grid or
from dedicated solar PV

Brick stores heat and delivers
continuous steam or heat

Dynamic Insulation delivers
world's highest energy efficiency

RONDO

Here is **how it works**



1 CHARGE 6-8 hours / day

The Rondo Heat Battery charges with **intermittent electricity** from local wind & solar or from the grid

2 STORE for hours or days

Electricity powers radiant heaters with zero loss; refractory brick is rapidly and uniformly heated to **1100 - 1500°C**, and stores heat for hours or days

3 DISCHARGE 24 hours / day

The battery delivers **continuous superheated air** for use as process heat, steam, or electric power at over 97% total efficiency

97% energy efficient from electricity IN to heat/steam OUT

[1] Combined Heat & Power; high pressure steam can drive a steam turbine to produce electric power and low-pressure steam, providing 95% efficient combined heat and power

RONDO

We size our product to **fit your heat load**

Steam Requirement

2.3 MW_t	**7** MW_t	**27** MW_t
1 Max Charge: **8** MW_{ac}	1 Max Charge: **24** MW_{ac}	1 Max Charge: **80** MW_{ac}
2 Storage Capacity: **33** MWh	2 Storage Capacity: **100** MWh	2 Storage Capacity: **345** MWh
3 Max Discharge: **2.3** MWt	3 Max Discharge: **7** MWt	3 Max Discharge: **27** MWt
		
4 Emissions Saved: **3**kt CO_2/y *Natural Gas Reference*	4 Emissions Saved: **9**kt CO_2/y *Natural Gas Reference*	4 Emissions Saved: **37**kt CO_2/y *Natural Gas Reference*

RONDO

Rondo is deploying Heat Batteries today

1 Pilot operations
Pilot unit running 2+ years

2 Commercial operation
RHB33 in Thailand; RHB100 in California

+3 Announced, in development
in Europe, CODs 2026-27

Breakthrough Energy

European Investment Bank

Greener food, fuel and chemical production in Europe boosted by EIB, European Commission and Breakthrough Energy

link

covestro

Covestro to deploy innovative heat battery from Rondo Energy

link

GreenLab

Heat battery replaces fossil fuels for companies in GreenLab

link

Heineken

HEINEKEN pioneers the largest heat battery system in food & bev industry in Portugal in partnership with EDP and Rondo

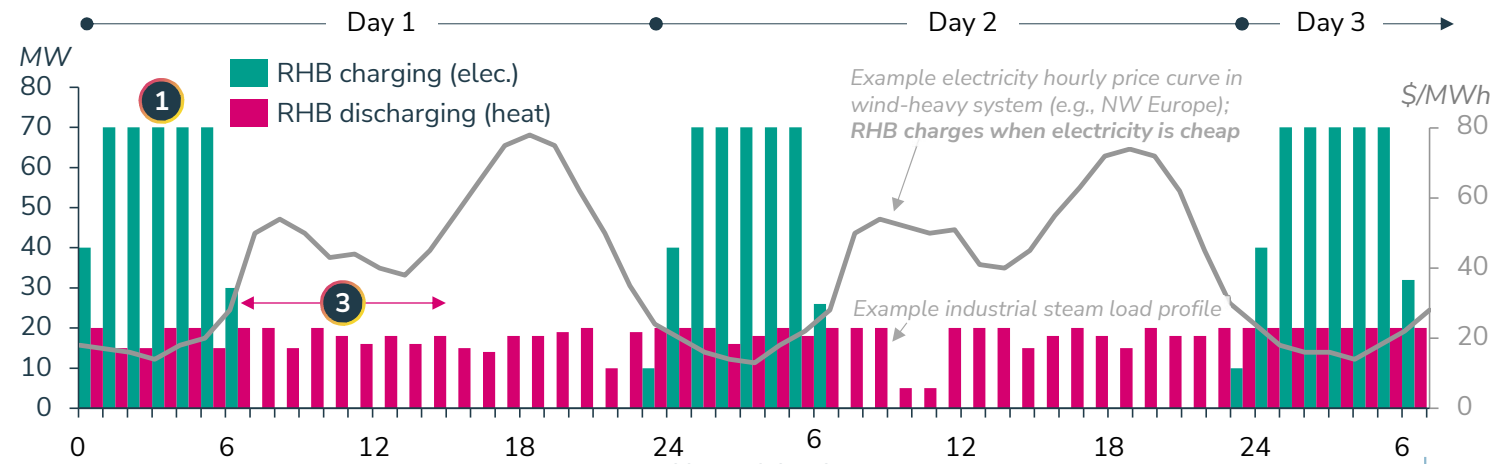
link

RONDO

6-8 hours of cheap electricity turned into **baseload steam**

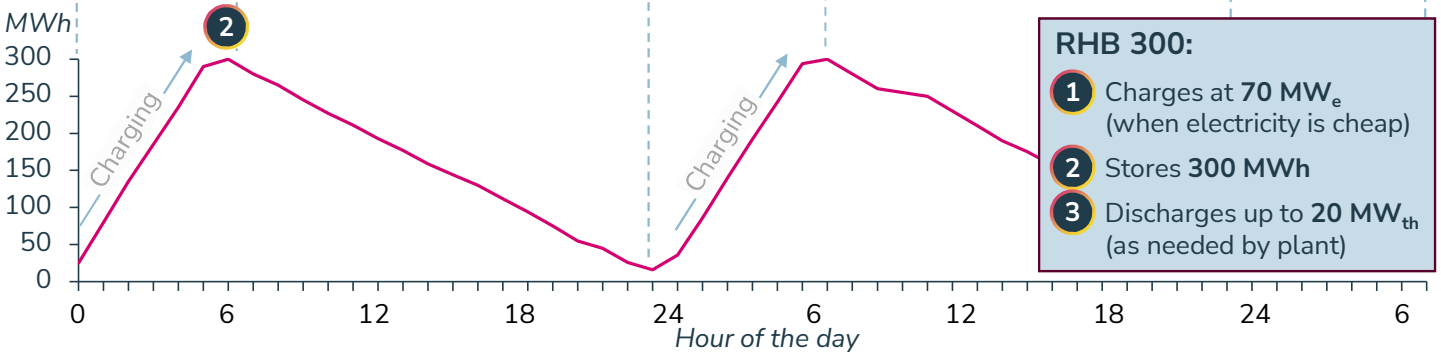
Rondo Heat Battery (RHB)
CHARGE & DISCHARGE

Example pattern for RHB300[1]



Rondo Heat Battery (RHB)
STORAGE

Energy stored in RHB



Notes: [1] RHB300 is a product size that refers to 300 MWh of energy storage capacity. See later slide for more information on product sizes.

RONDO

The RHB enables you to **save money vs. using natural gas**

ILLUSTRATIVE
Approximate Danish market analysis

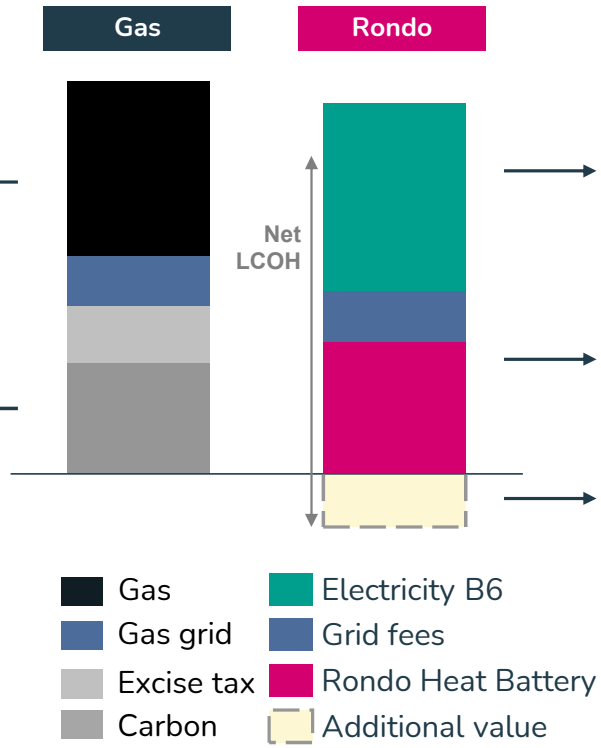
Natural Gas cost

- (TTF + mark-up + grid tariffs ÷ [85%, gas boiler efficiency] = **33 €/MWh**
- Gas grid fees ÷ 85% = **9 €/MWh**
- Excise tax ÷ 85% = **11 €/MWh**
- Significant **volatility** experienced

Carbon cost

- ~100 $/tCO$_2$ ÷ 85% = **21 €/MWh**
- Prices **expect to rise,** EU free allowances reducing from 2026

Levelized Cost of Heat (LCOH)
€/MWh



Electricity cost

- Low-cost hours B6 **<40 €/MWh**
- Electricity grid operator fees **>10 €/MWh**
- **Offshore wind** parks to be operational around 2032

Rondo Heat Battery

- **Amortization**

Additional value captured

- **Ancillary services** Rondo can operate on mFRR and aFRR markets
- **Grants** Opportunity to capture nation and European level decarbonization initiatives

RONDO

Rondo Heat Batteries use proven technologies to deliver systems that are low cost, dense, and safe

	PROVEN	LOWEST COST	DENSE & MODULAR	SAFE
RONDO	▪ Applies conventional technologies with **decades of industrial operating experience** ▪ Materials rated for **decades of cyclic operation**; minimal maintenance downtime	▪ **Fast-charging** enabled by heat transfer through radiation ▪ **97% energy efficiency** enabled by dynamic insulation	▪ Brick refractory and large single unit enables **energy dense footprint** ▪ 3 RHB unit sizes and **modular deployment** enabled stepped deployments where applicable	▪ Avoids toxics, liquids, and combustibles for **safe operation** ▪ Already contracted for chemical site, enabled by zero safety risks
Other ETES	▪ Materials and/or processes **unproven at scale and over time**	▪ **Same charge & discharge rate**, and/or inability to do both at once	▪ Smaller units that create **large footprint** when compiled to serve larger load	▪ Risk of **combustion, toxic gas release, overheating,** or **pressure bursting**

RONDO

Contractual model options, to **match your preference**

CAPEX Direct Sale

Developer

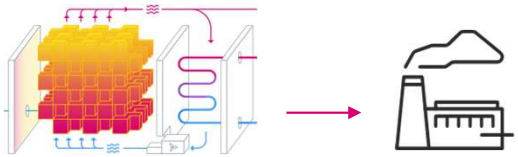
Renewables Developer sells electricity to Heat User under a PPA

or

Heat User

Heat User develops its own off-grid wind / solar

Heat User



Heat User owns RHB, charges it with renewable electricity, and uses it to generate heat for its industrial processes

SaaS *(Storage as a Service)*

Developer

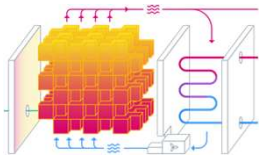
Renewables Developer sells PPA or turnkey CAPEX to Heat User

or

Grid

Utility or Retailer / Trader sells electricity to Heat User

SaaS SPV



SaaS SPV owns RHB and sells service to the Heat User

Heat User

Heat User purchases the RHB service & purchases electricity separately

HaaS *(Heat as a Service)*

Developer

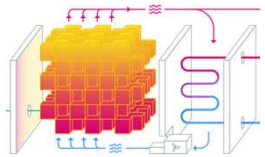
Renewables Developer sells PPA or turnkey CAPEX to HaaS SPV

or

Grid

Utility or Retailer / Trader sells electricity to HaaS SPV

HaaS SPV

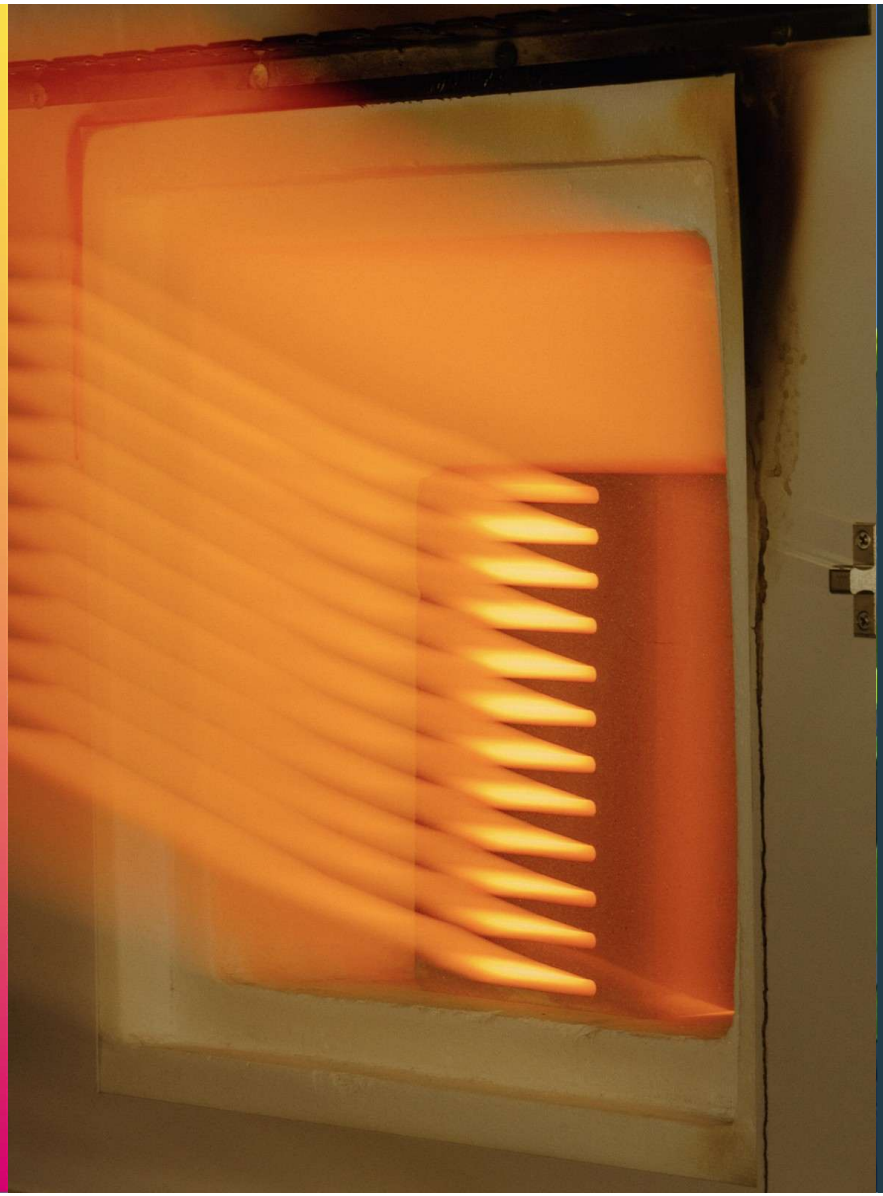


HaaS SPV owns RHB & charges it with renewable electricity

Heat User

Heat User purchases the heat / power from HaaS SPV

RONDO

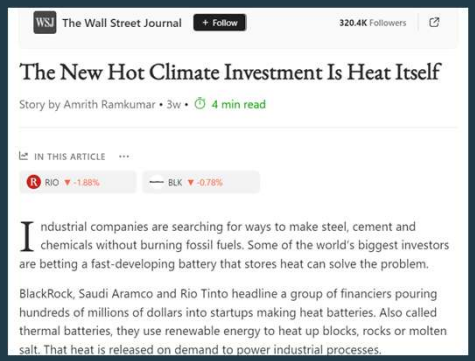


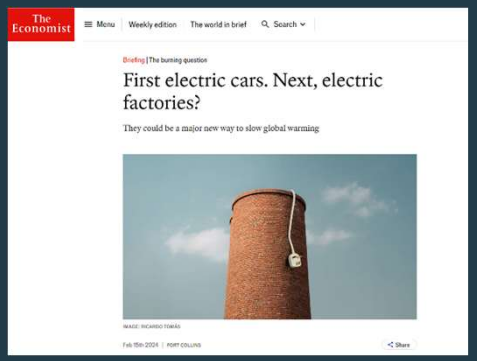
Let’s turn industry green!

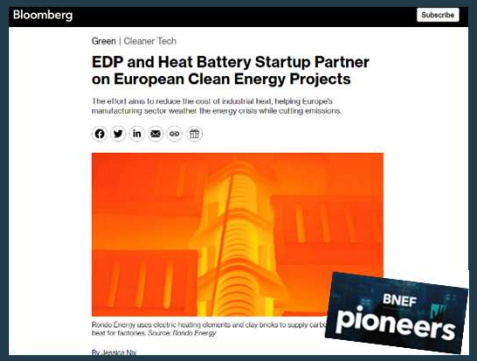
janis.bethers@rondo.com (VP, Commercial Development)

RONDO

Worldwide recognition of Rondo







‘Can a simple brick be the next great battery?’

‘The Breakthrough Battery Technology’

‘These bricks can hold as much energy as a Tesla’

Advanced Energy Storage Conference

See you next time for Advanced Energy Storage 2026