The Energy Challenge of 21st Century: LSMDES

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HERRICK ENERGY SEMINARS

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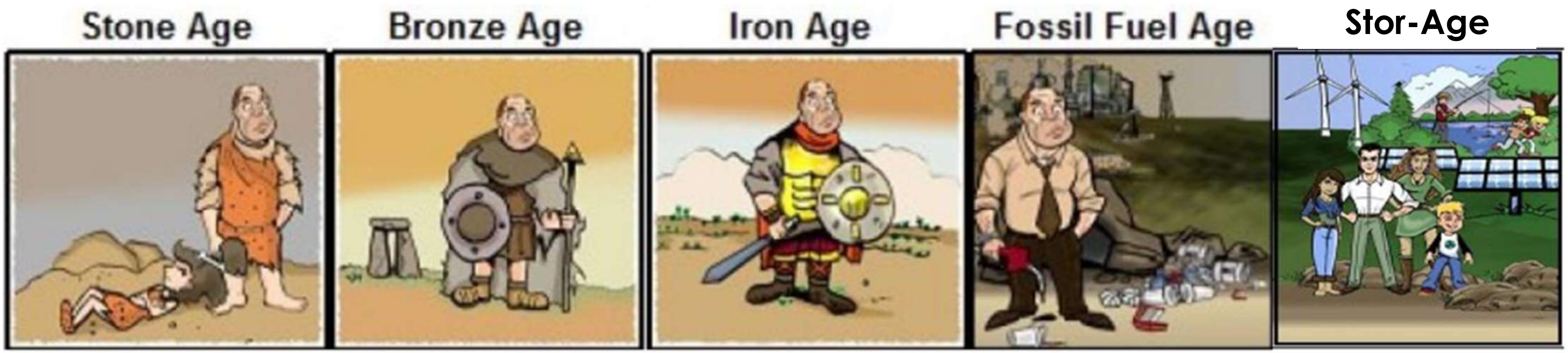
PURDUE UNIVERSITY | Ray W. Herrick Laboratories

From Stone Age to Store-Age



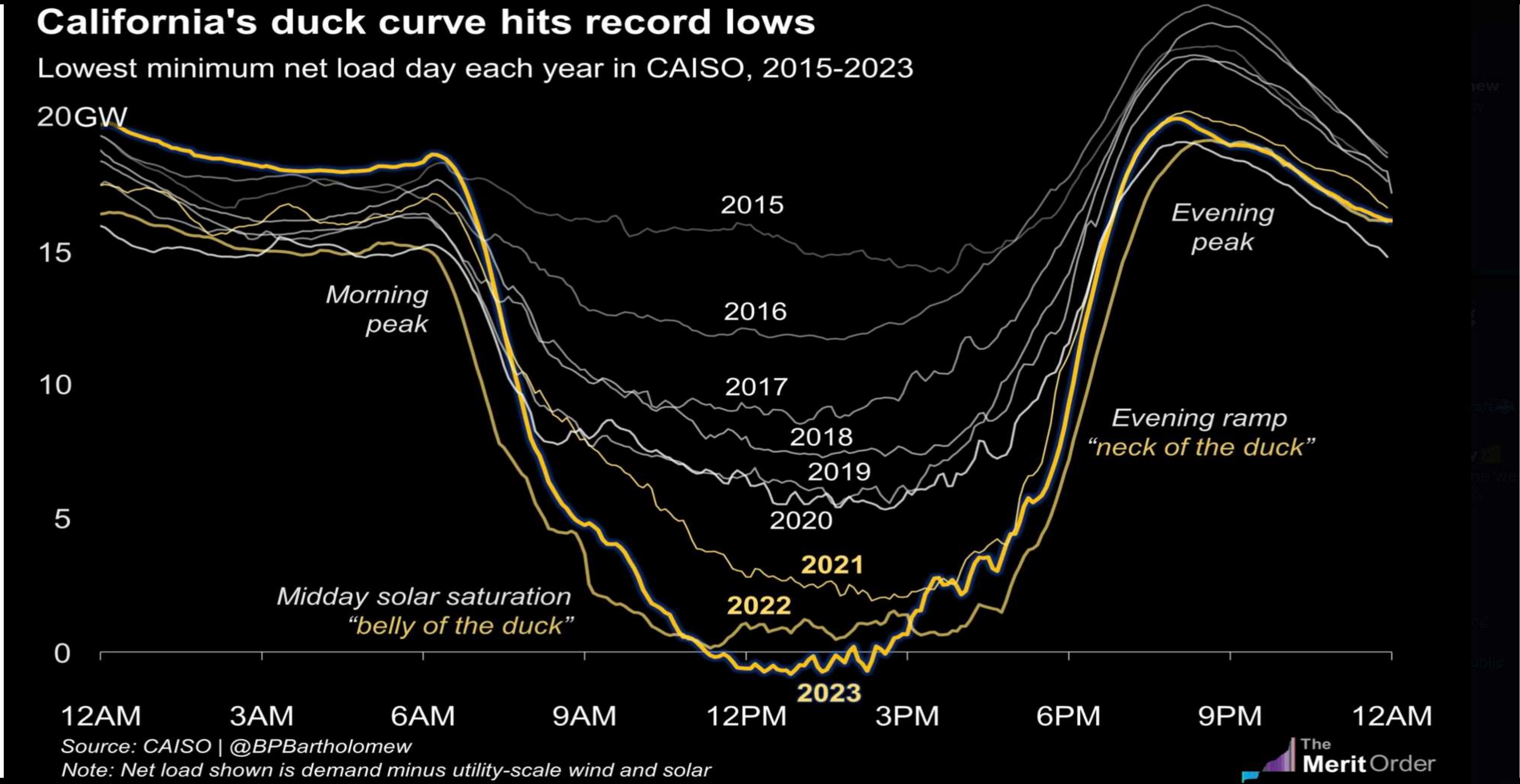
Motivation and background

- **Current megatrends** in energy systems that will unlikely change:
  - Addition of highly volatile ren. en. sources to the grid
  - Electrification in all the sectors – HVAC, industrial process heat, BEVs, rising living standards
    - (fyi total worldwide electricity consumption doubled since I was born)
  - Phase out of the biggest energy storage – dispatchable fossil fuel (coal-fired power plants to be phased out 2038 in most of EU countries, probably earlier (2028?) due to EU-ETS)

- All these result in:
  - high volatility in electricity prices (negative intraday market and day ahead market prices every weekend in ENTSO-E)
  - relevant questions about stability of the grid (decrease in rotating mass inertia sources, less dispatchable sources)
  - increase in electricity costs due to „regulated component of the electricity price“ (ancillary services)

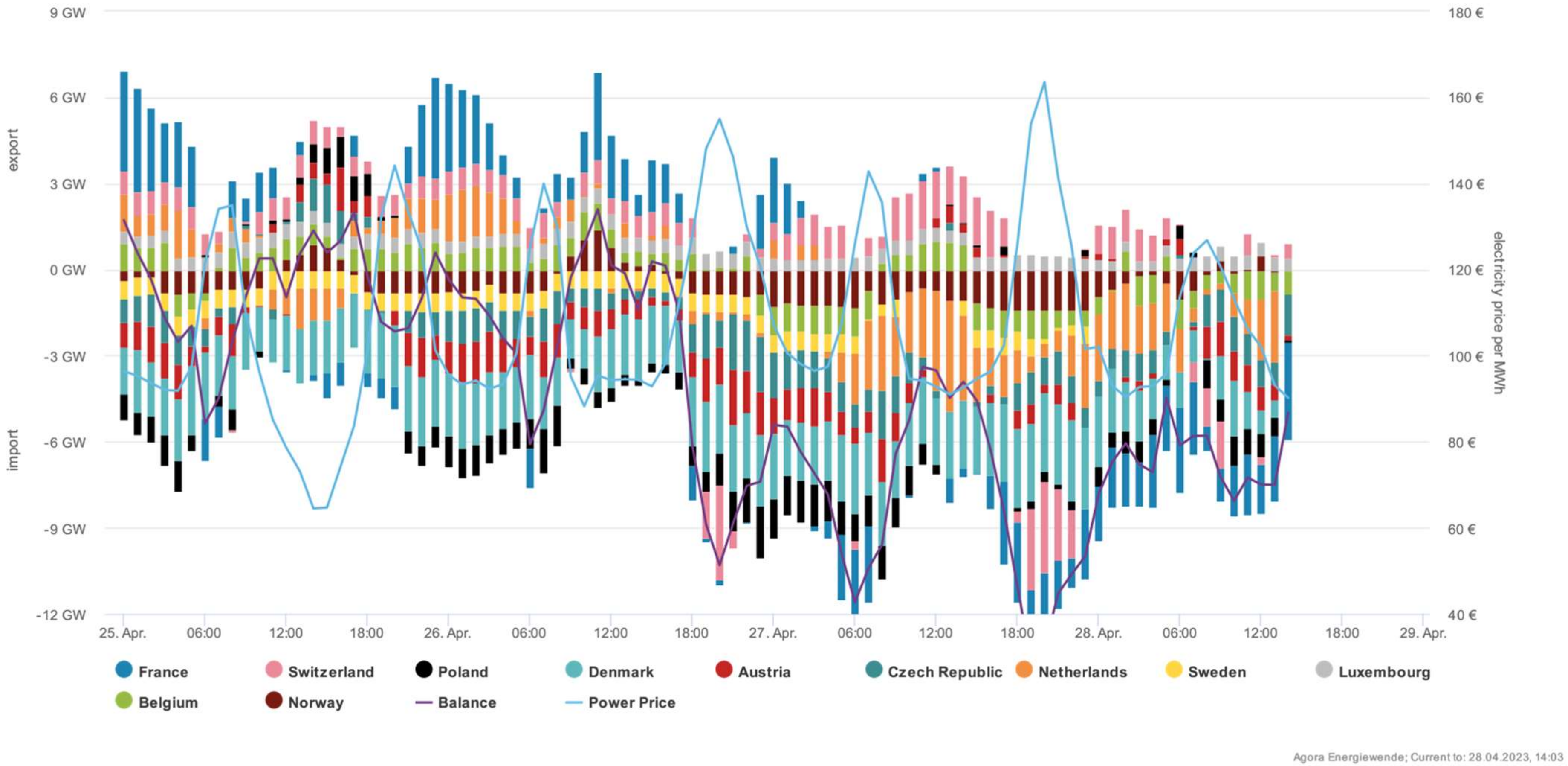
Motivation and background

#flattenthecurve

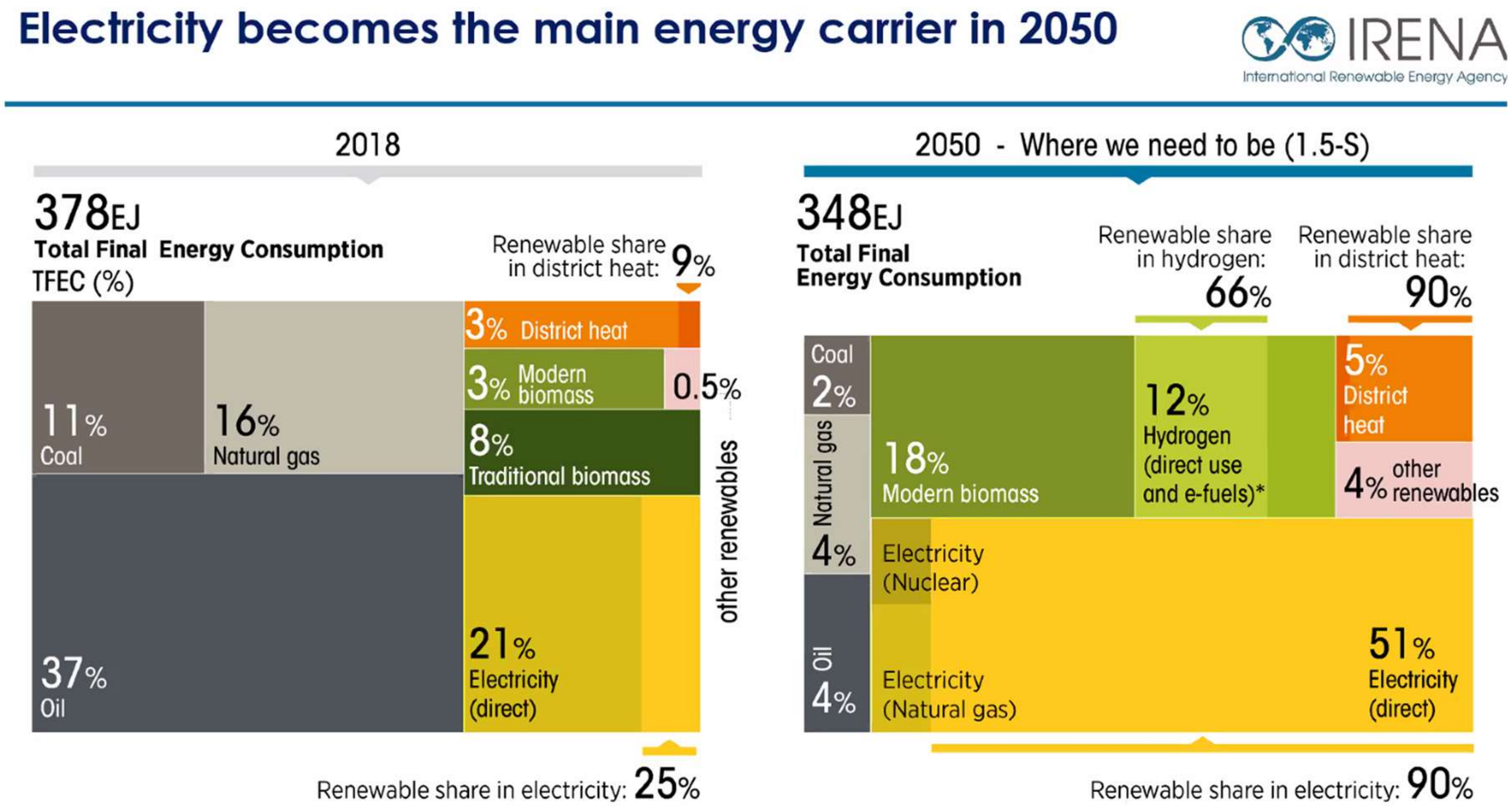


„duck curve“ => „camel curve“

Motivation and background



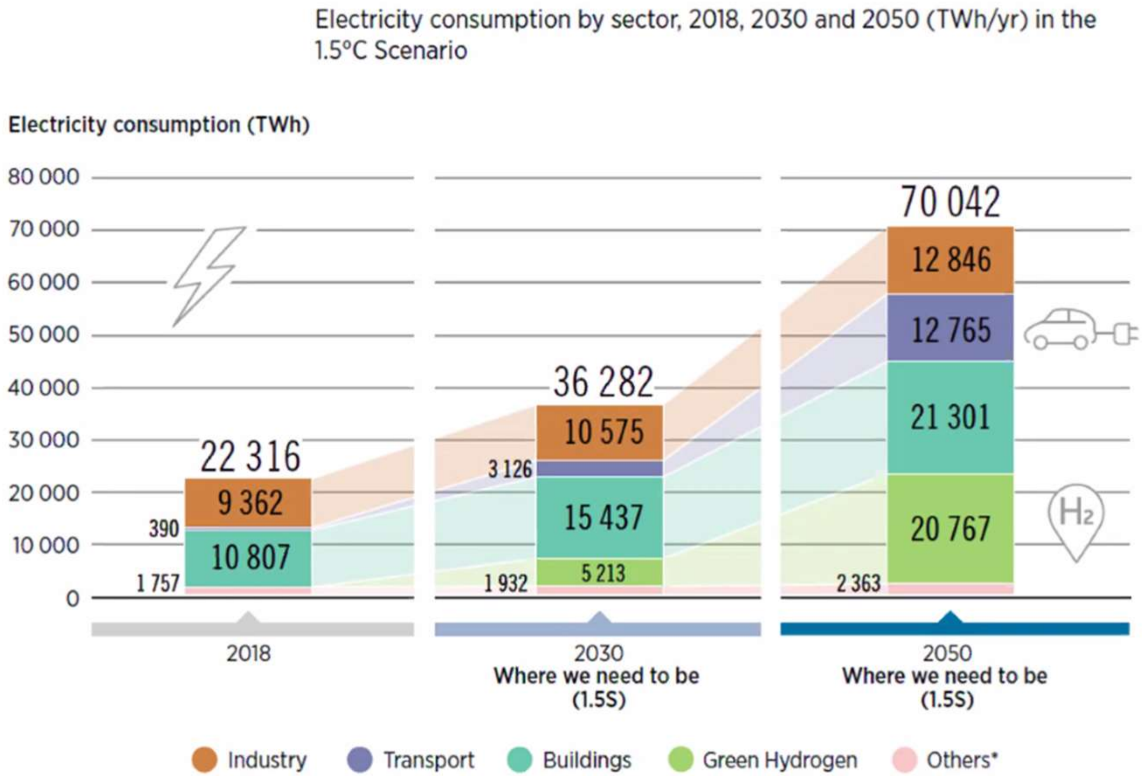
Motivation and background



90% of total electricity needs will be supplied by renewables by 2050.

Motivation and background

Electrification – what's the magnitude of the challenge?



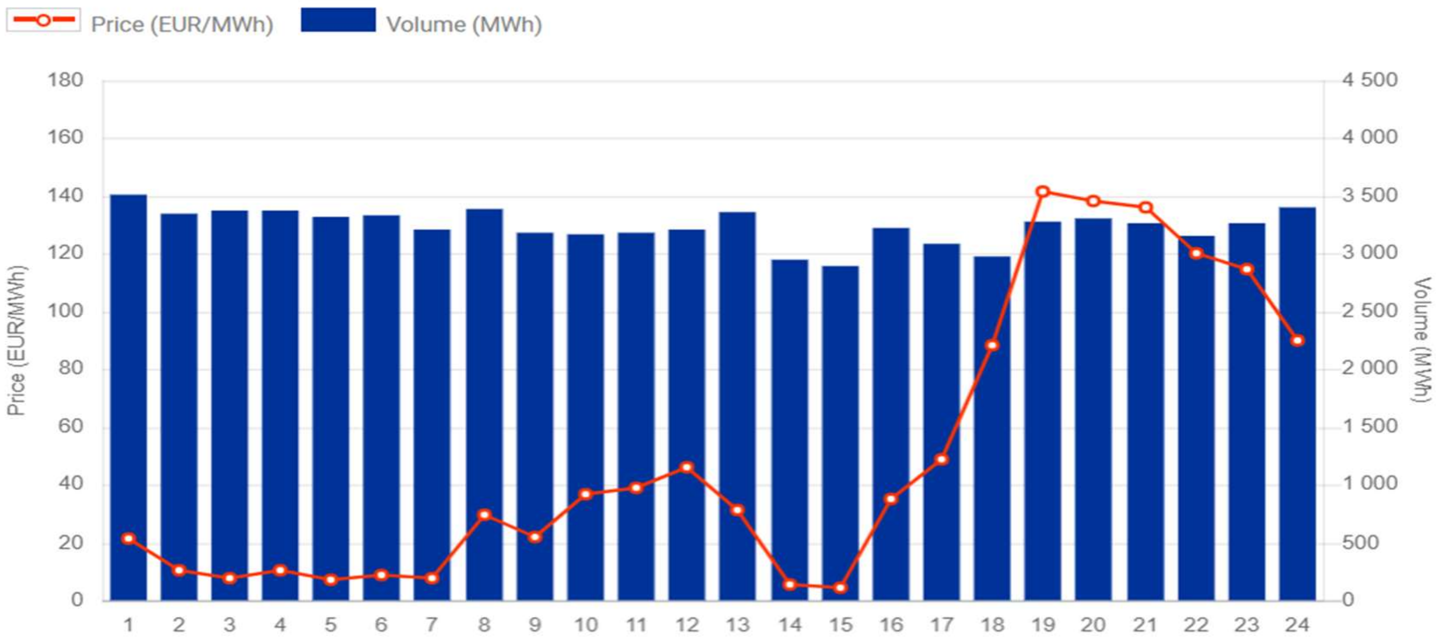
Motivation and background

Day-Ahead Market

14. October 2023

https://www.ote-cr.cz/en/

Day-Ahead Market CZ Results - 15.10.2023



Motivation and background – results of change

- Large scale backup gas fired power plants built to „secure the grid“ and run „peak load only“
- EU does not want to list those as green investment, which makes it difficult to be bankable
- Nobody knows what to do (read as: investors feel insecure)
  - => no power plants are being built due to high risk and no guaranties
    - => possible shortage of power? (we need more el., power plants aging…)
      - NO –this will result in electricity **marginal cost increase** and more polluting source to fire up despite CO2 tax (EU ETS)
- **There is a huge need for grid scale energy storage system** that would be:
  - Geographically independent
  - Cheap to built and operate
  - Efficient
  - Bankable (ESG friendly, low risk)
  - Geopolitically independent
  - **Thermomechanical?**

Motivation and background – Energy storage

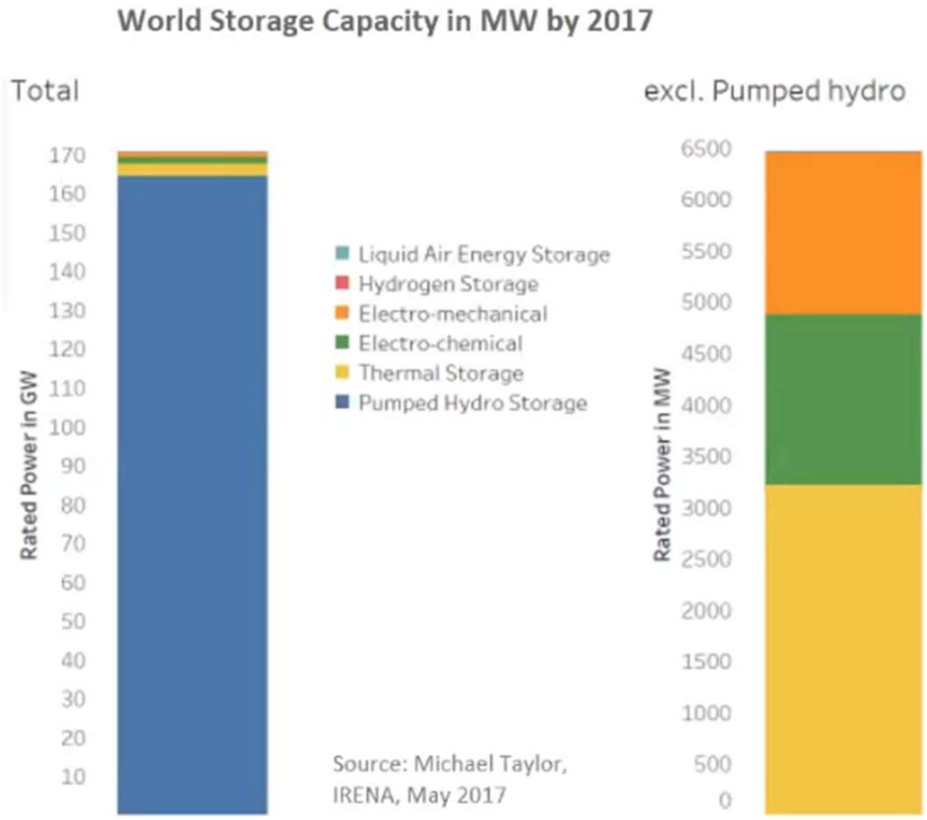
Ok, let's talk Large Scale energy storage

- A technology gap identified, huge influx of capital especially from venture and cleantech funds
- A chance for thermal energy engineers to shine (and compete with ECE guys)
- There is a great competition of different technologies over what's a potentially $T market

Motivation and background – Energy storage

Common presumption:
Electricity *storage = Li-Ion electrochemical batteries*

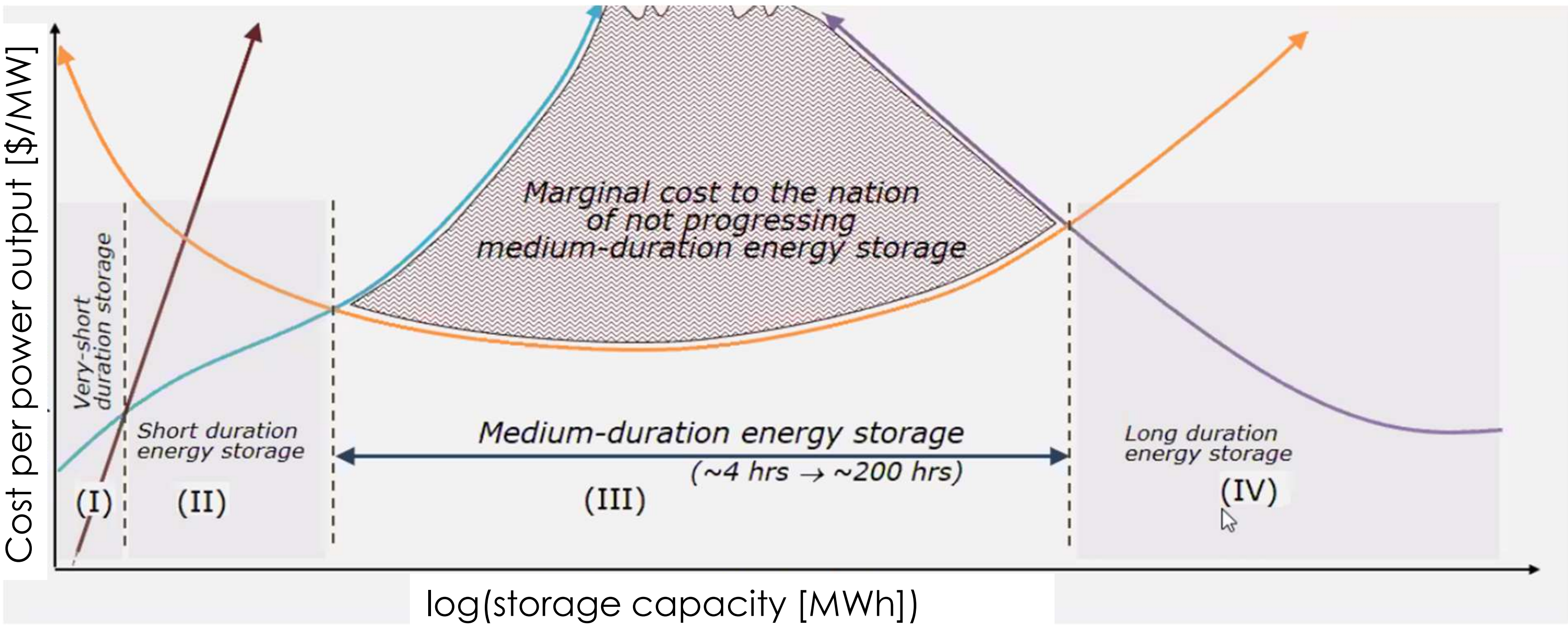
Reality :
Electricity *storage = Pumped hydro >>>> thermal > electro (mech, chem.)*



https://www.irena.org/-/media/Files/IRENA/Costs/Slides/Battery-storage-Council-23-May-2017-MICHAEL-TAYLOR-PDF.pdf?la=en&hash=B61257FC3AB1AF0C516EA8D241890DD426980974

Motivation and background – Energy storage

DIFFERENT TIMESCALES => DIFFERENT TECHNOLOGY SETS



(y axis basically power output – $/MW,

x axis **storage capacity** - MWh).

Brown – e.g. Flywheels, Ultracapacitors

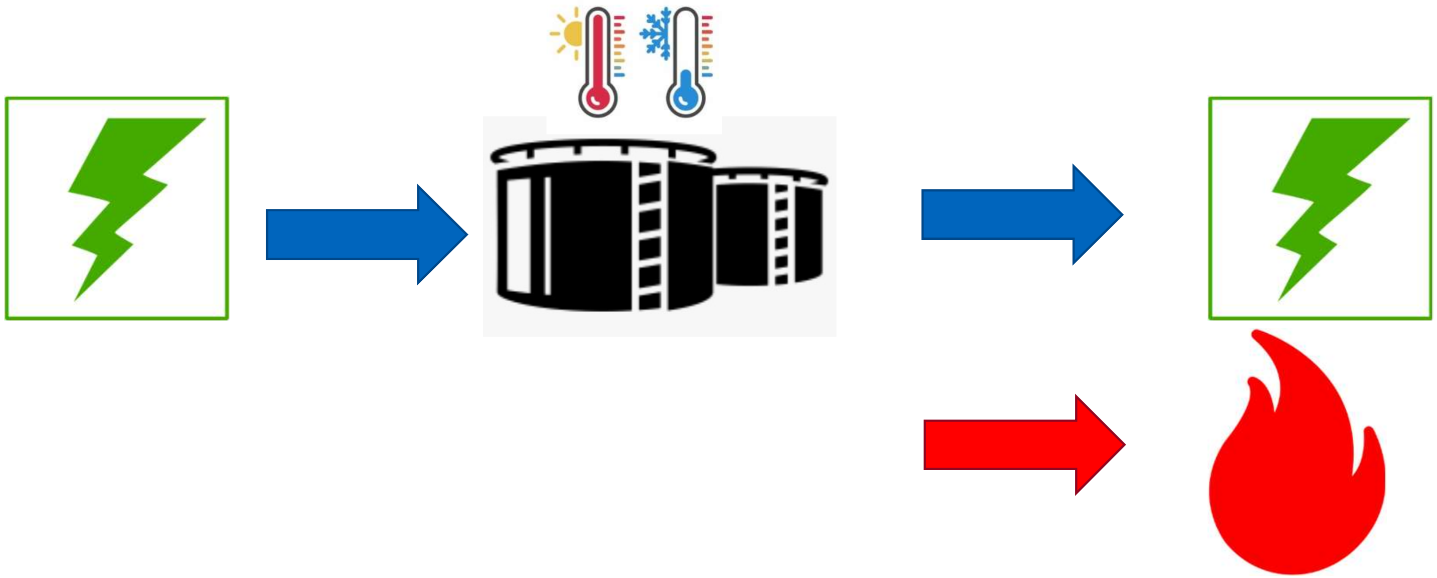
Blue – el.chemical

Orange – e.g. PHS or Carnot Batteries

Purple - Hydrogen

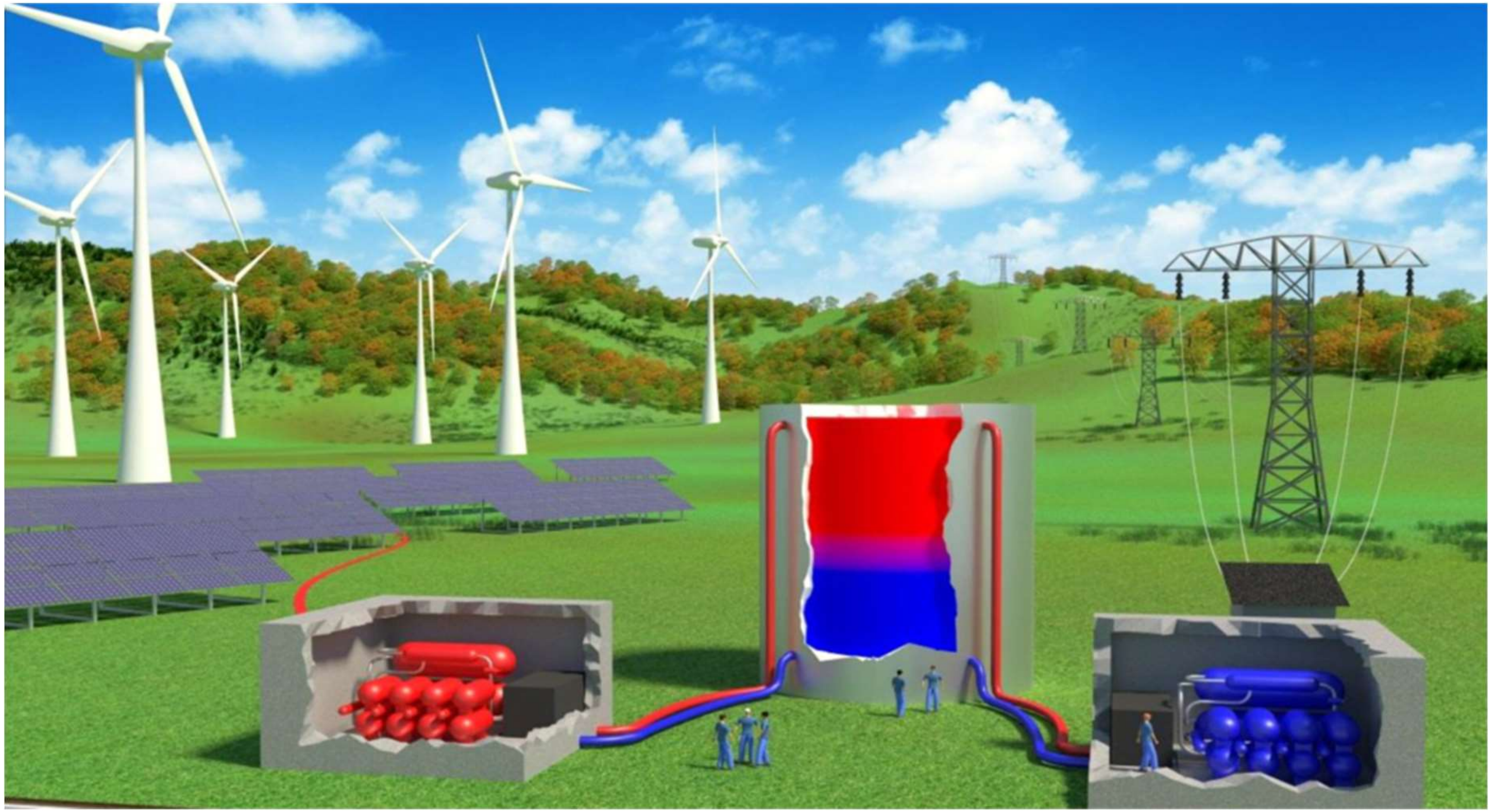
Img courtesy of prof. Seamus Garvey, University of Nottingham, fellow IEA Energy Storage member

Proposed solution – Carnot battery



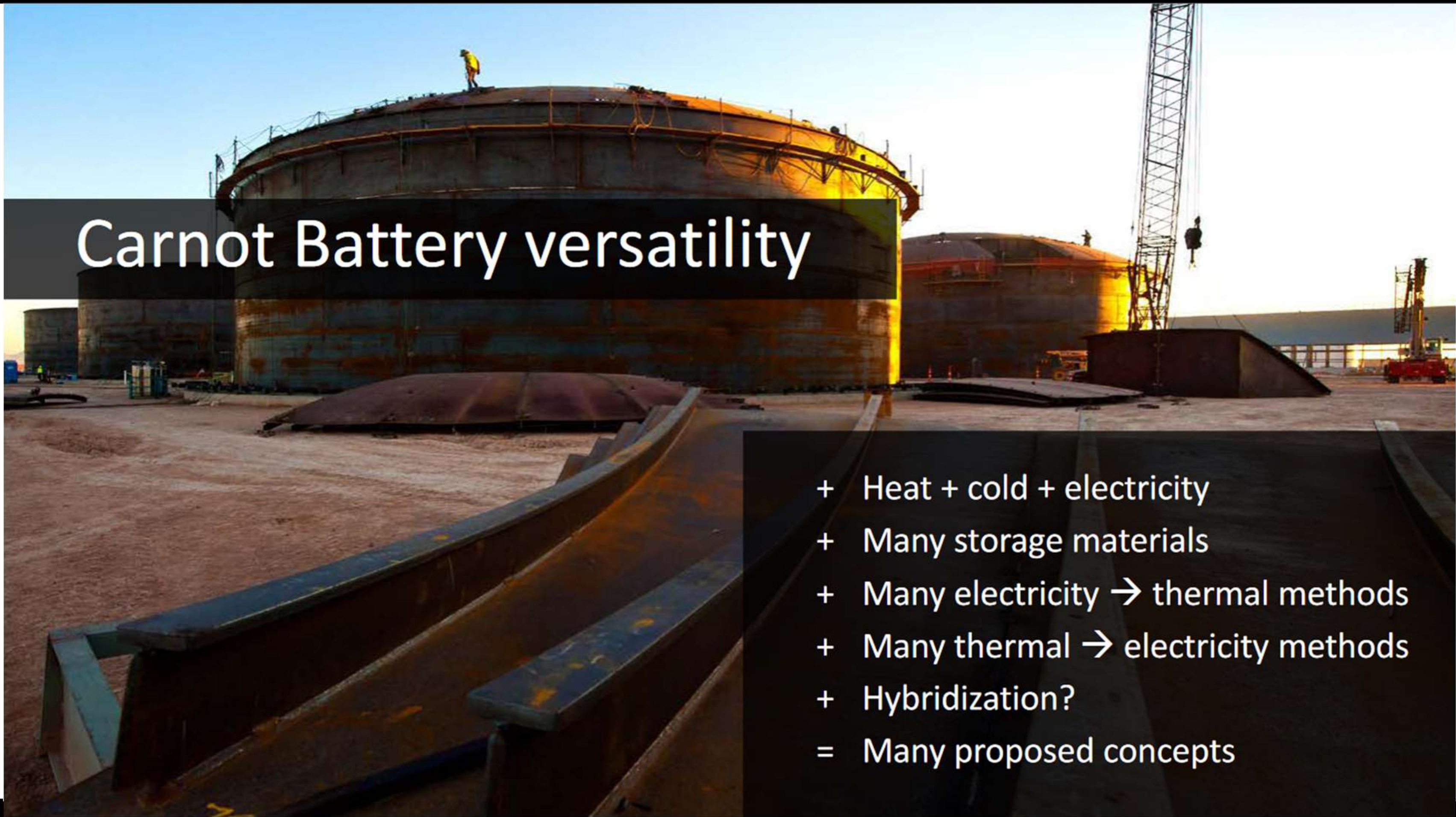
A **Carnot battery** is a type of energy storage system that stores electricity in thermal energy storage. During the charging process, electricity is converted into heat and kept in heat storage. During the discharging process, the stored heat is converted back into electricity and/or can be used for other purposes

Proposed solution – Carnot battery

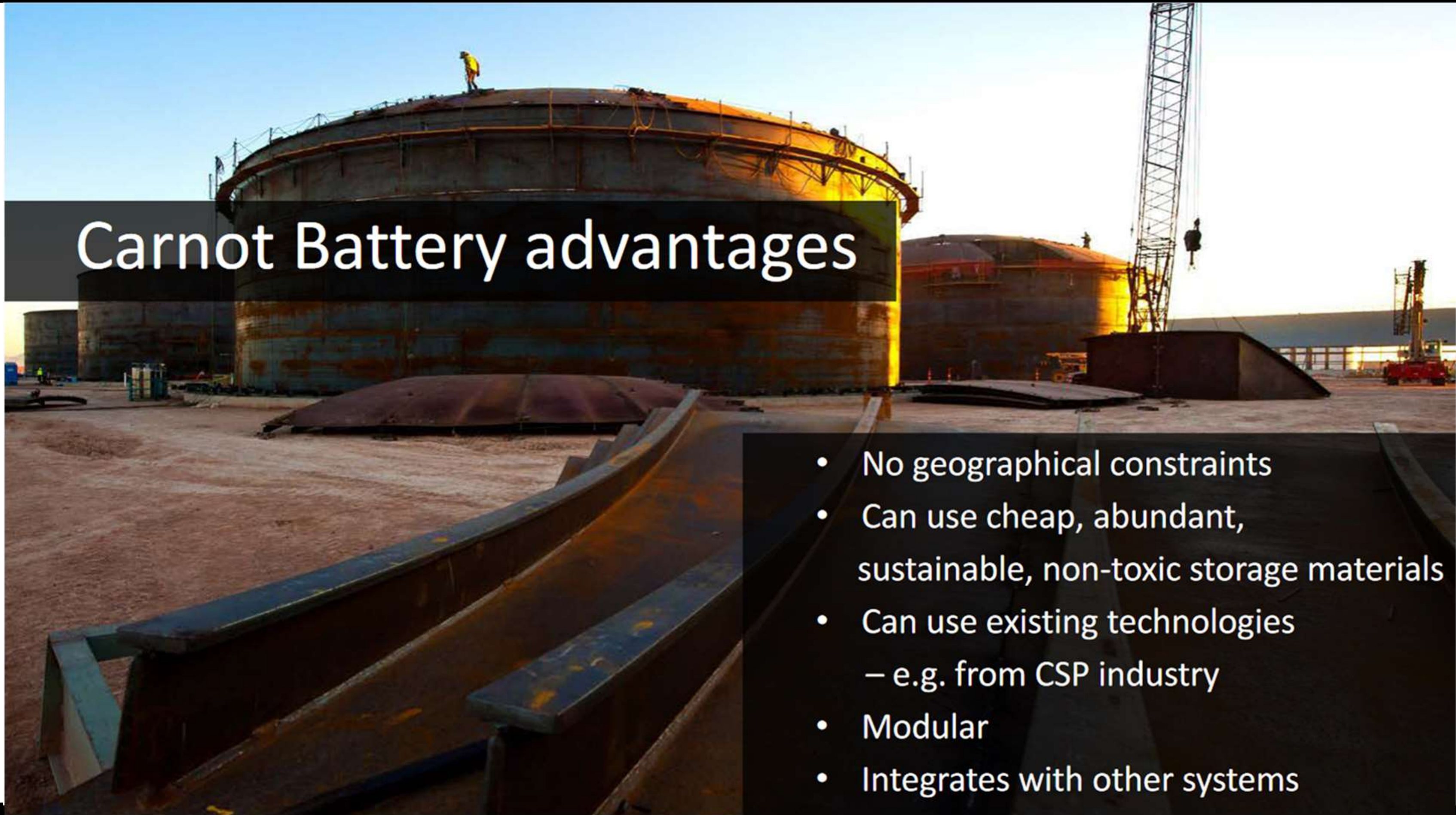


Img courtesy of Deutsches Zentrum fur Luft und Raumfahrt (DLR)

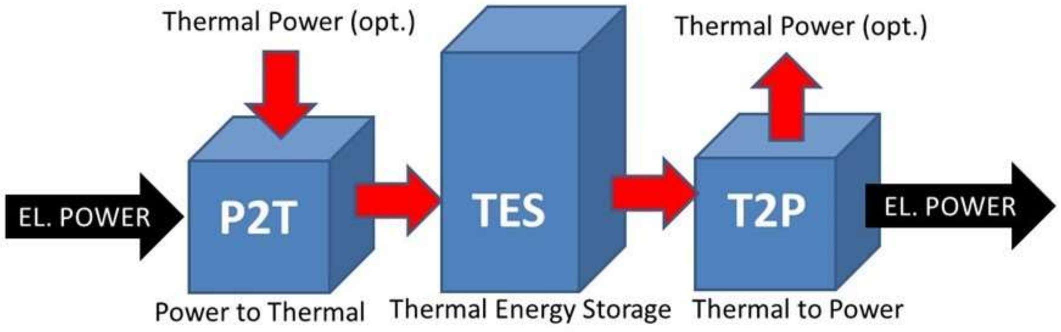
Carnot Battery



Carnot Battery



Carnot Battery

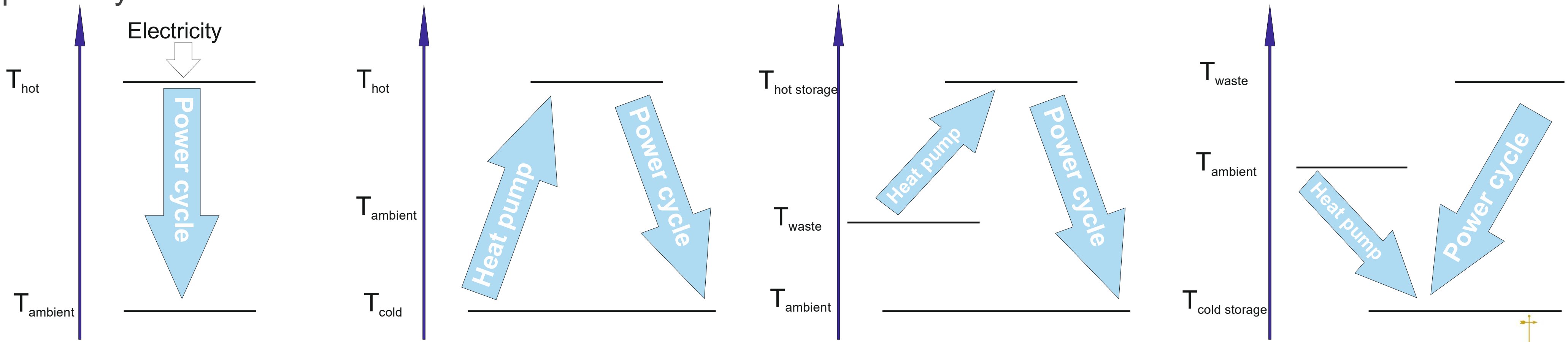


Unification of names such as PTES, ETES, LAES, PHES… =>
Carnot Batteries

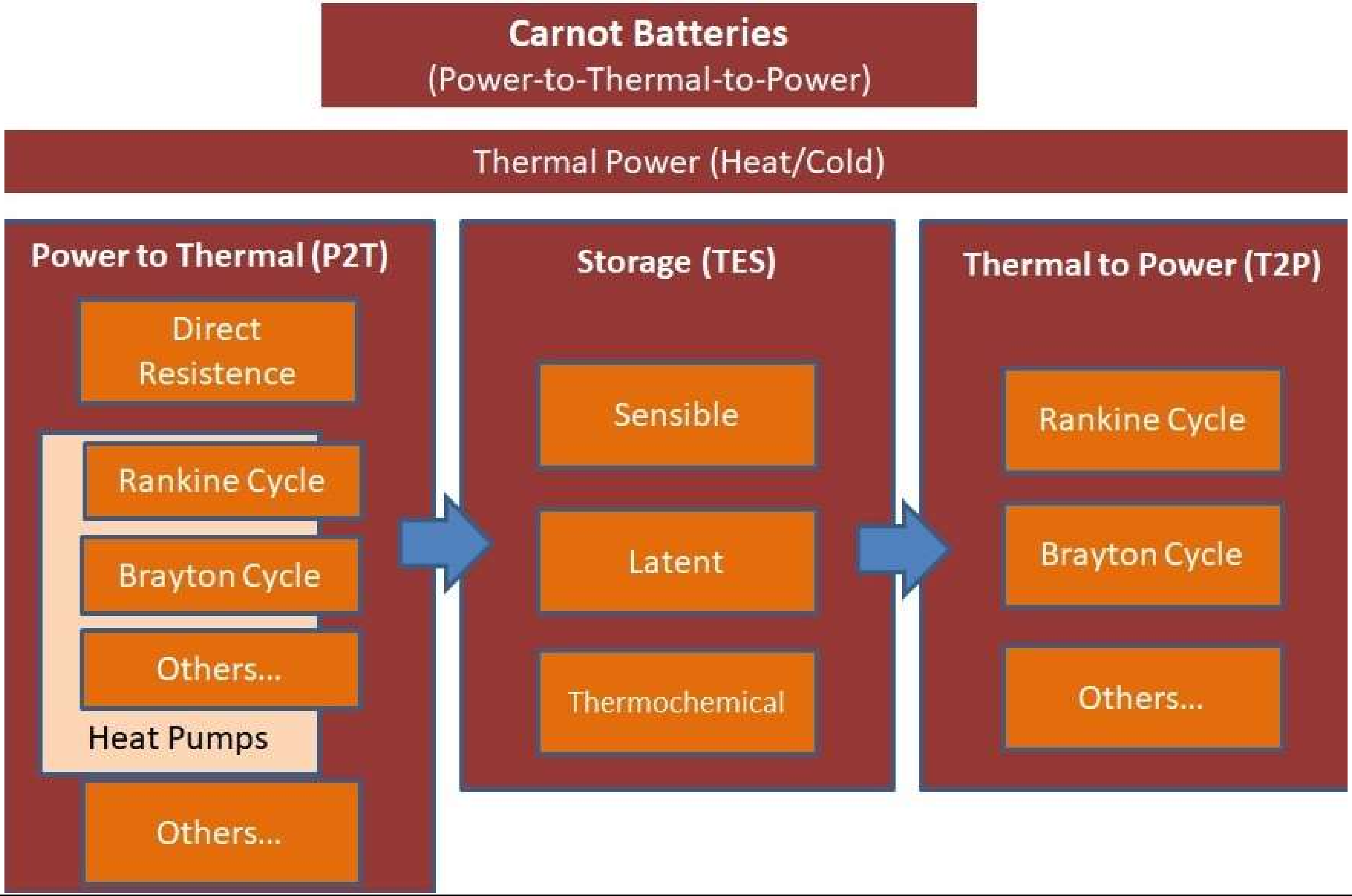
- Direct el. Heating

+ power cycle

- PTES
- TI-PTES (hot)
- TI-PTES (cold)



Principles and technologies for CB



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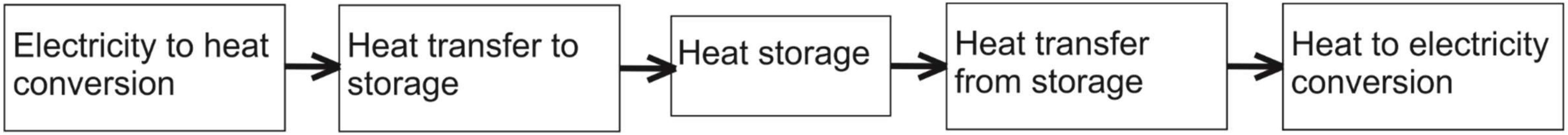
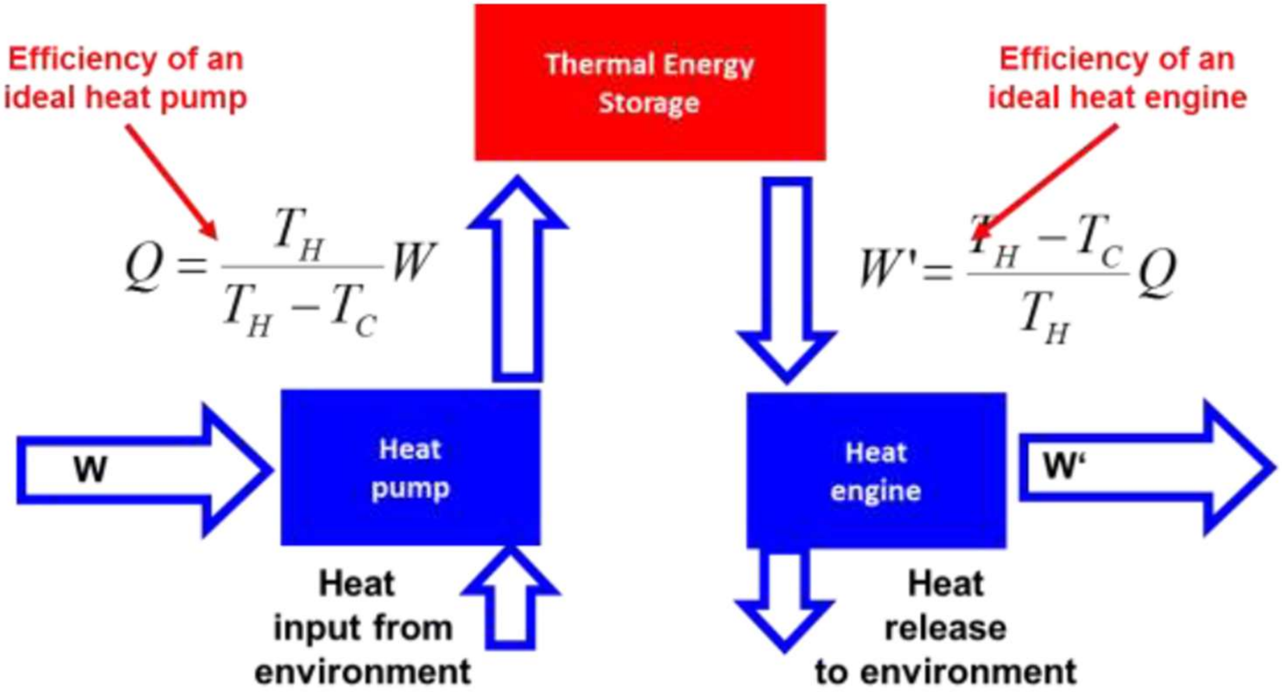


Power to heat	Transfer to storage	Storage type	Transfer from storage	Heat to power
Resistance heaters	n.a. (heating storage directly)	Solid beds (rocks, glass, concrete, ceramics…)	same as to storage	RC simple
Compressor (heat pump principle)	liquid -storage fluid	Solid particles (sand systems)	power cycle fluid	RC highly regenerated
Induction heating (of cond. mater.)	Liquid/ gas -intermediate fluid	Solid monoliths (steel, concrete,…)	other intermediate fluid	Brayton (direct / indirect; open / closed)
	heat pipe	Liquid inorganics (salt, metal, water)		ORC
		Liquid organics (oils, antifreeze)		Absorption cycle (Kalina)
		Phys. absorption systems (liquids)		Trilateral cycle
		Phys. adsorption systems (solid beds)		S-CO_2 cycles
		Thermochemical conversion - liquids		Stirling
		Thermochemical conversion - solids		combinations (e.g. Brayton + RC)
		PCM - solid-liquid (metals, salts, paraffin)		Thermophotovoltaic, thermionic, Thermoelectric…
		PCM - solid-solid (change crystal. structure)		
		PCM – gas-liquid (liquefied air cold storage)		

Efficiency of an „ideal CB“



→ Total theoretical round-trip efficiency: Ψ=1=100%

→ Predicted real round-trip efficiency: 35% < Ψ < 75%

Img courtesy of Deutsches Zentrum fur Luft und Raumfahrt (DLR)

Economic aspects of CB

Cost of fluctuating power

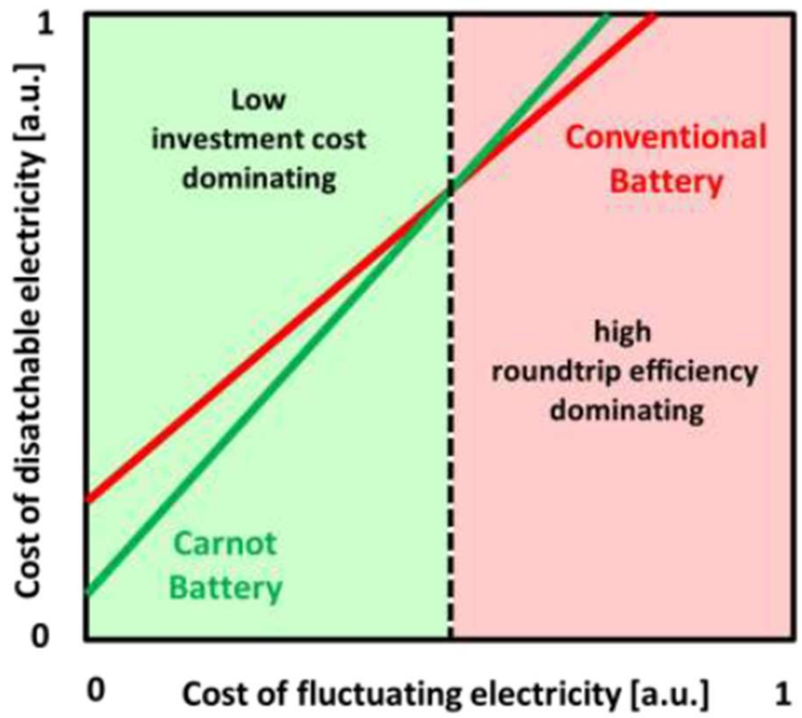
Investment costs

Cost of dispatchable power

$$\mathbf{P_d} = \frac{P_f}{\eta} + \frac{I}{N}$$

Storage efficiency

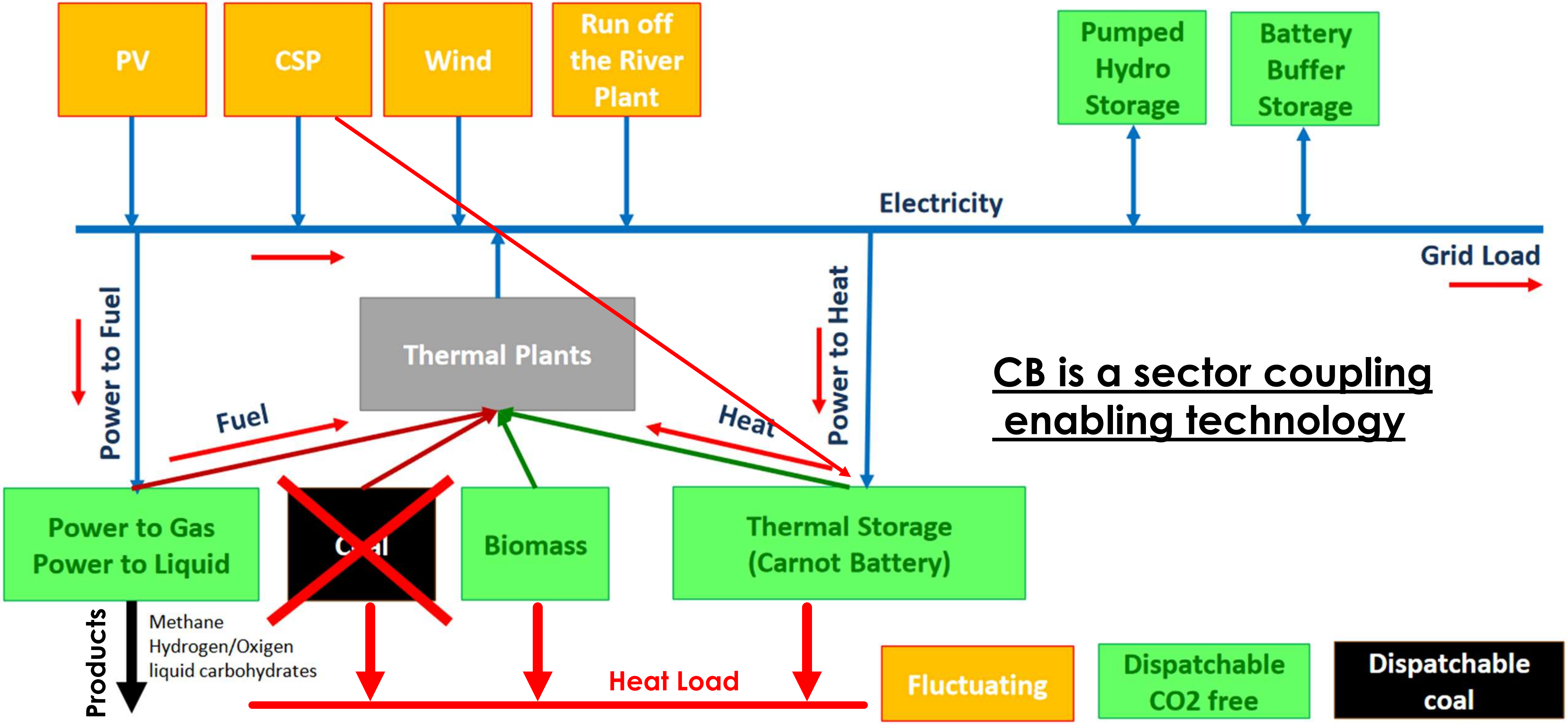
Number of cycles



That's not accounting for the heat as an output…

Img courtesy of Deutsches Zentrum fur Luft und Raumfahrt (DLR)

Carnot Batteries for decarbonization

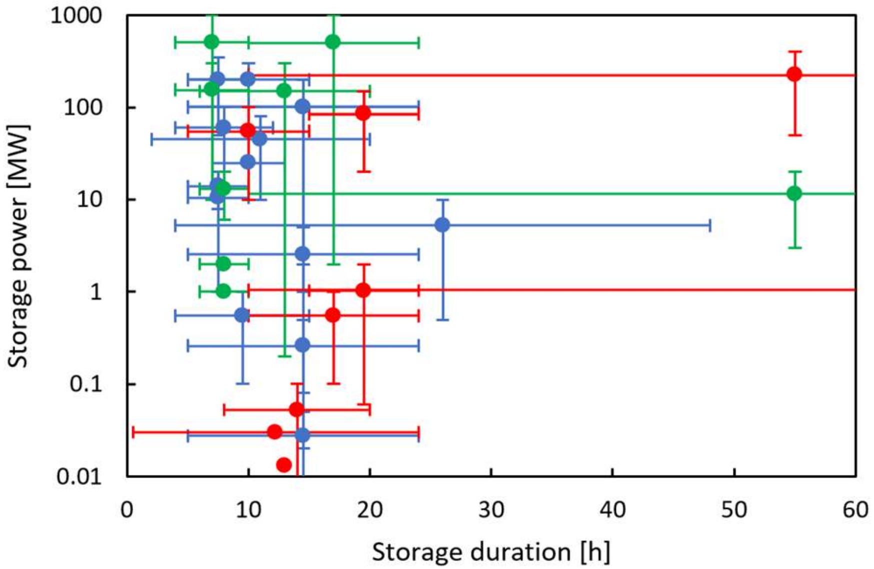


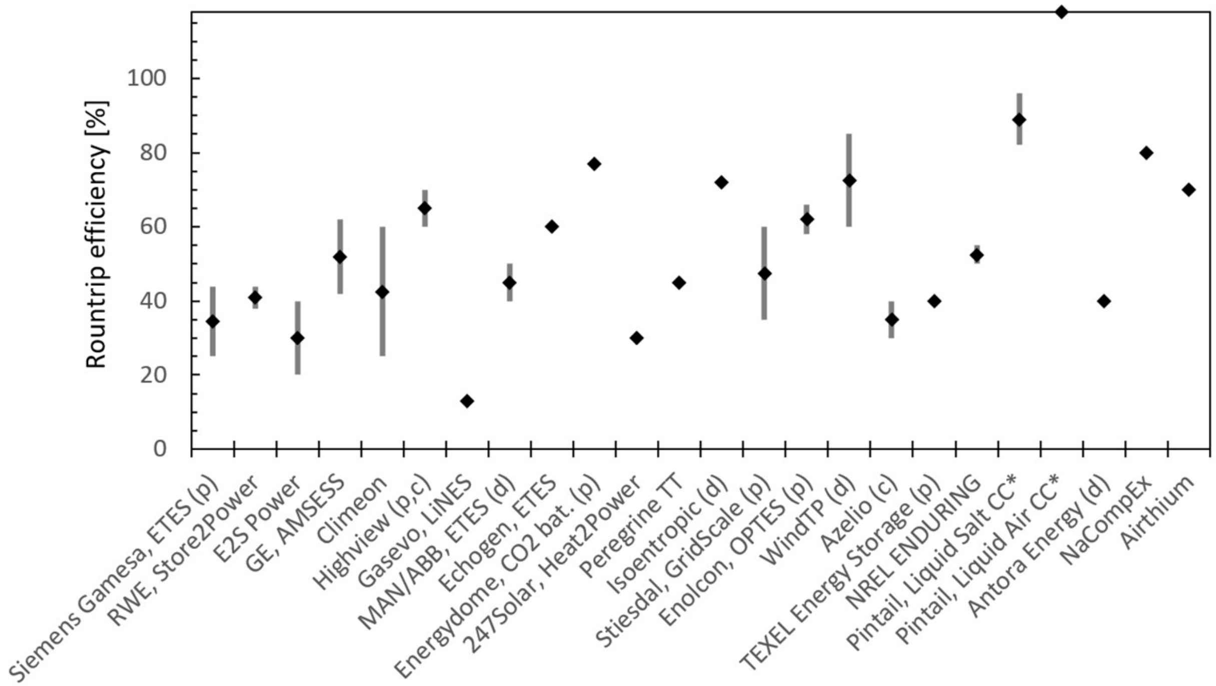
<u>CB is a sector coupling enabling technology</u>

Global overview of CB – state of the art

- Several demonstration and proof of concept systems, multiple announced projects
- Several companies with basic to detailed design – funded by some of the largest Energy investment groups
- Number of prototypes of parts and components, which are key to the CB systems
- Many principles similar to existing applications (e.g CSP, ORC, high temperature heat pumps, power plants…), the major part of technical know-how in sector coupling and predictive control
- Increasing interest in research – ORC community and Storage community more and more inclines to the topic of Carnot Batteries

State of the art





Proposed solution

1864	Perkins calcium chloride engine (p)			
1885	Honigmann fireless locomotive (p)			
2004	Isentropic ltd 1st prototype (d)			
2011	Highview LAES 350 kW (d/p)			
2012	Isentropic ltd 2nd prototype (d)			
2014	Siemens G. rock storage 1st prot.			
2015	Isentropic ltd 3rd prot. construction			
2016	Isentropic Ltd bancrupt			
2018	Futurebay 50 kW (d/p)	Highview LAES 5 MW (p)		
2019	1414 unit (d/p)	Isentropic 150 kW (d/p)	CCT Energy Storage (p)	Siemens Gamesa 1.2 MW (p)
2020	Antora prototype (d)			
2021	CHESTER, E2S (d)	Prototypes kW scale heat pump Echogen, TČ Mach (d)	MAN ETES MW scale (d)	Azelio 13 kW unit (c)
2022	Kraftenlagen 60 kW (p)	Highview LAES 50 MW (c)	EnergyDome 2.5 MW (p)	Stiesdal 2 MW (p)
2023	Highview LAES 50 MW (c)	MAN heat pump 50 MWth (c)		

SoA - example - Siemens Gamesa

- **Siemens Gamesa CB - demonstrator in Hamburg**
  - 5.4 MWe charging power – direct heating
  - 1.2 MWe discharging power
  - 24 h storage capacity
  - 1000 t storage material
  - 25% round trip efficiency (claimed possibility for 50% in larger and optimized case)
  - Rock packed bed thermal energy storage
  - Discharge: steam cycle 65 bar, 480°C
  - ... BUT discontinued in 2023 due to financial problems of Siemens Gamesa

Hamburg, Germany. 12th June, 2019. The technology group Siemens Gamesa Renewable Energy has started testing an electrothermal energy storage system in the Port of Hamburg. (aerial photo with drone) Credit: Axel Heimken/dpa/Alamy Live News

Development steps

- High temperature storage: proof of concept ✓
- Demonstrator (2018): 1.2 MW / 1 d* / η ~ 25%
- Pilot plant (2020): ~30 MW / 1-3 d* / η ~ 35%
- Large scale storage (202X): 100 MW / 2-7 d* / η ~ 50%

*Continuous discharge time

https://windenergietage.de/wp-content/uploads/sites/2/2017/11/26WT0811_F11_1120_Dr_Barmeier.pdf

CB research @ CTU in Prague

1. 2nd life for coal fired DH CHP plants by CB – **modelling, feasibility studies**
2. High temperature rock packed bed storage, stratification and dynamic response – **test rig**
3. Pumped thermal energy storage with stone dust storage and ORC - **demonstrator**

CTU

UCEEB

2nd life for fossil DH CHP plants by CB

- CZ – 40% households connected to DH
- DH usually built in 60s-70s,
- old „Soviet" technology, coal-fired, 5-50MWth
- CB creates new possibilites for revenue streams for outdated fossil-fueled DH CHP plants
- Thermoeconomical modelling of seasonal revenue on real data from Czech market
- LCOS 150€/kWhe for 5hrs molten salt storage

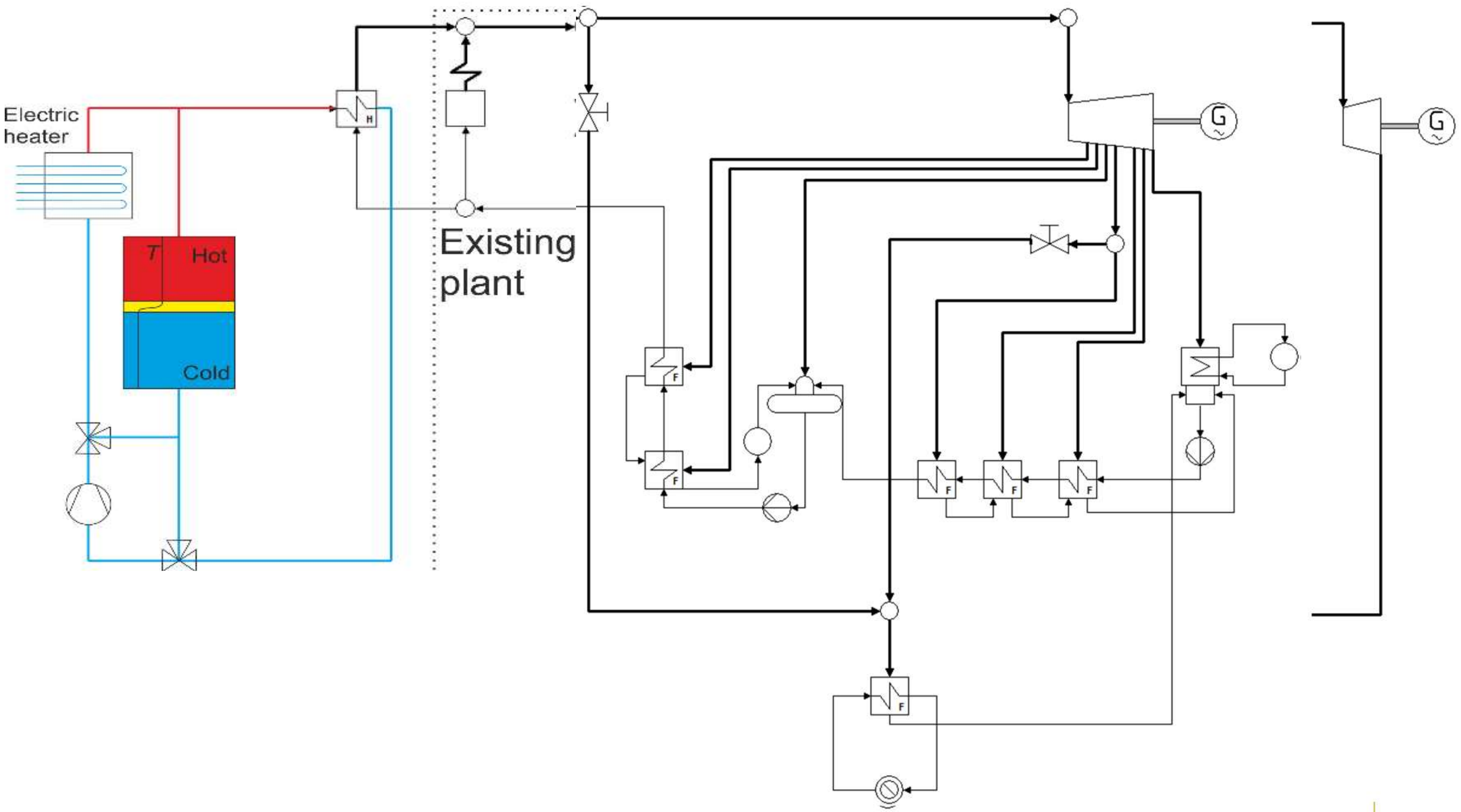
https://www.sciencedirect.com/science/article/pii/S2352152X22015390?via%3Dihub

2nd life for fossil DH CHP plants by CB

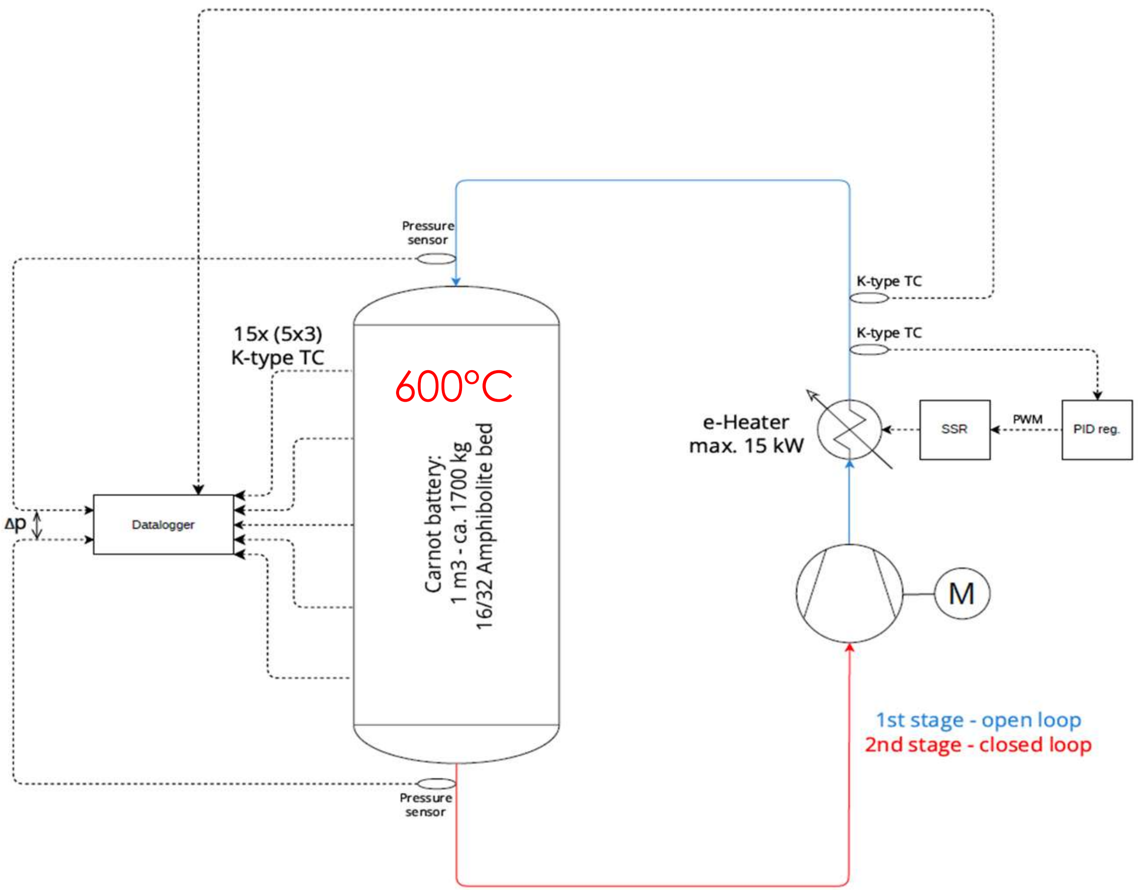
- Typical CHP plant with one condensing extraction and one backpressure turbine
  - Possibly also multiple extractions
  - Simplification of layout
    - 0-100% extraction
  - Addition of storage

    and el. heating
  - Molten salt

    or rock packed bed

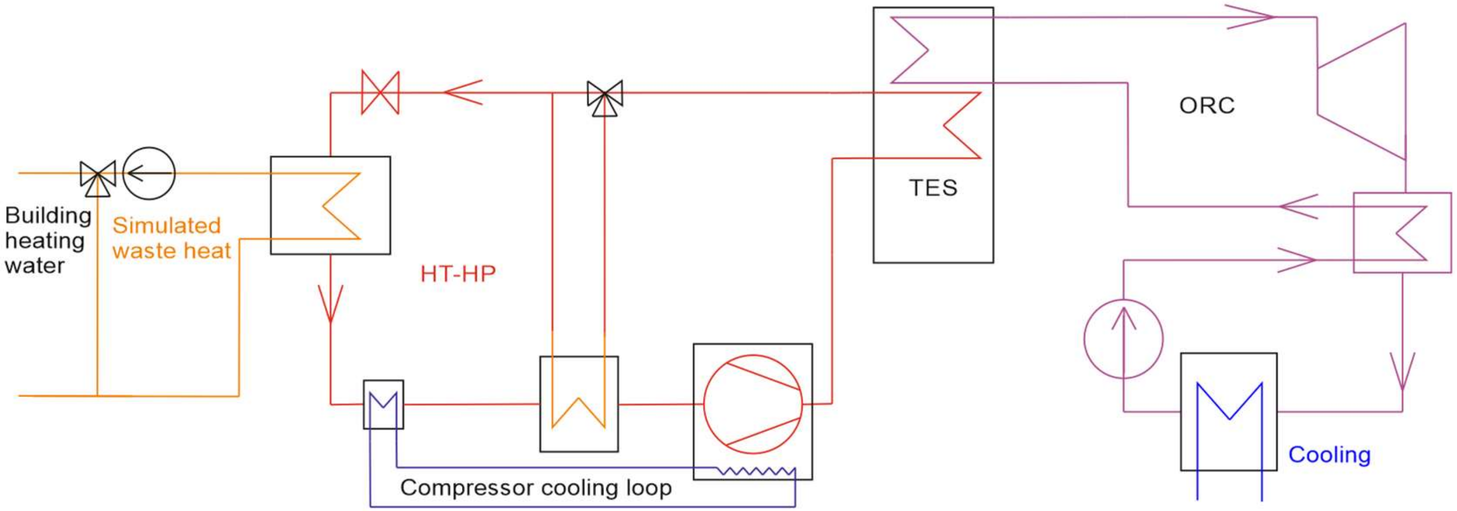


High temperature packed bed storage



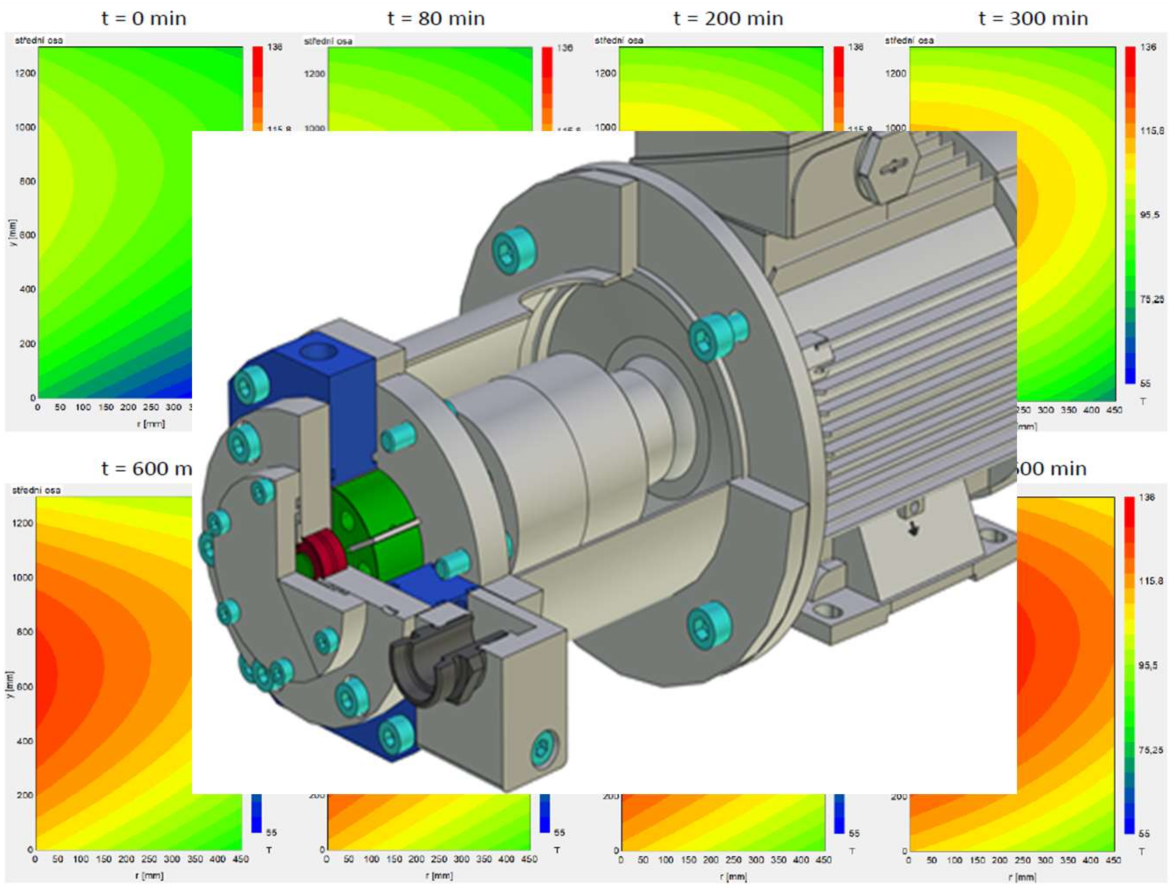
- Stratification in rock packed bed storage based on rock properties and granulometry
- Resistive heating, air as HTF
- Measurements of rock distribution: dynamic response versus storage capacity and pressure drop
- Currently under construction (size 2tons of rocks)

CB for small-scale WHR with stone dust



- demonstrator unit (12kWh storage, 1kW compressor)
- HTHP + stone dust storage tank (direct condensation to stone dust) + LT ORC
- Simulated WHR heat source by UCEEB building load
- R1233zde wf
- Piston compressor with customized oil cooling by liquid refrigerant
- rotary vane expander

CB for small-scale WHR with stone dust



OK, I want to know more about CB

International Energy Agency

IEA Technology Collaboration Programme

https://iea-es.org/

TASK 36 CARNOT BATTERIES

https://www.eces-a36.org/

- Self-promotion time!
  - Novotny, V., Basta, V., Smola, P., Spale, J. *Review of Carnot Battery Technology Commercial Development*. Energy 2022, 15, 647. https://doi.org/**10.3390/en15020647**
  - Basta A., Basta V., Spale J., Dlouhy T., Novotny V. *Conversion of combined heat and power coal-fired plants to Carnot batteries - Prospective sites for early grid-scale applications.* Journal of Energy Storage, 2022 55. https://doi.org/**10.1016/j.est.2022.105548**
  - Task 36 „Carnot Batteries“ report to IEA – available at https://iea-es.org/ (anyday soon)

Final words

Think about Carnot Batteries when you hear quotes as such:

- **Robert Laughlin** (Stanford University), lauerate of the Nobel Prize in Physics: *„power-heat-power storage units (known as Carnot batteries) will be the key technology for storing large quantities of energy in a carbon-neutral energy system of the future"*
- *„**Bill Gates, Jeff Bezos and Jack Ma** invested 26mil USD into a pumped thermal energy storage company Malta Inc. to develop a so-called grid-scale Carnot battery…"*
- **„Malta** raises another $50M to Commercialize its Long Duration Energy Storage System named Carnot Battery…"
- „**Antora Energy** raise $80M from Bill Gates, Chris Sacca and other venture funds to breakthrough low-carbon large scale electricity storage (Carnot Battery) …"

Acknowledgement

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