From Sadi Carnot to Carnot batteries

A presentation of research activities at the thermodynamics laboratory of ULiege

Vincent Lemort and co-workers

Carnot Commemorative Session

Herrick Conferences at Purdue University, July 17th 2024

LIÈGE université

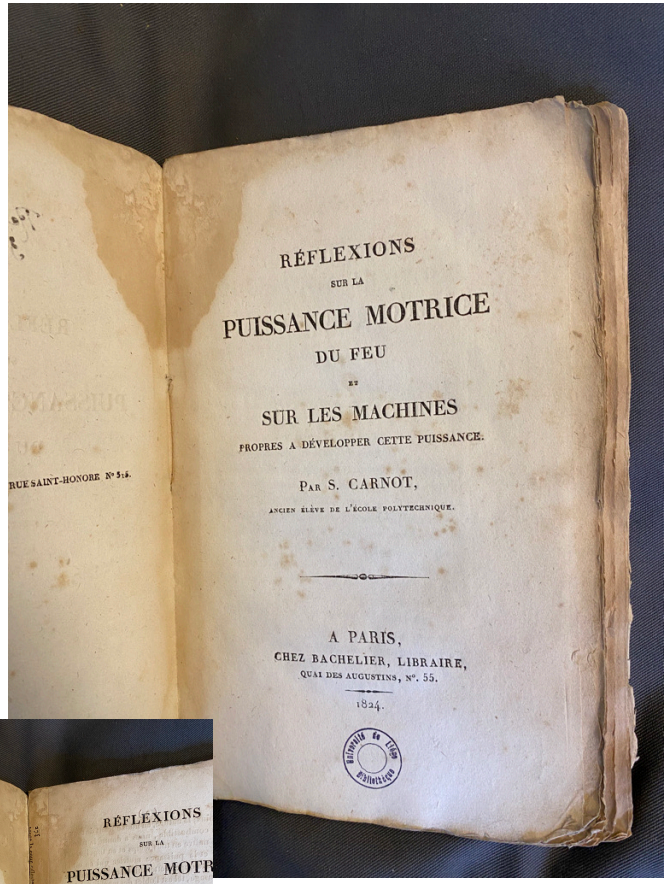
LABORATOIRE DE THERMODYNAMIQUE UNIVERSITÉ DE LIÈGE

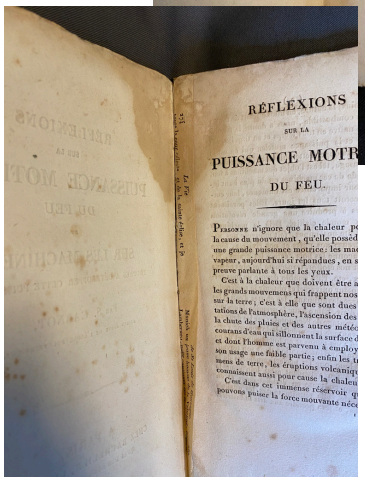
Introduction

The impact of "Reflexions" (1824)

- Published 200 years ago by Sadi Carnot (28-year-old)
- Not a success: almost no sales (less than 600 copies)
  - not enough practical
  - didn't conform to conventional "scientific" writing style?
  - not sent to major Academies of Sciences (Paris, London,…)
- Latter recognized as the foundation of the 2nd Law of thermodynamics
- (hopefully largely digitized)

What are more specifically the contributions?

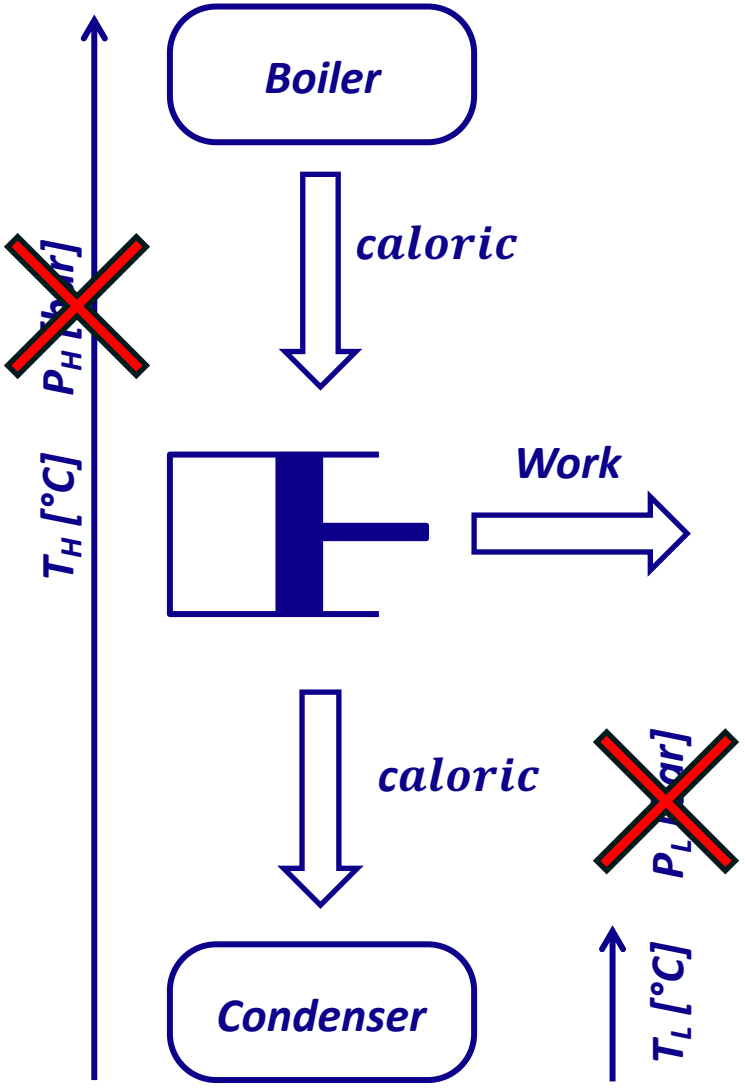

RÉFLEXIONS
SUR LA
PUISSANCE MOTRICE
DU FEU
ET
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.
PAR S. CARNOT,
ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.
A PARIS,
CHEZ BACHELIER, LIBRAIRE,
QUAI DES AUGUSTINS, N°. 55.
1824.


RÉFLEXIONS
SUR LA
PUISSANCE MOTR
DU FEU.

Recycled paper used?
« La vie de Saint Louis de Gonzague »

Introduction

The impact of "Reflexions" (1824)



1. The maximal power is related to the **temperatures**

Temperature (and not pressure) is the critical variable.

2. The cycle must be **closed** for analysis

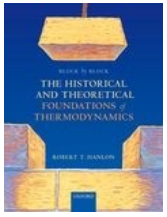
The piston expander, the boiler, the condenser and the pump(s) considered as a whole.

3. The maximal performance is not function of the nature of the **working fluid**

Going beyond the debate between air and water

4. Carnot cycle is **reversible**

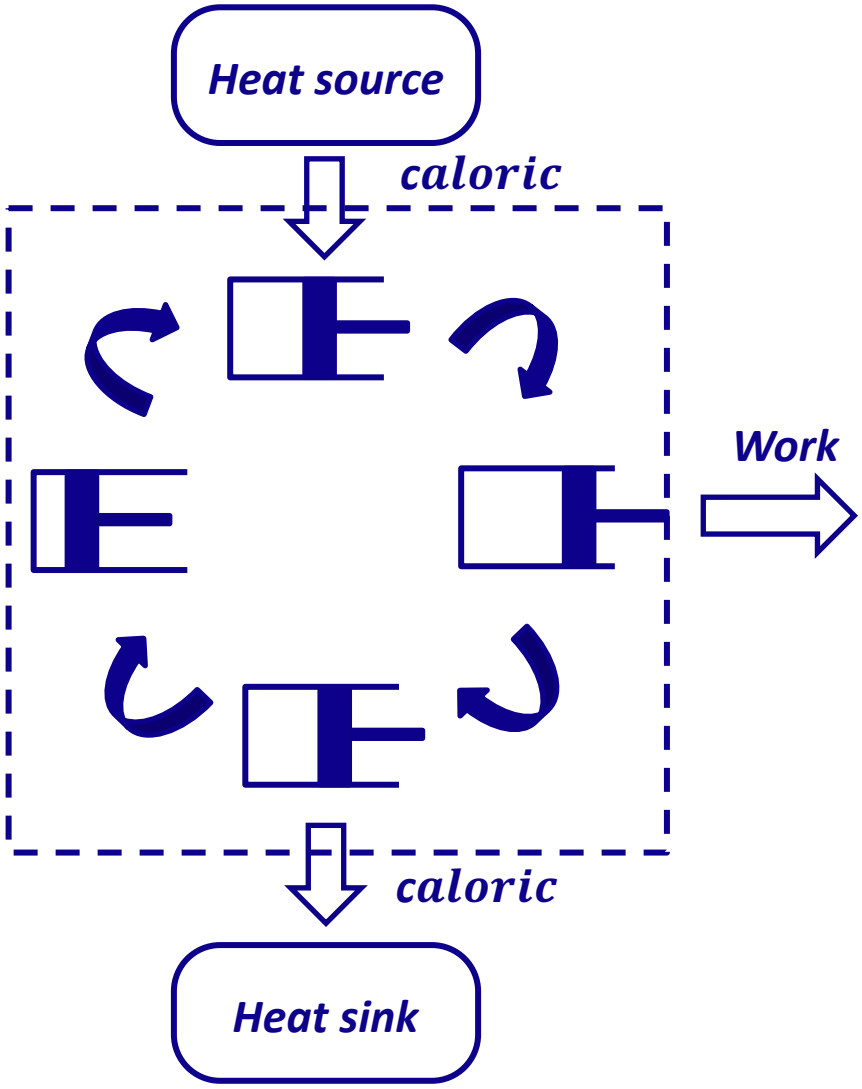
Pursuing the work of his father on reversibility



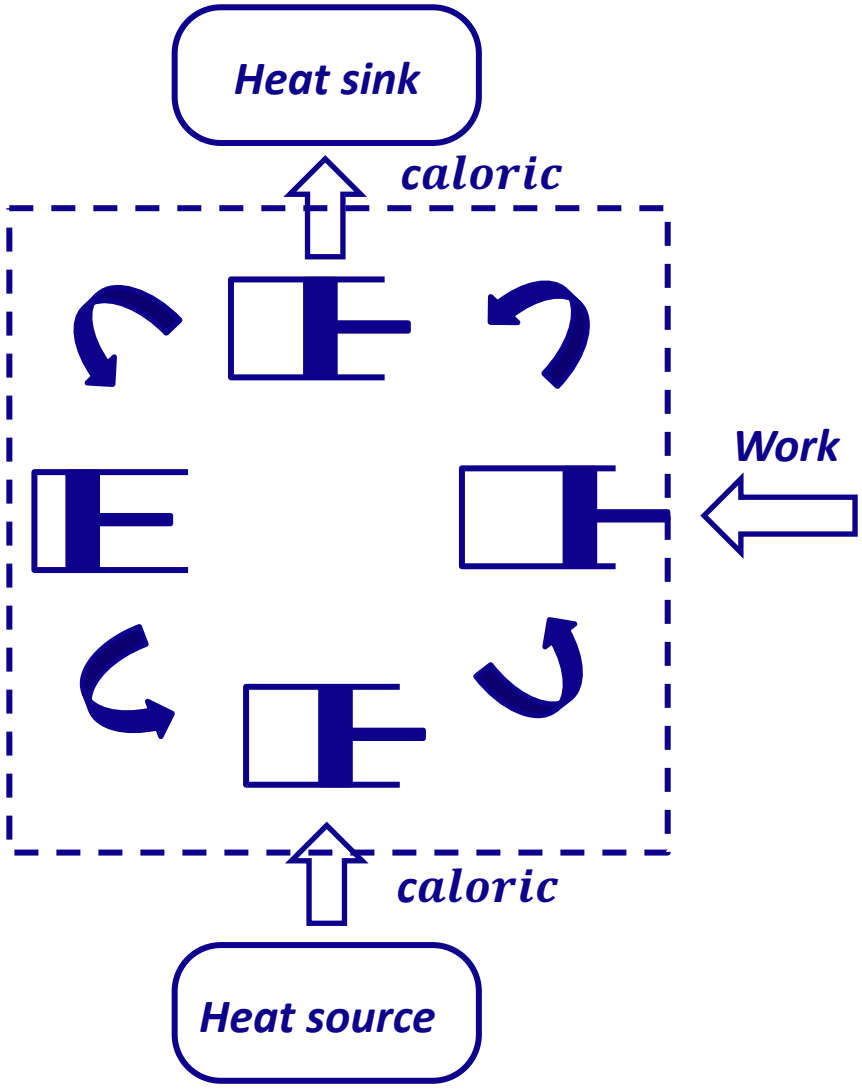
Most information presented here and in next slides was found in Hanlon, Robert. *Block by Block: The Historical and Theoretical Foundations of Thermodynamics*, Oxford University Press, 2020.

Introduction

The impact of "Reflexions" (1824)



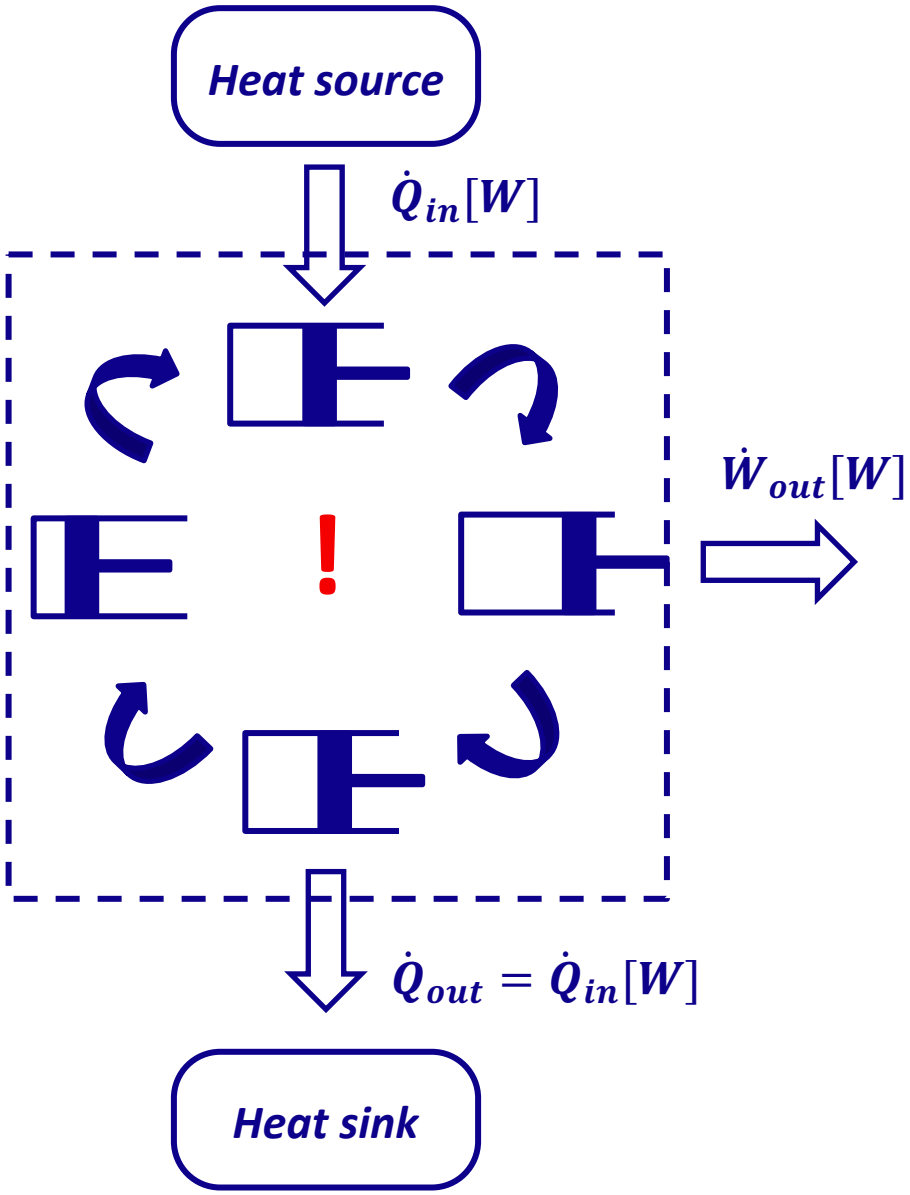
Heat engine



Heat pump

Introduction

The impact of "Reflexions" (1824)



- The supporting caloric theory was wrong… but it hasn't prevented Carnot to draw the right conclusions (2nd Law).
- 1842: Mechanical Equivalent of Heat (1st Law) discovered/quantified by **Mayer** and (then, though independently) **Joule**.

Carnot's legacy is of tremendous importance in the context of:

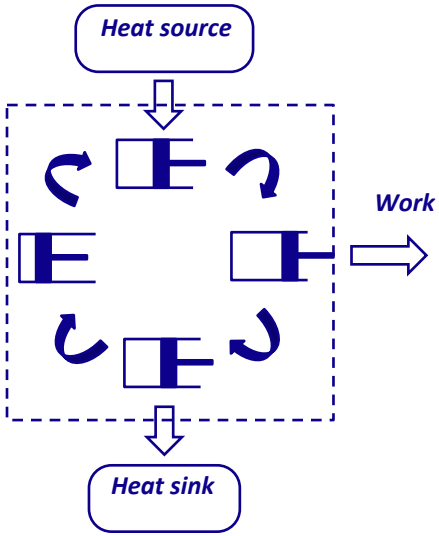
- *Electrification of heating/cooling*
- *Energy storage needs*
- *Waste heat valorization*
- *…*

What is (modestly) illustrated in this presentation

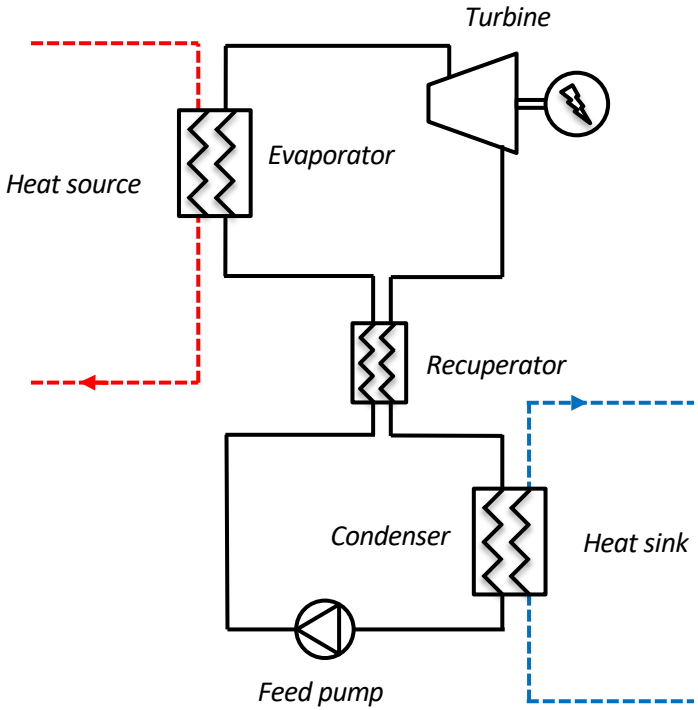
Agenda of the presentation

1. Introduction
2. **Heat engines: Organic Rankine Cycle Power systems**
3. Heat pumps
4. Hybridization of heat engines and heat pumps
5. Combination of heat pump and heat engines
6. Take-away messages

Organic Rankine Cycles

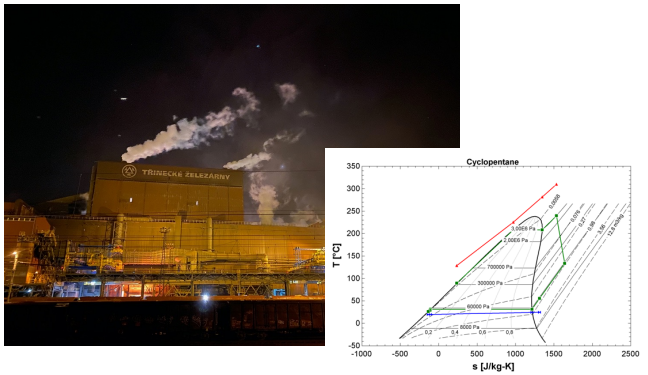


"Vapors of all substances capable of passing into a gaseous condition, as of alcohol, of mercury, of sulphur [sic], etc., may fulfil the same office as vapor of water".
(Carnot's Reflexions (1824) translated by Thurston, 1880)

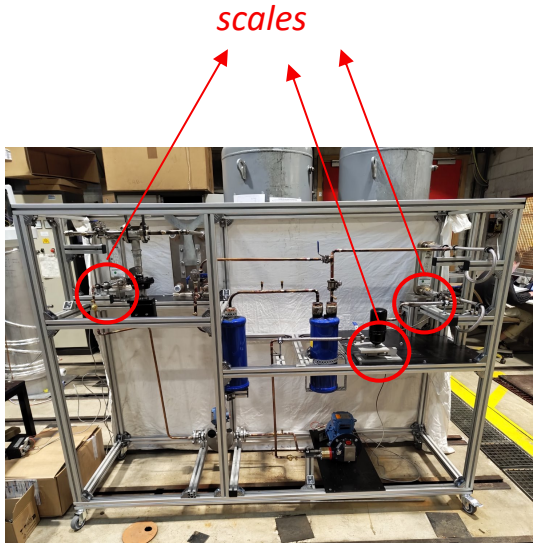


Organic Rankine Cycles

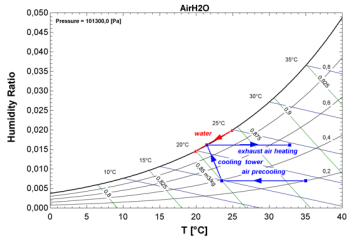
- Context
  - Tremendous amount of **waste heat** around 100-250°C
  - ORC is a promising solution with still room for improvement.
- Research topics
  - Waste heat recov. exchangers (limited pressure drop, cost)
  - Use of natural fluids (cyclo-pentane), oil/fluid mixture properties
  - Active Charge Management/charge sensitive modeling.
  - Use of thermal storage to damp heat source fluctuations
  - FDD/Predictive maintenance
  - Dew point cooling towers

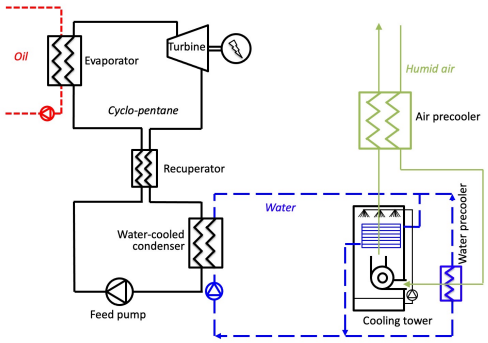


2 MWe ORC installed in a slab reheating furnace



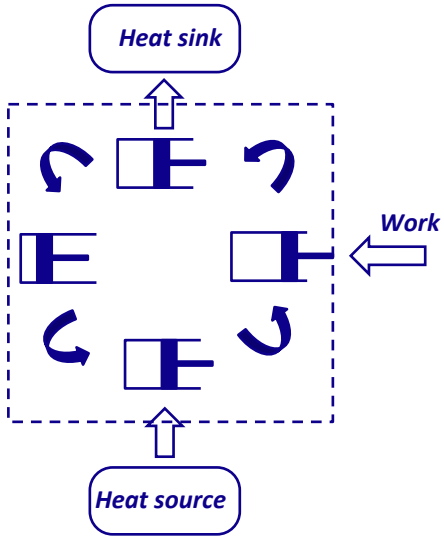
Charge-sensitive test bench (cyclo-pentane)





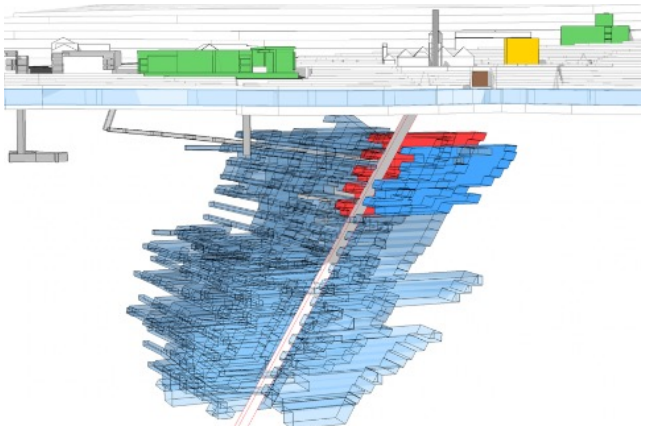
Coupling with dew point cooling tower

Heat pumping and air-conditioning



- Context
  - Electrification of heating and cooling sectors
  - Need of cheap, efficient, and multi-term energy storage solutions

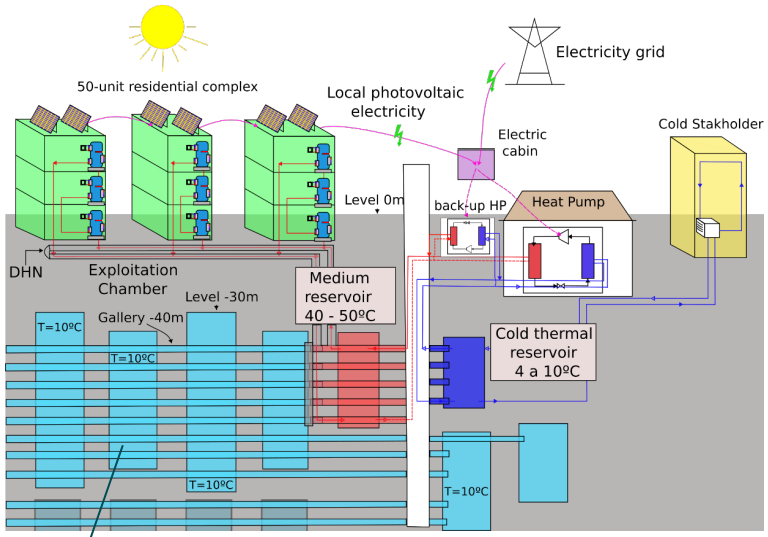
= > Abandoned **flooded** slate **mines**: massive storage (500,000 m^3)

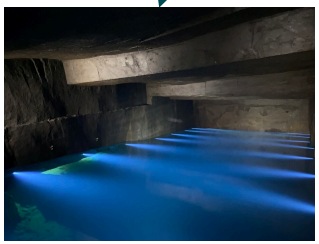


Heat pumping and air-conditioning

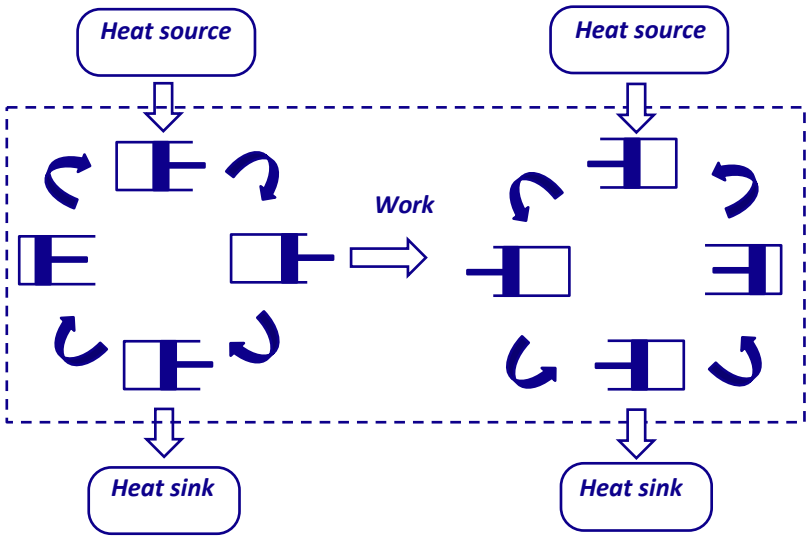
Massive thermal energy storage

- Research questions
  - Water-to-water HP + PV panels
  - Hot storage (50-40°C): 6840 m^3
  - Cold storage (10-5°C): 20000 m^3 (currently partially regenerated naturally: a cold user is being sought)
  - Investigate the possibility to store heating and cooling energies for building HVAC and commercial refrigeration.
  - "RE-entracking" energy storage: **maximization of self-consumption** of local PV production (95.2%).
  - Simulated yearly (heating) COP of 2.86





Hybridizing heat engines and heat pumps



Combining heat engine and heat pump cycles allow to derive heat-driven heat pumps, chillers, polygeneration systems.

(first VC refrigeration machines were driven by steam engines)

Hybridizing heat engines and heat pumps

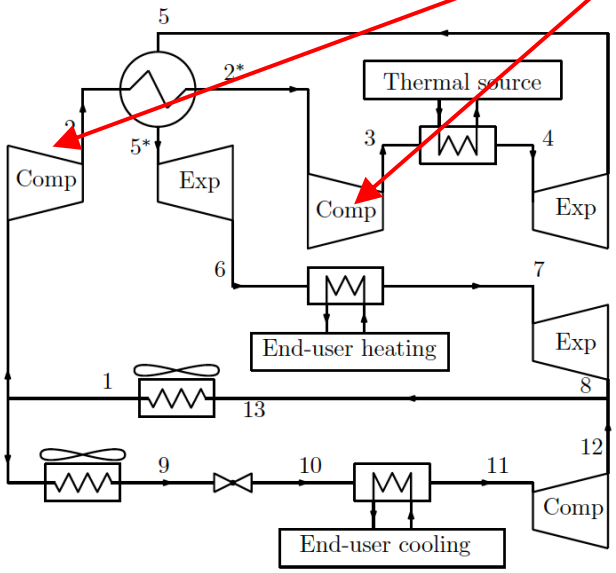
Multi-energy generation machines

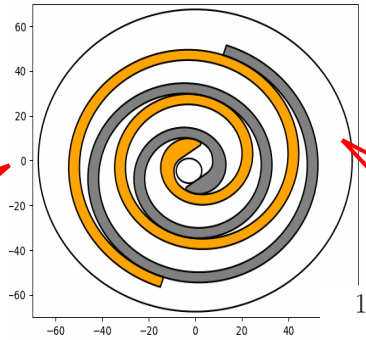
- Multigeneration of cooling, heat and electricity (CCHP) based on one single machine valorizing a low-grade heat source.

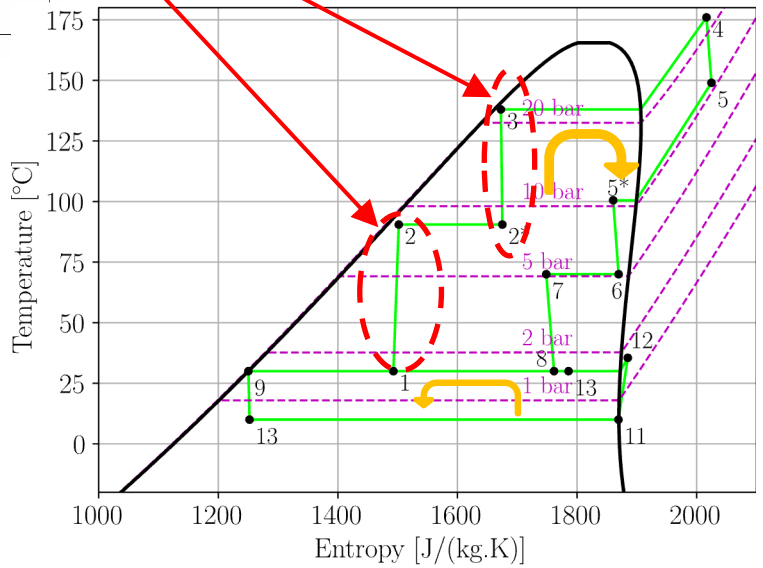
Research question

- 2-phase scroll compressor design

(2020-2026)





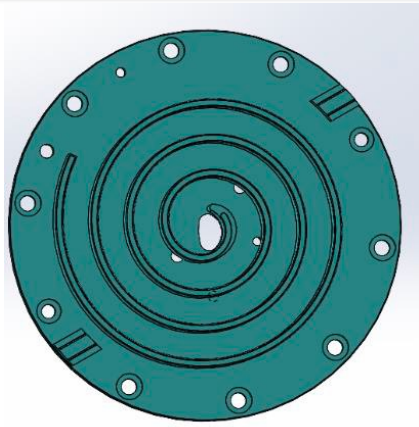


Regen-by-two: Next REnewable multi-GENeration technology enabled BY TWO-phase fluids machines.

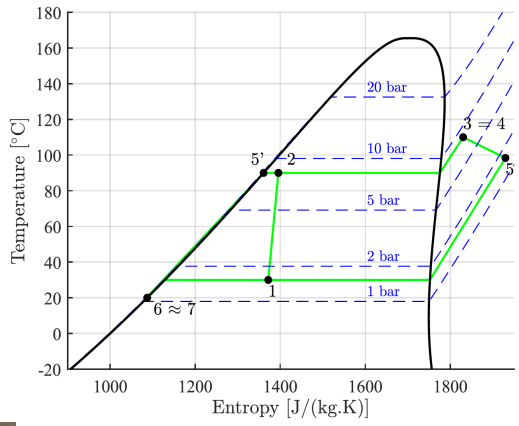
Hybridizing heat engines and heat pumps

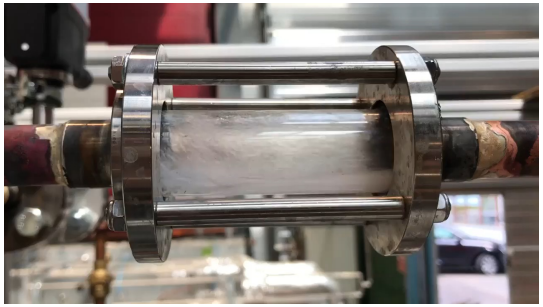
Multi-energy generation machines

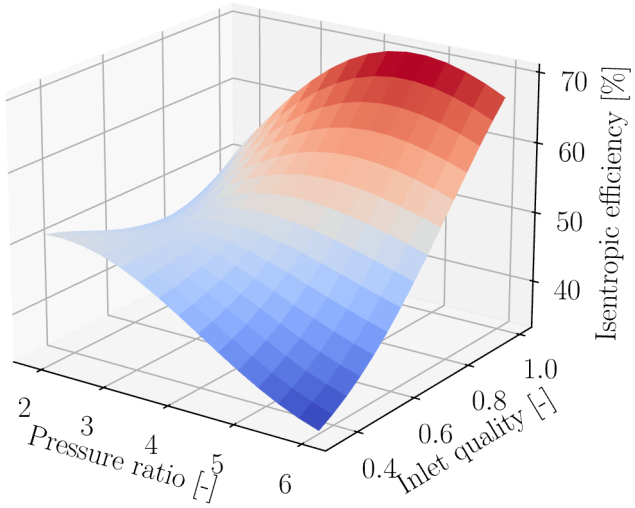
- **Compressor prototype** design:
  - Larger pressure losses in supply/discharge ports
  - Larger under-pressure losses with low quality
- **Test bench** : tests with **inlet quality** around **40%** have been achieved



Prototype of 2-φ compressor



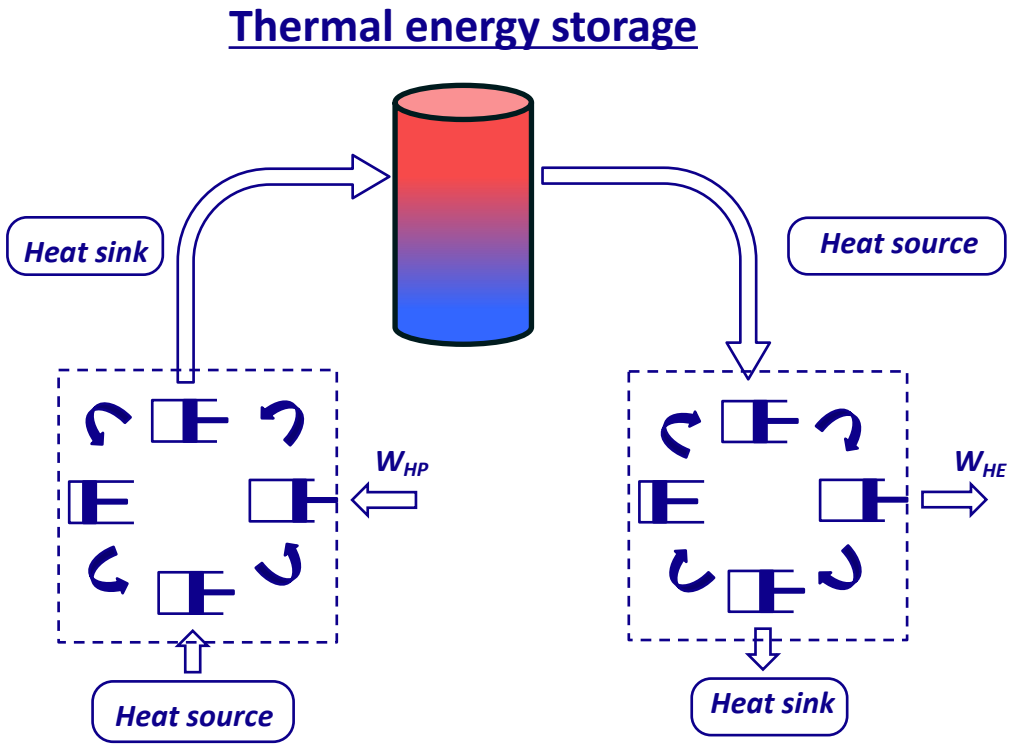




Measured isentropic effectiveness

Reversibility of heat engines

Carnot batteries



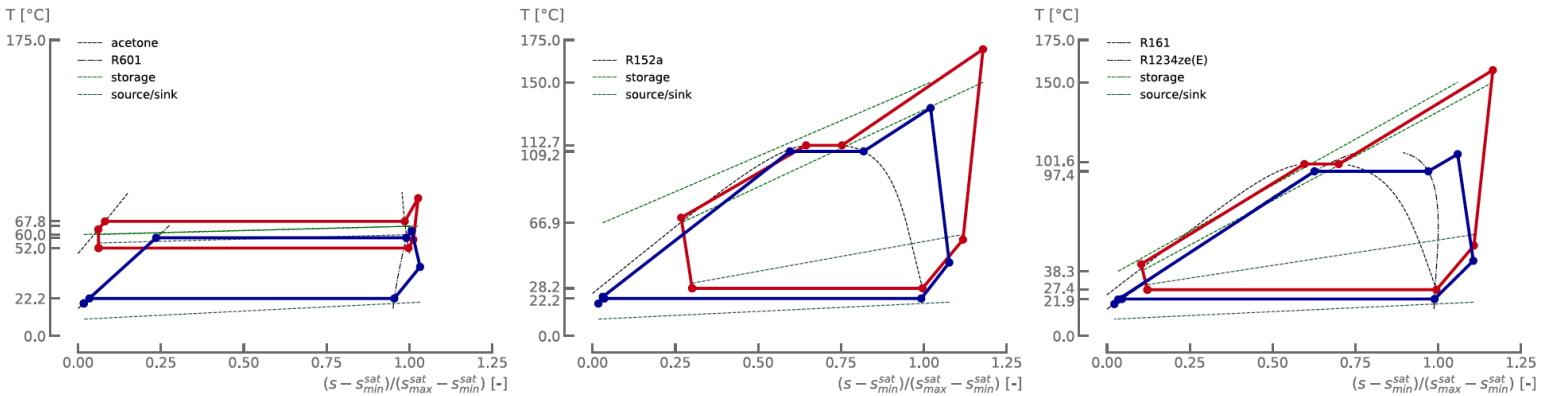
$$\eta_{P2P} = \frac{W_{HE}}{W_{HP}} = COP_{hp}\,\eta_{ORC} = \eta_{II}^{hp}\,\eta_{II}^{ORC}\,COP_{HP}^{carnot}\,\eta_{ORC}^{carnot}$$

Reversibility of heat engines

Carnot batteries

Research questions

- **Design** and **control** optimization
- Performance can be improved when valorizing **waste heat** (trade-off η_{P2P}, η_{II} and ρ_el)
- Immersion of ORC evaporator/heat pump condenser with a compact **PCM storage** (no secondary fluid => less ΔT_{pinch}): 20 kW_{th} heat pump with $T_{cd} = 130°C$ (Sehrene EU project)

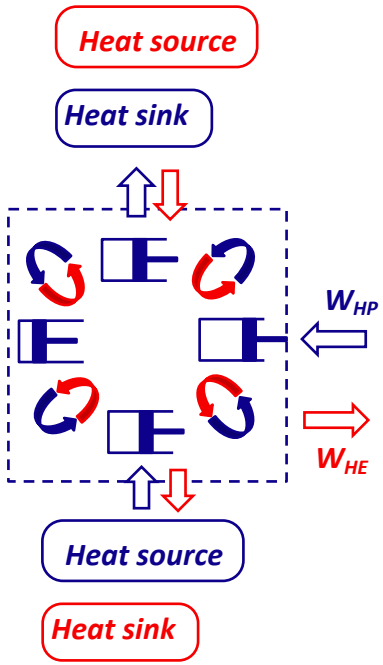


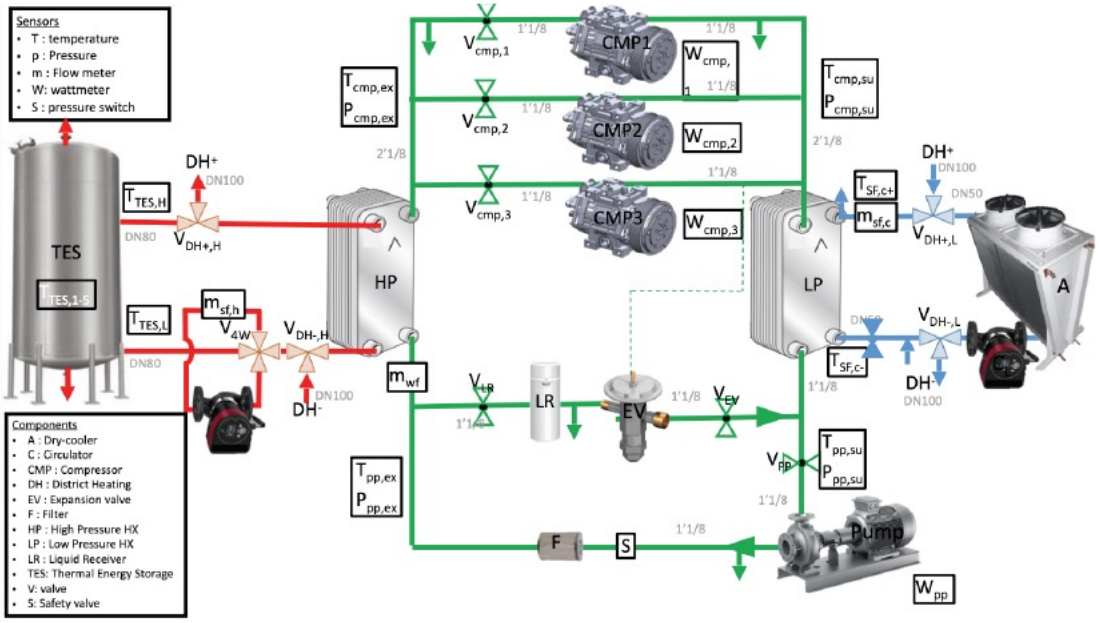
(g) $t_{hs} = 60°C$, $t_{cs} = 10°C$, max. η_{P2P} **(h)** $t_{hs} = 60°C$, $t_{cs} = 10°C$, max. η_{II} **(i)** $t_{hs} = 60°C$, $t_{cs} = 10°C$, max. ρ_{el}

Source: Antoine Laterre et al., Extended mapping and systematic optimisation of the Carnot battery trilemma for sub-critical cycles with thermal integration, Energy, Volume 304, 2004

Reversibility of heat engines

Inversible heat pump/ORC units for Carnot batteries





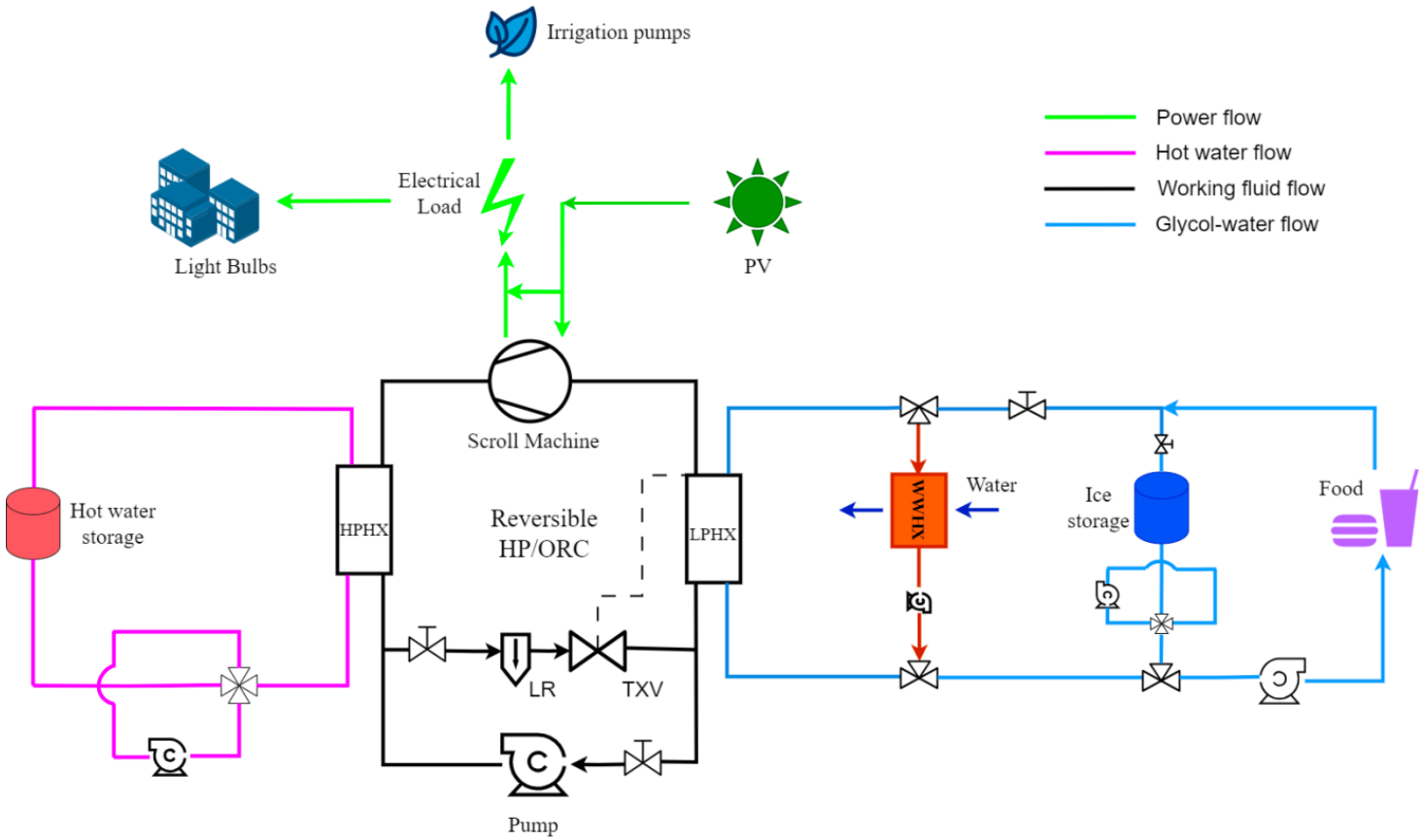
5-kWe prototype of reversible CB

- **Active charge management**: maximization of the refrigerant in ORC and HP modes
- Dynamics and **services to electricity grid** (day ahead, tertiary reserves (mFRR)).

Reversibility of heat engines

Inversible heat pump/ORC units for Carnot batteries

- Ice thermal storage can be used for covering **cooling** demand: case study of an off-grid Nigerian farm



Source: B. Guo and V. Lemort. « Designing of an off-grid reversible heat pump/organic rankine cycle system for electricity and cooling demands of a nigerian family farm. » In *37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. ECOS2024, 2024.

LEAP-RE REPTES

Take-away thoughts

Temperature

- Temperature glides, temperature lifts = key optimization variables
- Temperature pinch should be reduced/eliminated
- Low ΔT => high heat transfer area, larger flow rates => high ΔP (fans, pumps)
- High temperature heat pumps opens avenues to R&D

Reversibility

- Heat pump + ORC + TES = electricity (+heat/cold) storage: “Carnot battery”
- Inversible machines

Fluids

- “All fluids are perfect but there is no perfect fluid”: technical (and other) constraints
- Trade-off between criteria
- Oil-fluid mixture properties

Cycle versus **compressor/expander**

- Two-phase scroll compressors remove constraints on cycle design
- High temperature compressors are needed.

Thank you for your attention!

Thank you to the contributors to this presentation

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