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THERMAL ENERGY RESEARCH

DEPT. OF MECHANICAL & MECHATRONIC ENGINEERING

Re-thinking thermal energy systems in a transforming energy context

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BACKGROUND: ENERGY SYSTEMS

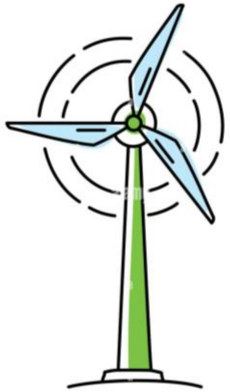
- Fossil fuels (chemical energy)
- Elevated water bodies
- Pressure differentials
- Temperature differentials
- Nuclear energy

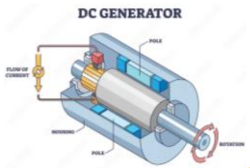
STORED ENERGY

HEAT

MECH. ENERGY (kinetic)

ELEC. ENERGY



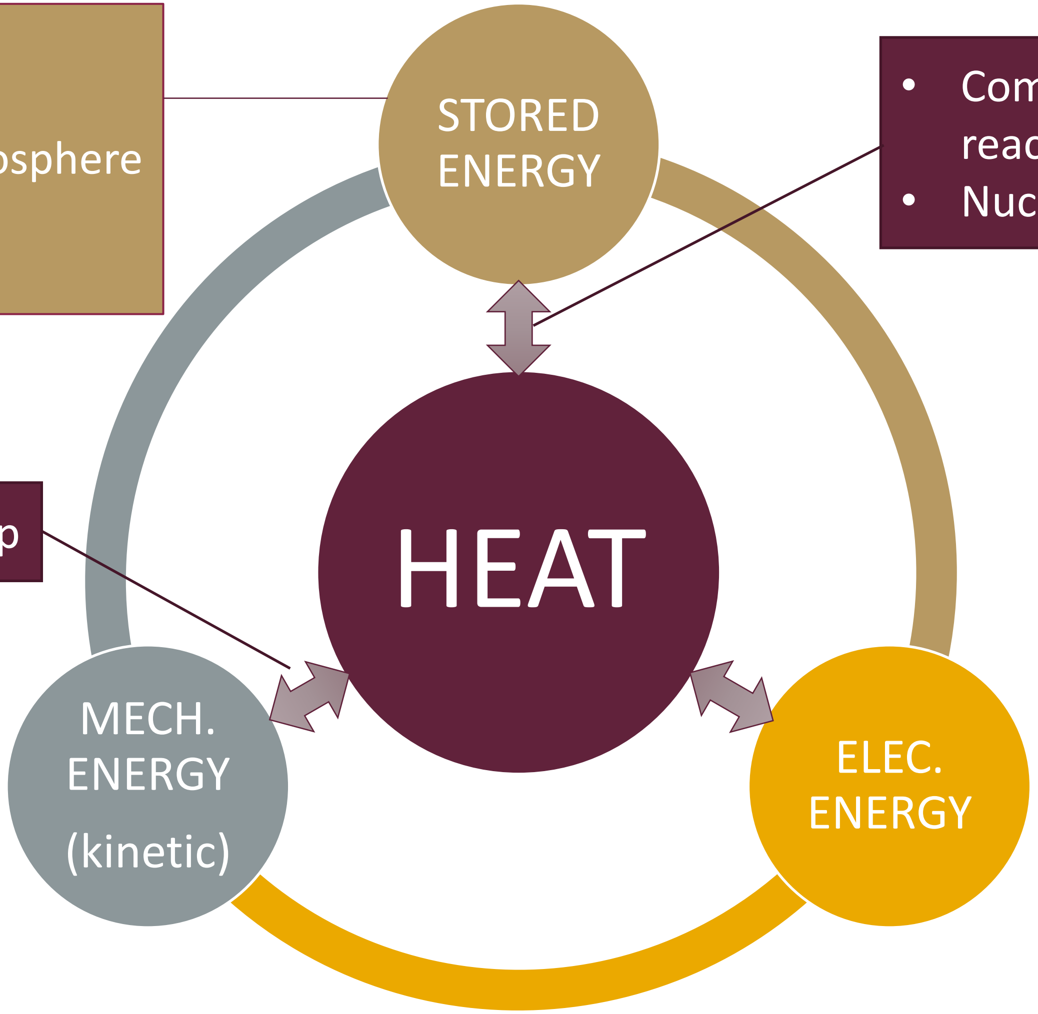


BACKGROUND: THERMAL ENERGY (HEAT)

- Fossil fuels (chemical energy)
- Elevated water bodies
- Pressure differences in the atmosphere
- Temperature differentials
- Nuclear energy

- Combustion / exothermic chemical reaction
- Nuclear fission

- Heat engine / pump



PROBLEM STATEMENT

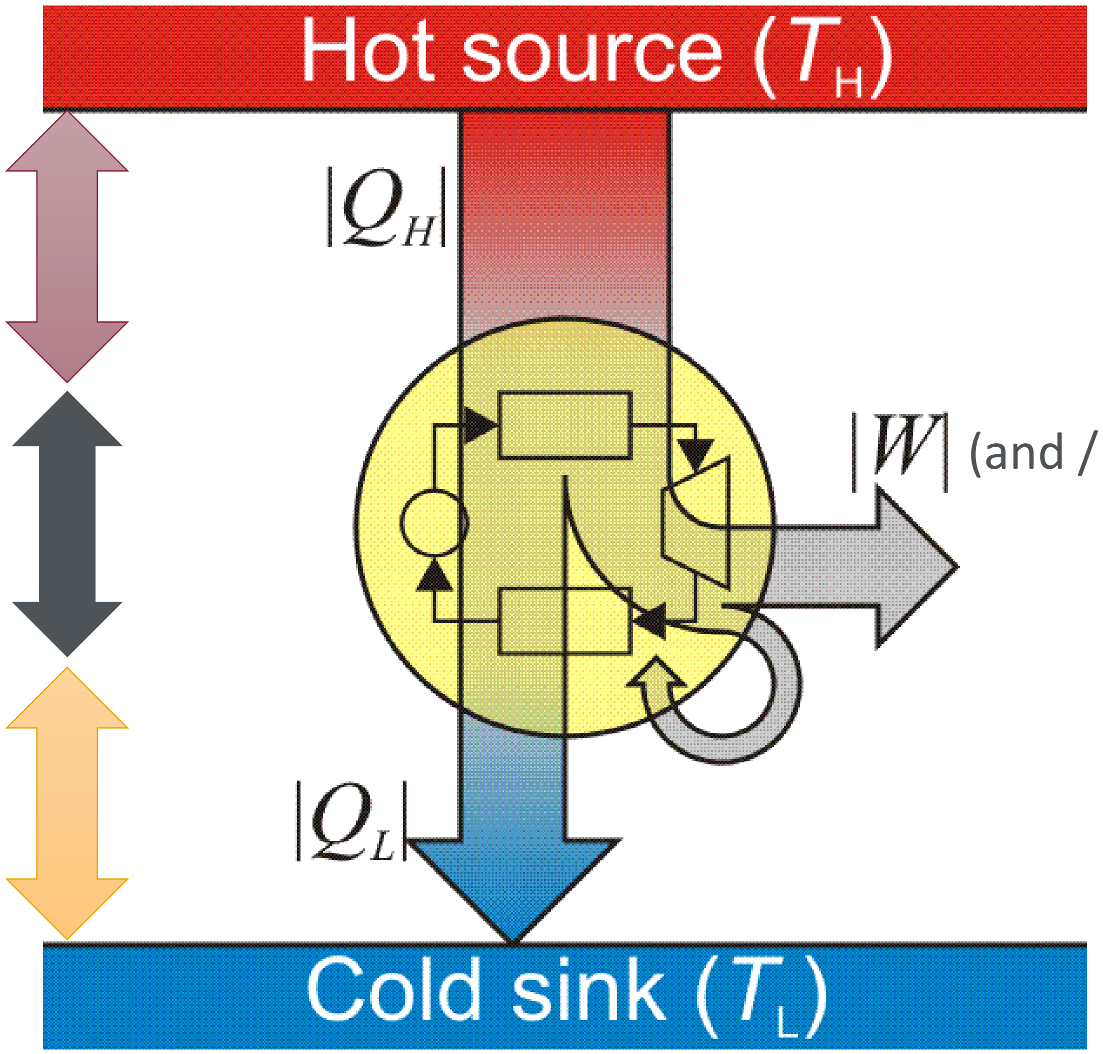
- Thermal energy systems (heat engines) are highly prevalent in our overall energy system
    - Thermal power plants
        - Fossil fuels
        - Nuclear
        - Renewable energy: concentrating solar, biomass, geothermal
    - Internal combustion engines
- These systems will remain large contributors for some time
- There are extensive value chains and infrastructure associated with these systems
- **Can we re-think these systems to leverage the available resources in support of the energy transition?**
    - Enhancement – can we get more for the same / less?
    - Repurposing – can we shift function to support transition?

HEAT ENGINE PRINCIPLES

HEAT GENERATION / CAPTURE

HEAT MANIPULATION

HEAT REJECTION



Base image source: https://en.wikipedia.org/wiki/Heat_engine

EFFICIENCY $\eta = \dfrac{Product}{Q_H}$

Theoretical maximum: $\eta_{max} = 1 - \dfrac{T_L}{T_H}$

Actual: $\eta = \dfrac{W}{Q_H} = \eta_{II} \times \eta_{max} < \eta_{max}$

HEAT ENGINE OPPORTUNITIES
Enhancement and repurposing

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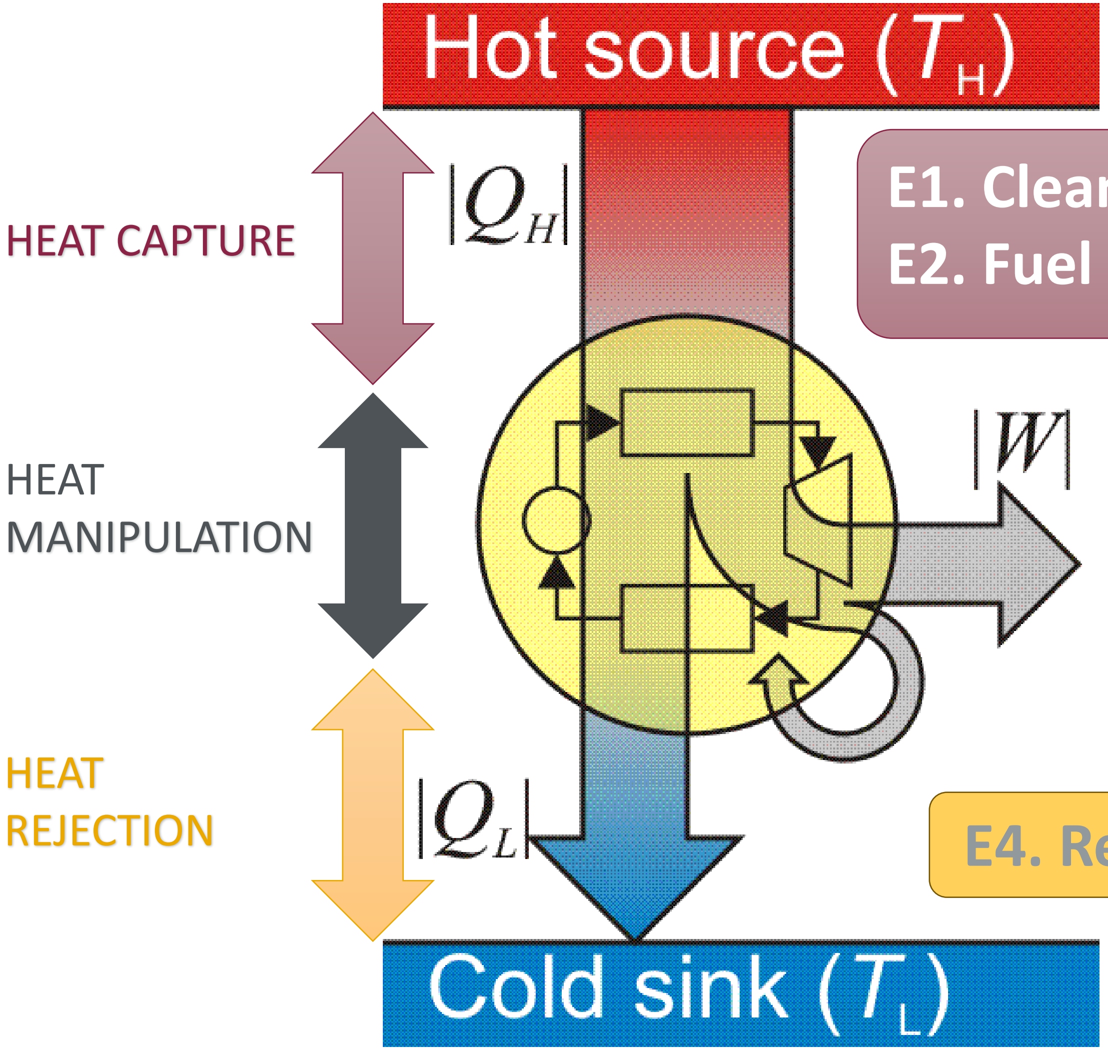

E1. Cleaner fuels (H_2 / NH_3 combustion)
E2. Fuel reduction (solar-aided)

R1. Fuel replacement (Carnot battery)

E3. Novel working fluids (sCO_2)

R2. Novel application

E4. Recoverable energy

Base image source: https://en.wikipedia.org/wiki/Heat_engine

ENHANCEMENT STRATEGY 1
CLEANER FUELS (H_2 / NH_3 combustion)

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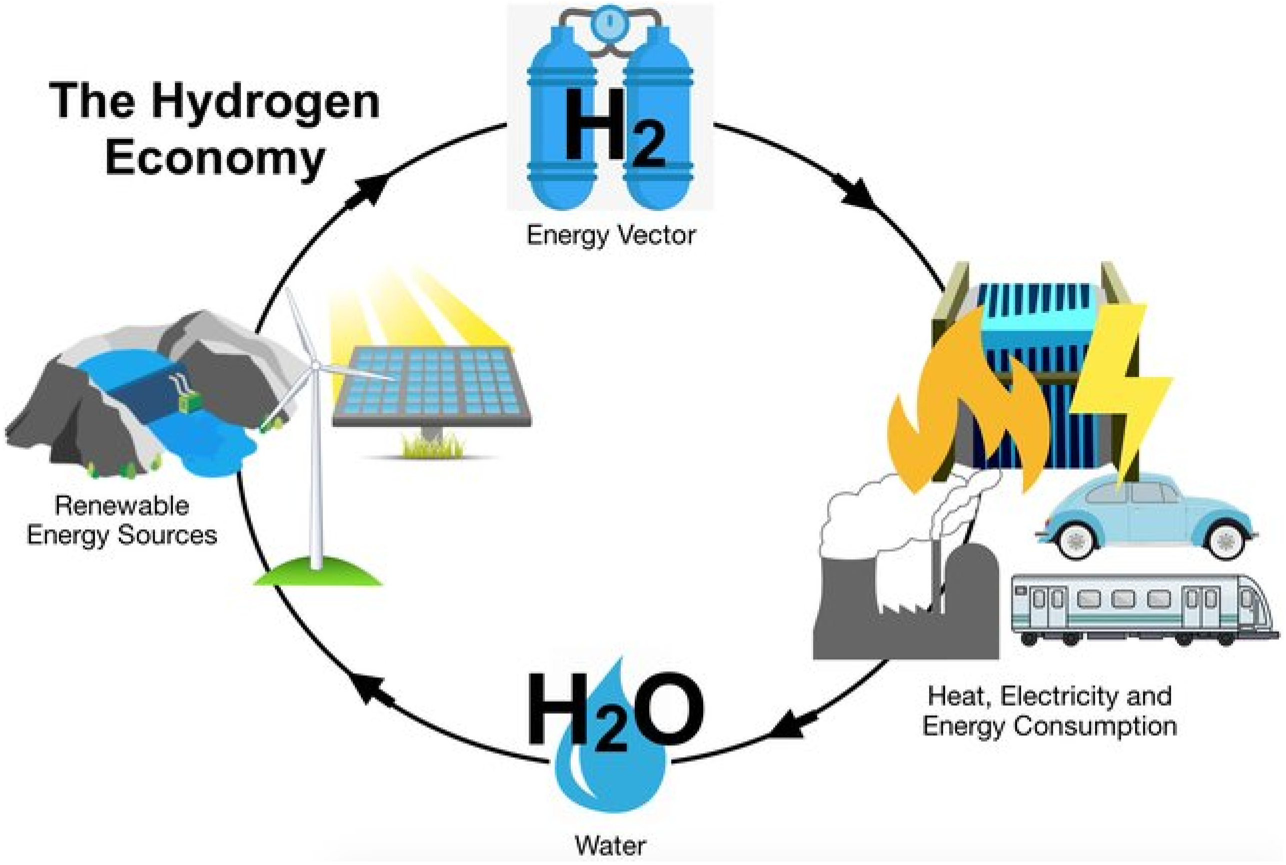


Image source: Grahame, A.; Aguey-Zinsou, K.-F. Properties and Applications of Metal (M) dodecahydro-*closo*-dodecaborates ($M_{n=1,2}B_{12}H_{12}$) and Their Implications for Reversible Hydrogen Storage in the Borohydrides. *Inorganics* 2018, *6*, 106. https://doi.org/10.3390/inorganics6040106

Combustion of H_2 / NH_3:

- Either pure or blended with fossil fuels (e.g. Methane)
- No / lower carbon emissions
- Higher temperatures resulting in increased thermal efficiency

Questions:

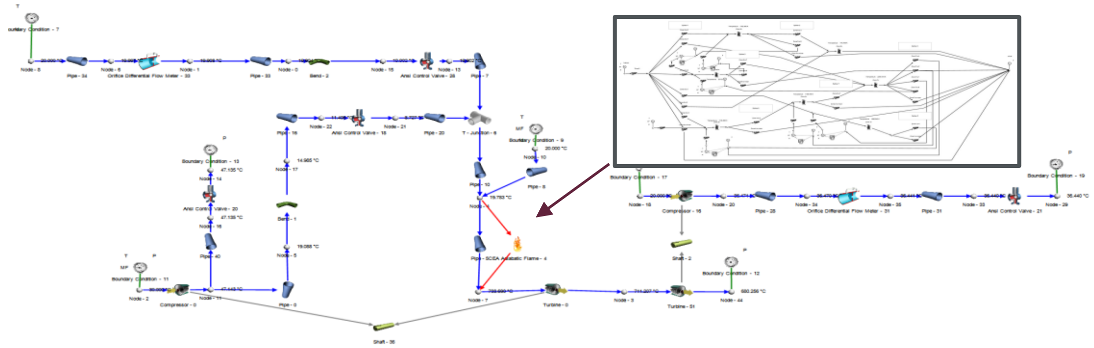
- NOx
- Component behavior and cycle dynamics

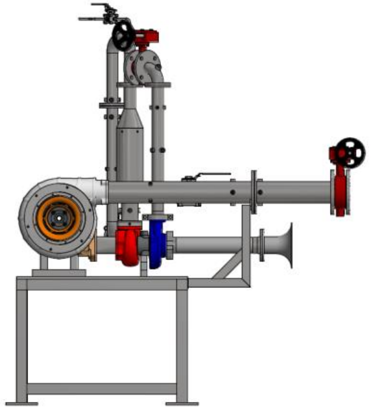
ENHANCEMENT STRATEGY 1 (cont.)

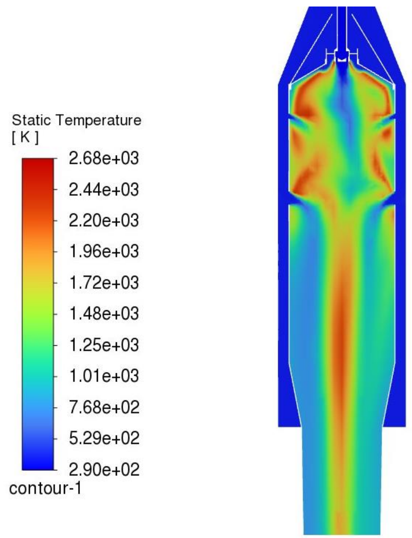
CLEANER FUELS (H_2 / NH_3 combustion)

Research focus areas:

- Multi-gas turbine development
  - Facilitate the combustion of H_2 / NH_3 along with other fuels
  - Blended / intermittent approach
  - Combination of experiment and simulation
- Combustor and turbomachinery simulation
  - Component level detailed computational fluid dynamics
  - Focus on NOx production
- Integrated power cycle simulation
  - Process models including complex turbomachinery performance.
  - Reactor network models capable of simulating emissions.







ENHANCEMENT STRATEGY 2
FUEL REDUCTION: Solar-aided power generation

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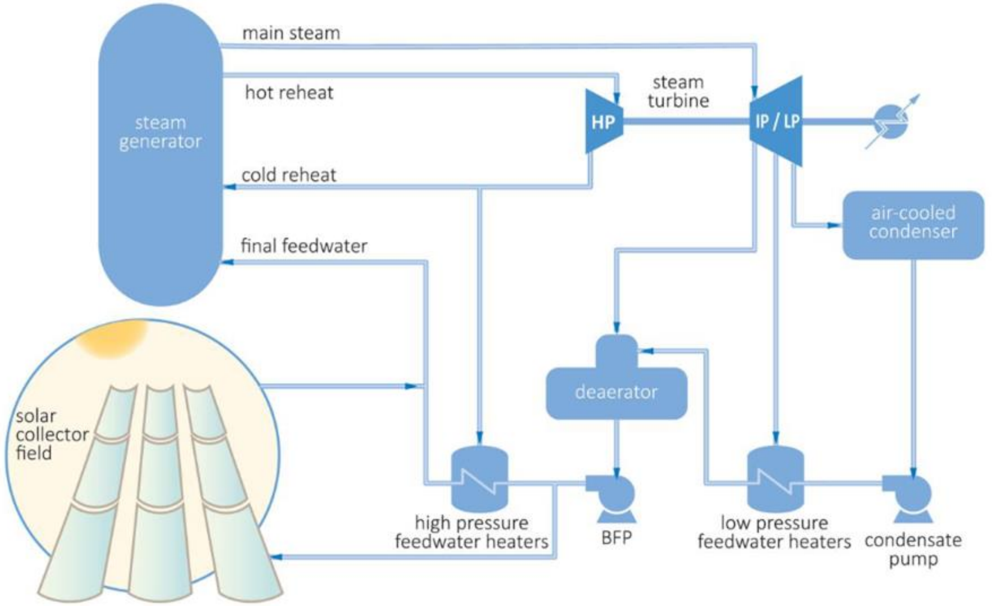
- Integrate solar heat into existing fossil fuel power plants for feedwater heating
- Reduce bleed steam requirements and thus mass flow through turbines
  - Power boosting: more power, same fuel consumption
  - Fuel saving: same power, less fuel consumption
- Benefits:
  - Leverages higher overall cycle efficiency to increase solar-to-electricity conversion
  - Leverages existing power block and grid infrastructure
  - Low(er) cost method of bringing solar thermal energy online (~30% cheaper than standalone CSP)



https://usea.org/sites/default/files/Combining%20solar%20power%20with%20Coal%20fired%20power%20plants%20or%20cofiring%20natural%20gas%20ccc279.pdf

REPURPOSING STRATEGY 1
CARNOT BATTERY

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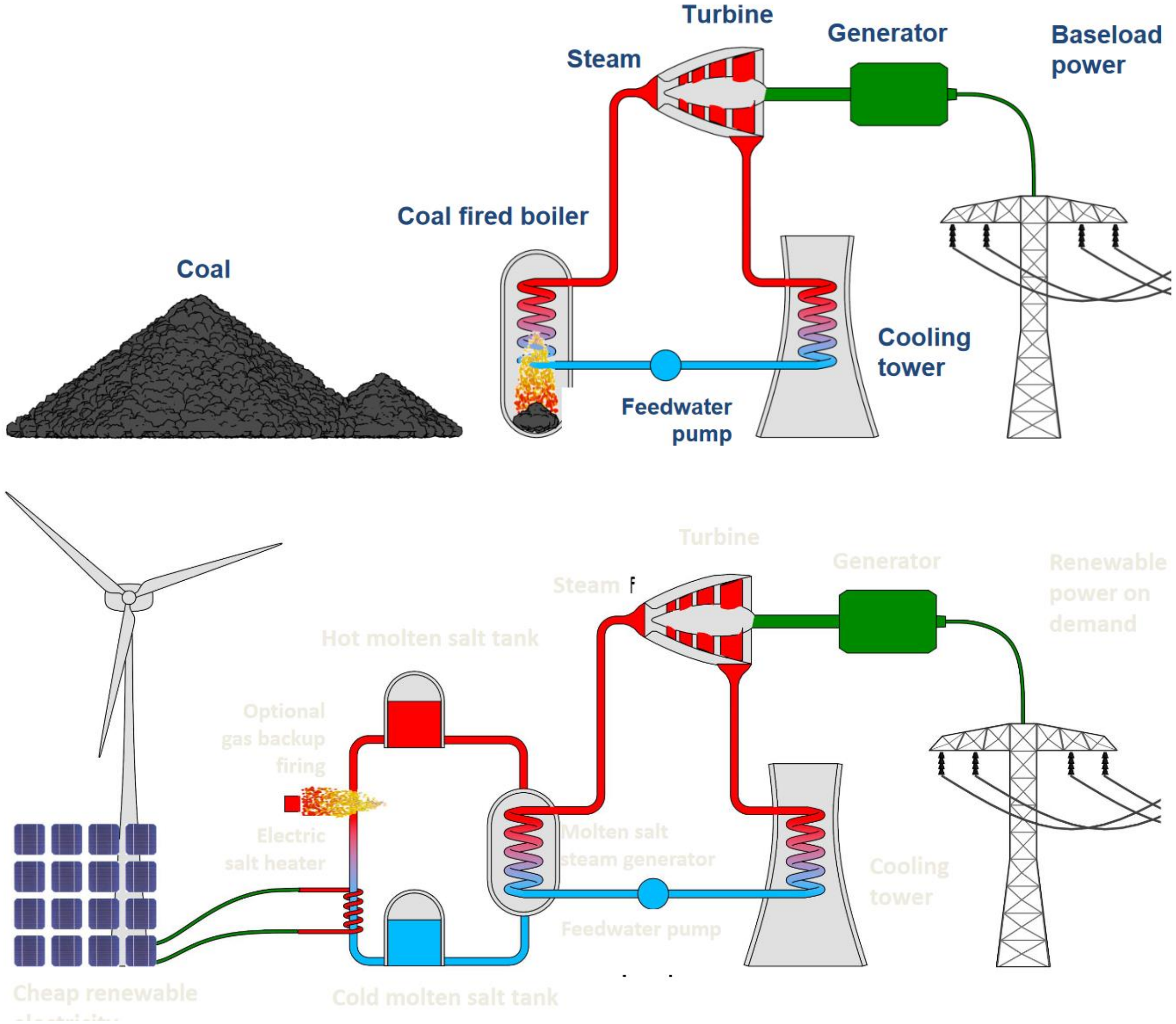
- Intermittency is supply is an issue with renewable energy sources
- Large scale storage solutions are needed
- Thermal energy storage (TES) offers a potential solution
- Carnot battery
  - Fossil fuel is replaced by TES
  - Heat input primarily from renewables
  - Allows existing plants to be repurposed
  - Preliminary studies indicate favourable economics

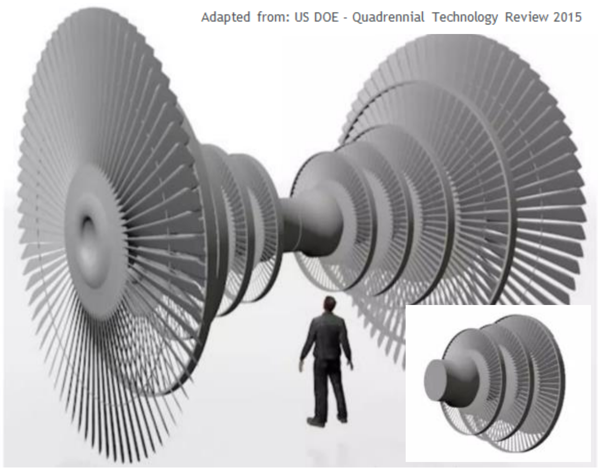


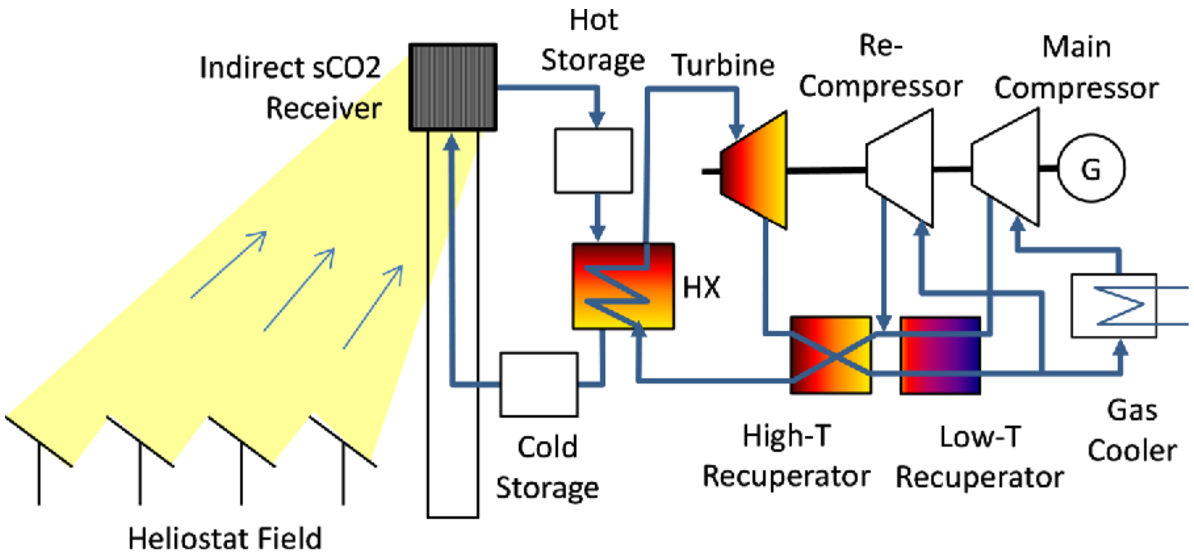
https://4echile-datastore.s3.eu-central-1.amazonaws.com/wp-content/uploads/2020/11/12182946/201112-MG-Chile-Carnot-Batteries-_Webinar.pdf

ENHANCEMENT STRATEGY 3

NOVEL WORKING FLUIDS: Supercritical CO_2

- Brayton (gas turbine) cycle with CO_2 at supercritical pressure ≥ 75 bar
- High temperatures with high density energy carrier
  - Higher cycle thermal efficiency
  - Reduced emissions from existing energy sources (fuels)
  - Integration of sustainable fuels (incl. solar
  - thermal energy)
  - Compact turbomachinery
    - modular / distributed generation
- Primary focus on cycle modelling





REPURPOSING STRATEGY 2
POWER CYCLES FOR MODULAR CSP

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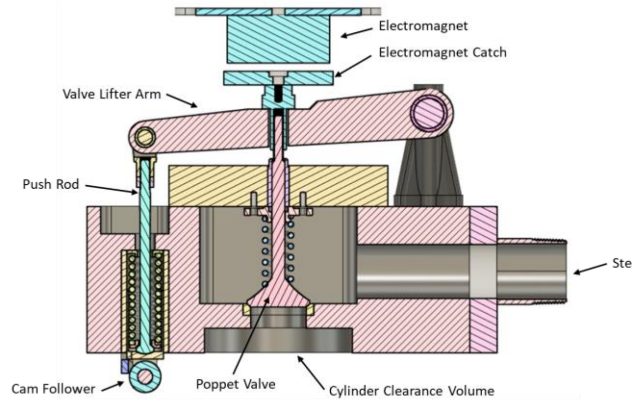
- Concentrating solar thermal power (CSP) has traditionally focus on monolithic systems (50 – 100 MW)
- “Imported” systems to South Africa
- Modular CSP (5 – 10 MW) is a growing field
- Reciprocating (piston / cylinder) steam expanders can be used as the power cycle
  - Effectively repurposed diesel engines
- Low cost, flexible power cycles
- Leverages existing internal combustion engine value chains



ENHANCEMENT STRATEGY 4
RECOVERABLE ENERGY: Cold-end enhancement

- Cold sink temperature (T_L) is linked to the ambient environment
- Lower T_L → higher cycle efficiency
- Wet (evaporative) cooling systems
  - Higher efficiency
  - High water consumption (~2 kL/MWh)
- Dry (air) cooling systems
  - No water consumption
  - Lower efficiency (~10 – 35 %)

ENHANCEMENT STRATEGY 4 (cont.)

RECOVERABLE ENERGY: Cold-end enhancement

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Hybrid coolers and recoverable energy

- Hybrid wet / dry units in a primarily dry cooling system
- Boost cooling strategically at the cost of water consumption
- Benefits:
  - 50% less water for equivalent wet-cooled system output
  - > 10% power boost relative to dry cooled system
- Allows for recovery of lost thermodynamic potential

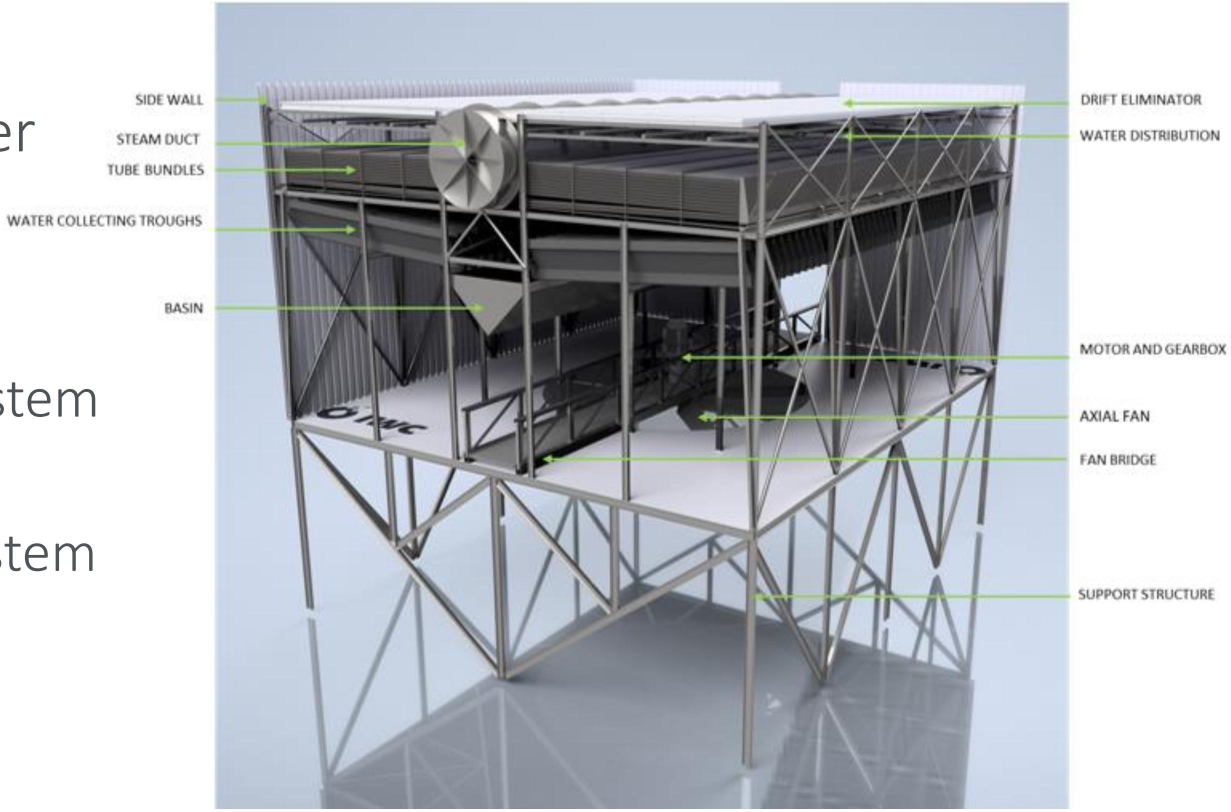

Image source: Reuter, H., Recoverable Energy Power Generation using Air-cooled Condensers, Industrial Water Coolers, 2023.

Conclusion

- Thermal energy systems are an important part of our current energy mix and will remain so for the foreseeable future.
- There are many ways in which these systems can be enhanced, reconfigured and repurposed to:
  - Improve existing systems and maintain energy supply with a lower emission footprint;
  - Support the growth of renewable energy technologies in an effective and affordable manner.

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Thank you
Enkosi
Dankie

Photo by Stefan Els