MITIGATION OF GLOBAL WARMING BY DIRECT COOLING OF THE ATMOSPHERE

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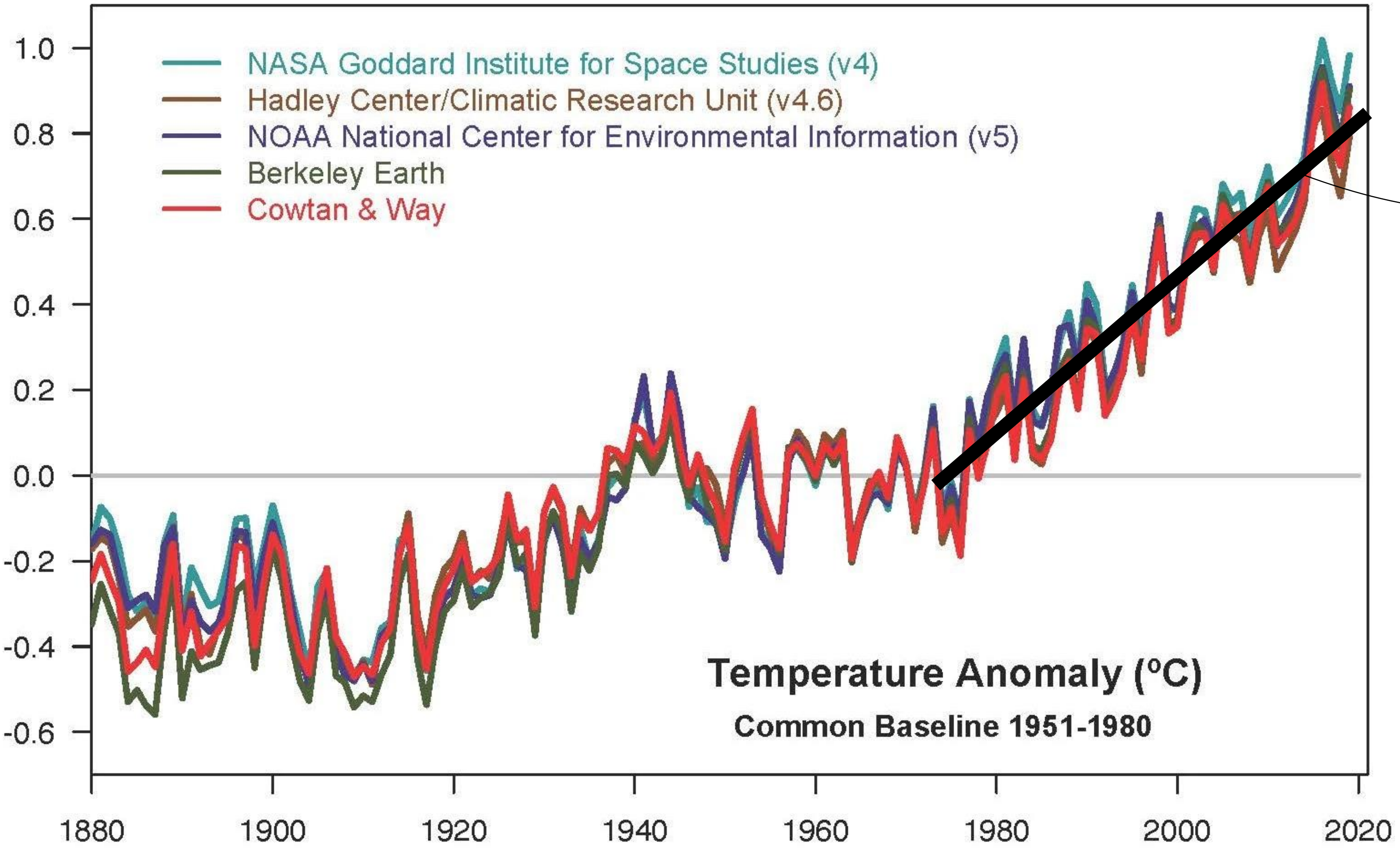
The problem (we all know that)



$$\frac{dT}{dt} \approx \mathbf{0.018\,°C/year}$$

www.climate.nasa.gov

Current approaches to mitigate global warming

- Reduction of greenhouse gas concentration in the atmosphere:
  - Emission reduction

    Problems:
    - *Very slow: decades to stabilize temperature rise and then centuries to decrease the temperature*
    - *Technological, industrial and political challenges*
  - *CO_2 removal from the atmosphere (carbon capture and storage)*

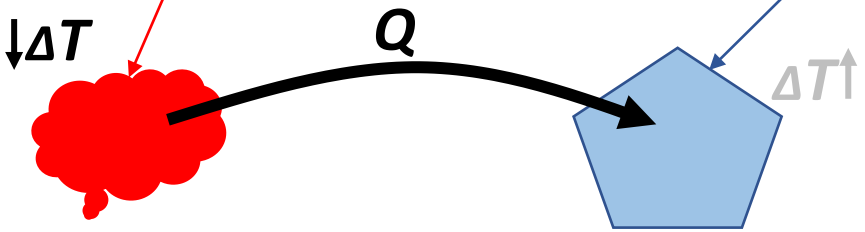
    Problems:
    - *Removal, transportation and storage of CO_2*
    - *High cost*
- Solar geoengineering

    Problems:
    - *Global uncertainties and risks*
    - *Challenging science and governance*
    - *Bleaching of the sky*

Decreasing temperature of a physical object?

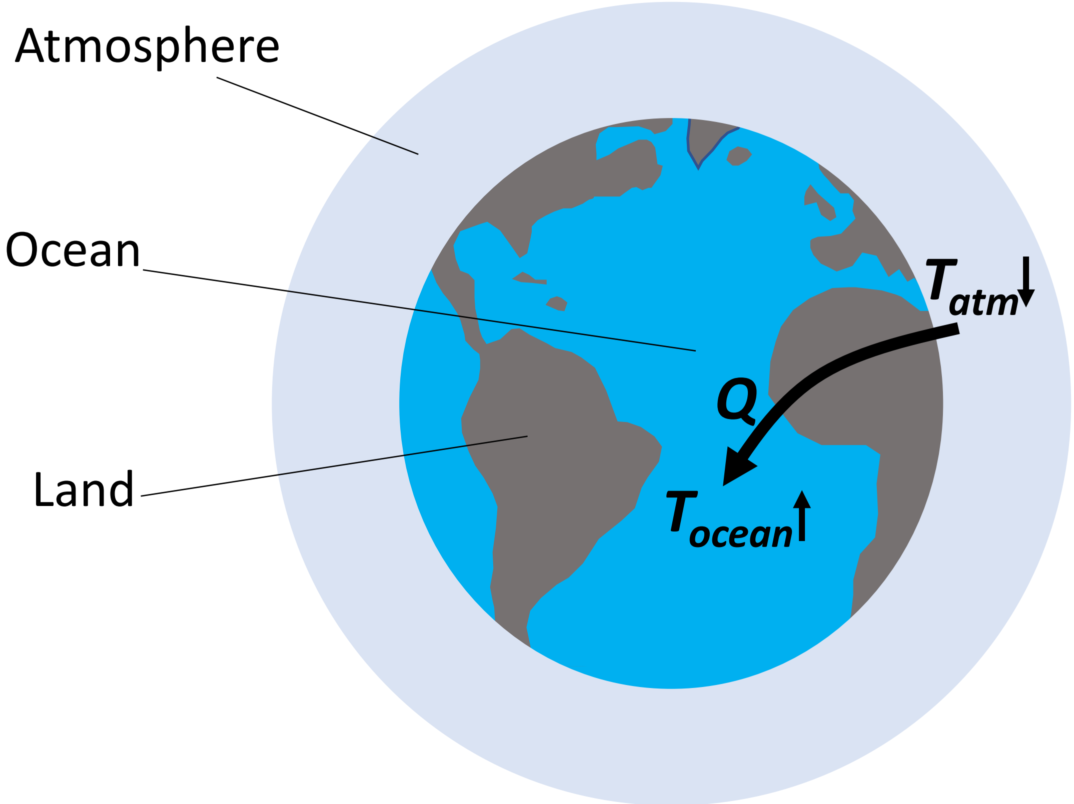
By removing heat energy from it and transferring to another object

$$Q=mC\Delta T$$



Mitigating global warming by heat transfer

By removing heat energy from the atmosphere and transferring to water (ocean or inland) and/or land



Amount of heat to be removed from the atmosphere?

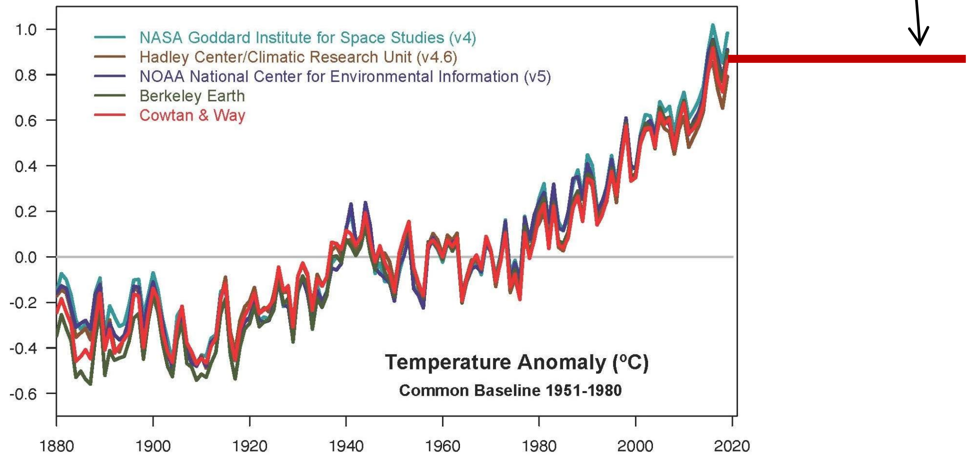
To get rid of the atmospheric global warming:

Air: 1006 J/kgK

$$Q=mC\Delta T = 0.94\ 10^{20} \approx 10^{20}\ J/year$$

0.018°C/year

Atmosphere: 5.15x1018 kg



By how much the ocean will warm?

To stop global warming: 10^{20} J/year

1000 times less than air

$$\Delta T = Q/mC = 0.000018°C/year$$

Ocean: $1.4 \cdot 10^{21}$ kg

Ocean water: 3850 J/kgK

Amount of heat introduced to the ocean

Annual heat input to ocean (0-2000 m) due to the greenhouse effect:

$1.5 \cdot 10^{22}$ J

Annual heat input to ocean from the atmosphere to eliminate global warming:

10^{20} J

That is only 0.6% of warming of the ocean by greenhouse effect

Proposed technologies for air-water heat transfer

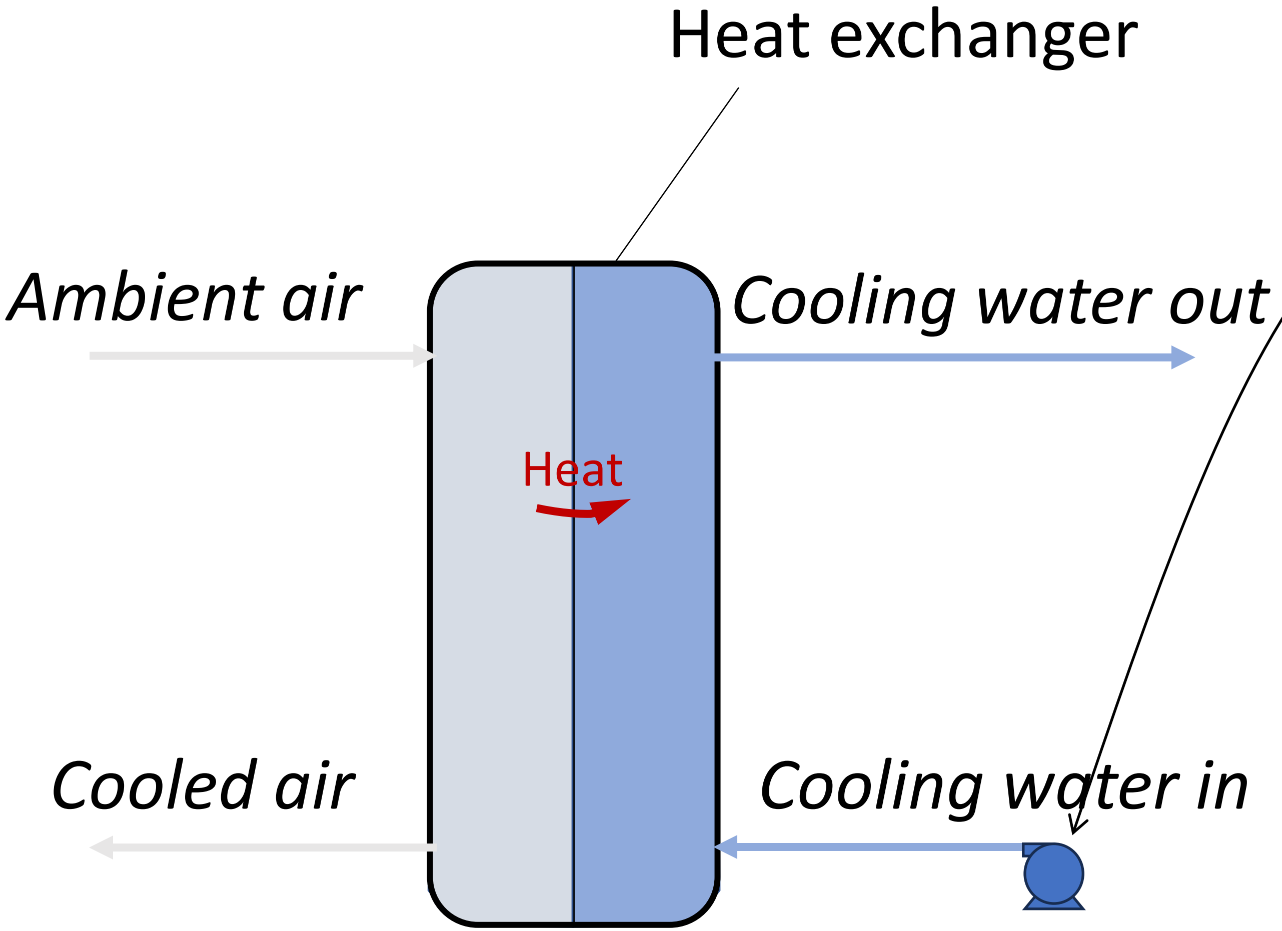
1. Direct heat exchange
2. Compression/expansion of air:

    2.1. Combined with energy storage

    2.2. Combined with energy transport

    2.3. Combined with power generation

1. Direct heat exchange

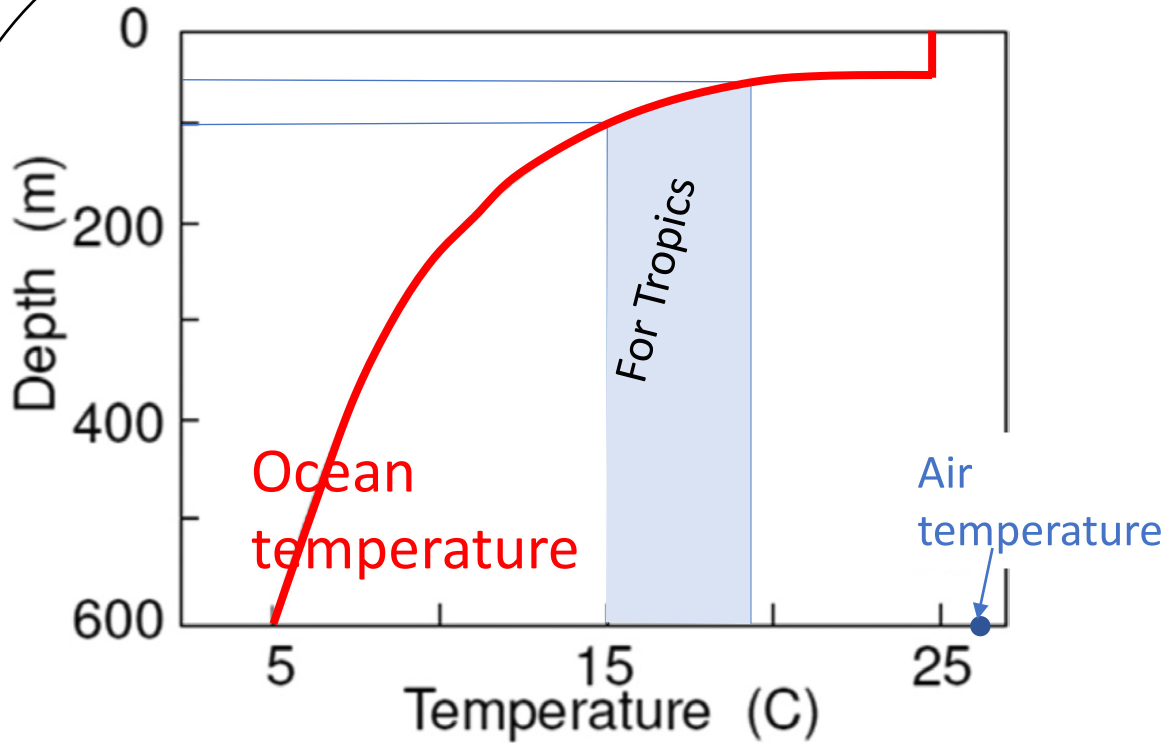


Requirements:

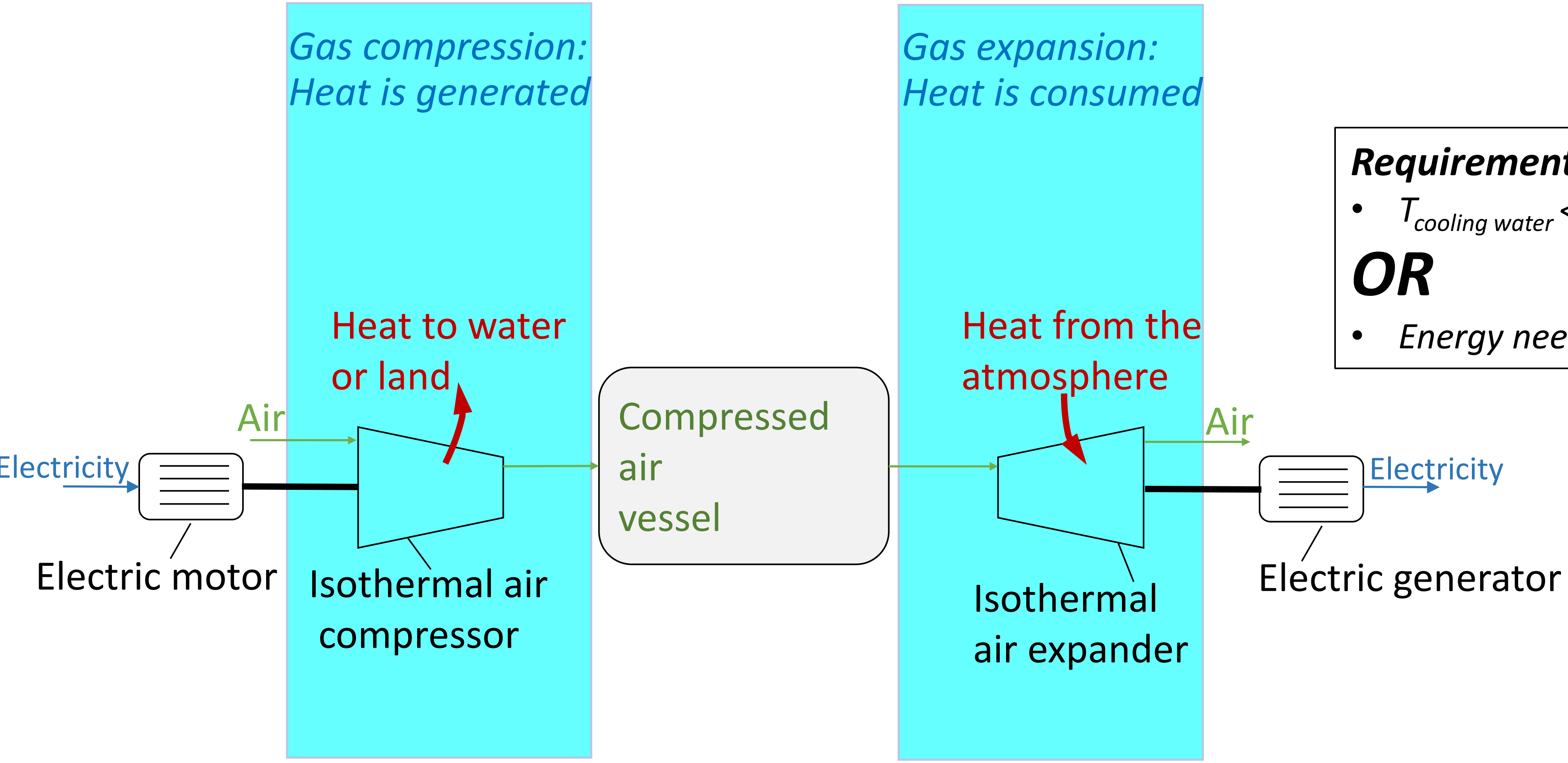
- $T_{cooling\ water} < T_{ambient\ air}$

AND

- *Energy needed for pumping air; water*



2. Atmospheric cooling by compression/expansion



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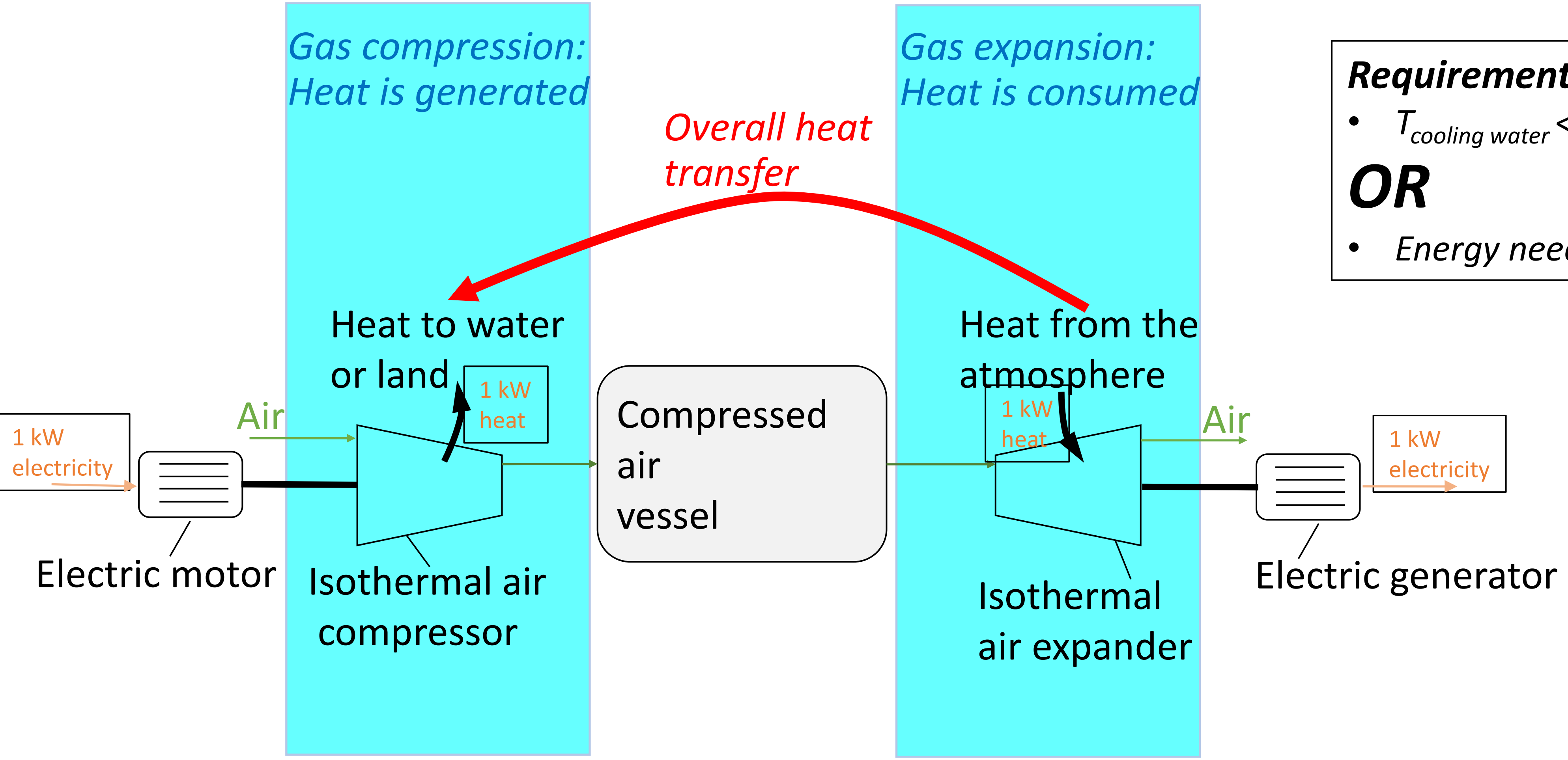

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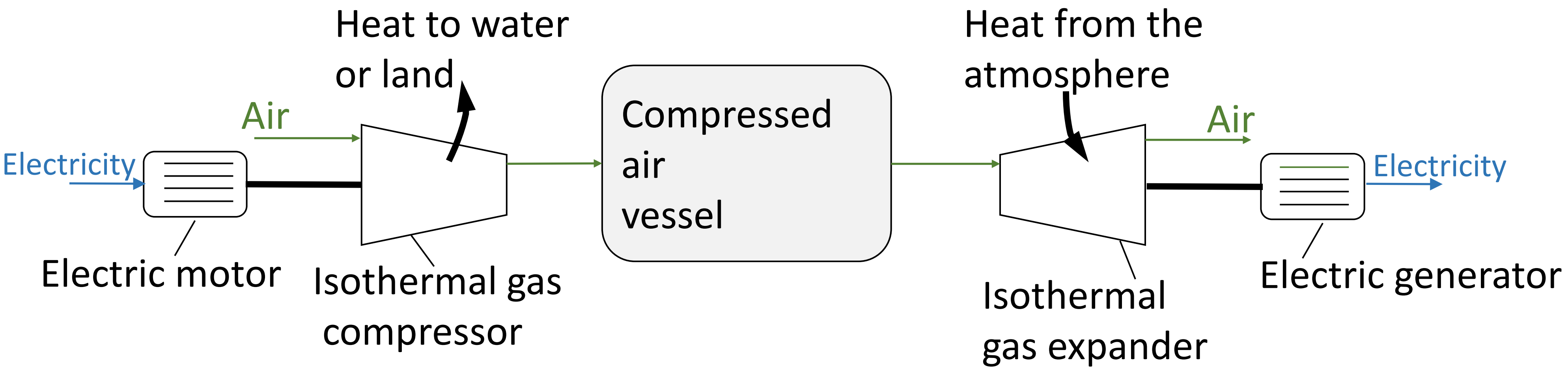
- *Energy needed for pumping air; water*

2.1. Compression/expansion with energy storage

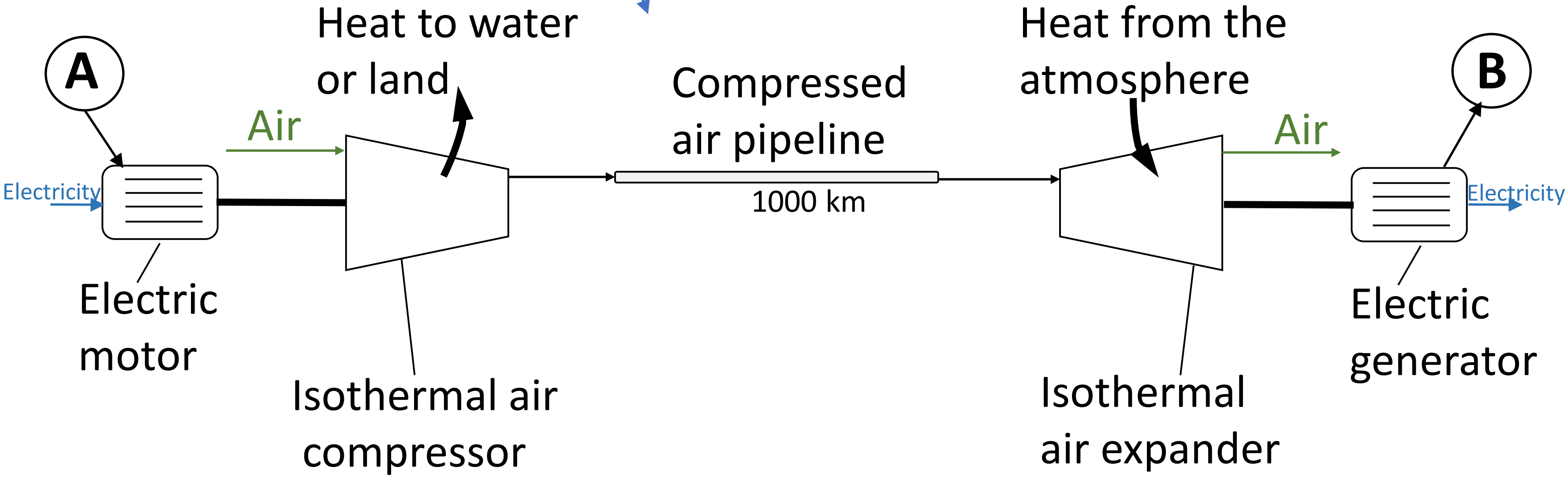
- ***The mechanical (electric) energy input can be done at different time than energy output***
- ***This is the definition of energy storage***



2.2. Compression/expansion with energy transport

Comparison of electric vs. compressed air energy transport:

- *Capital costs are similar*
- *Transportation losses are similar*
- *Compressed air energy transport has an <u>intrinsic energy storage</u>!*



2.3. Compression/expansion with power generation

$$\eta = \frac{T_{expansion} - T_{compression}}{T_{expansion}}$$

Requirement:

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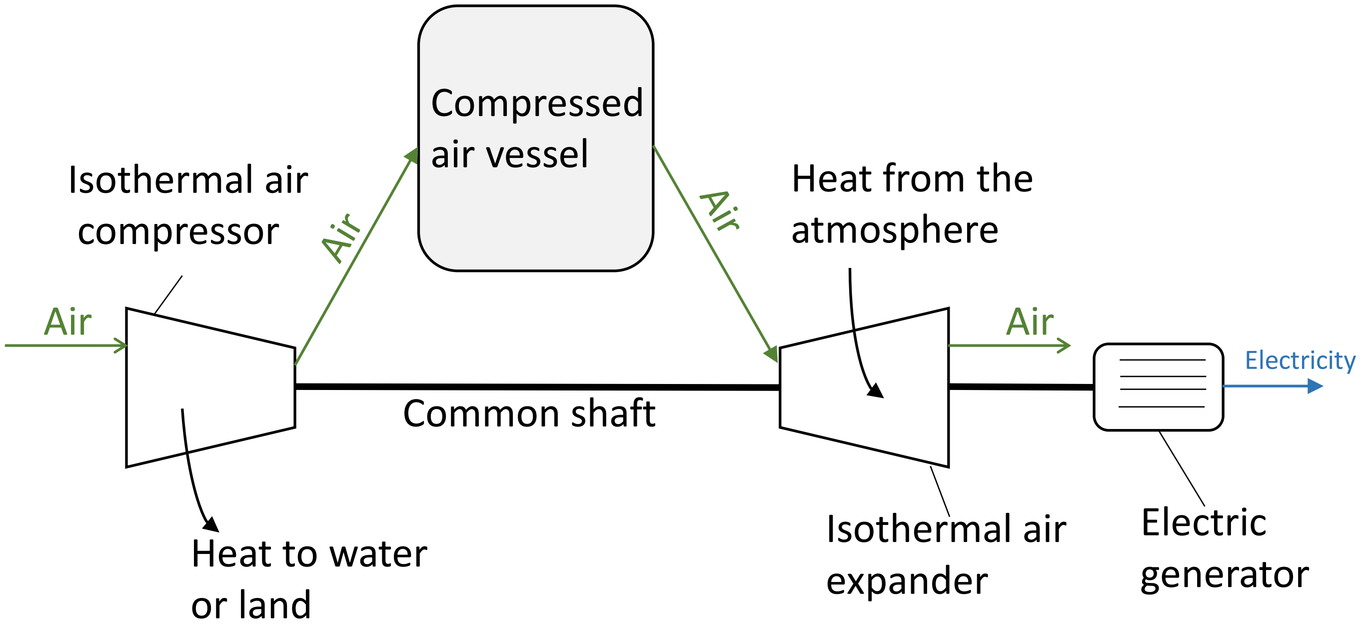
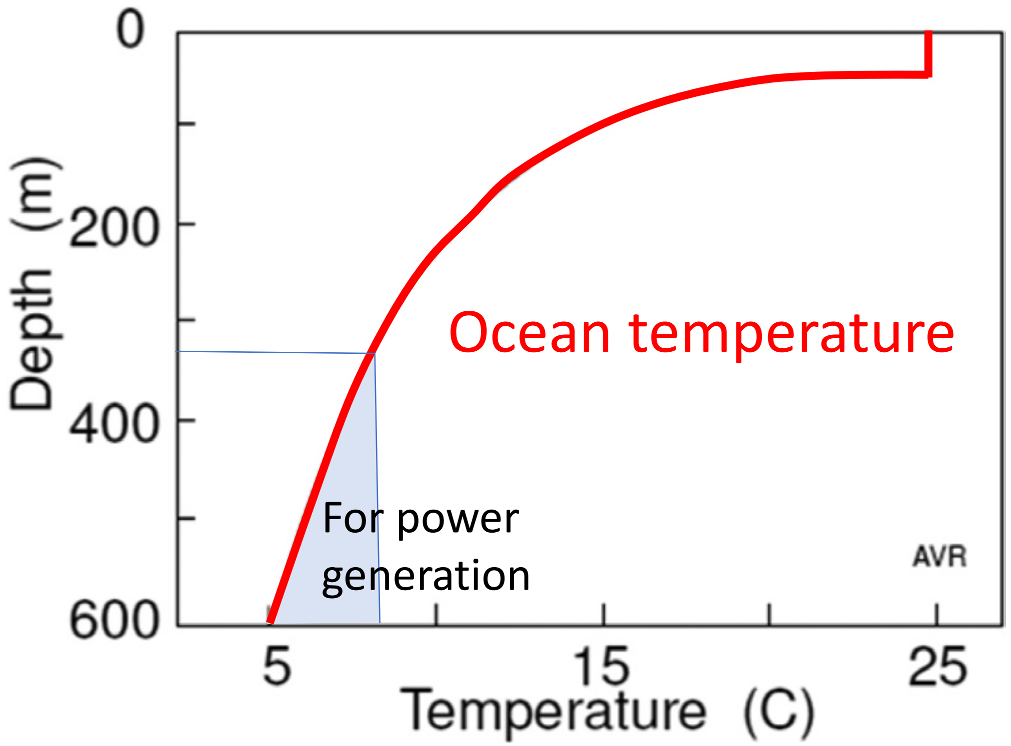
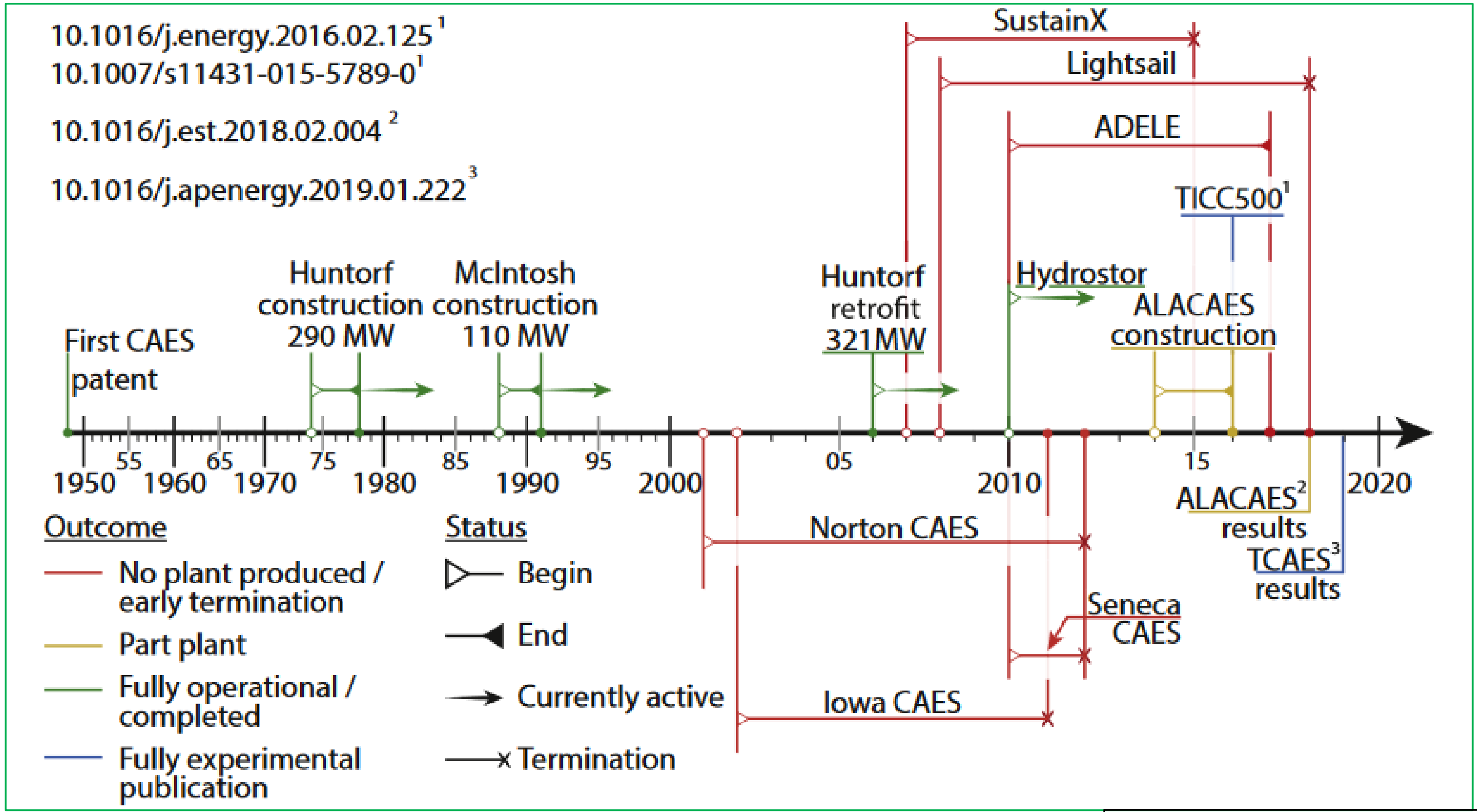




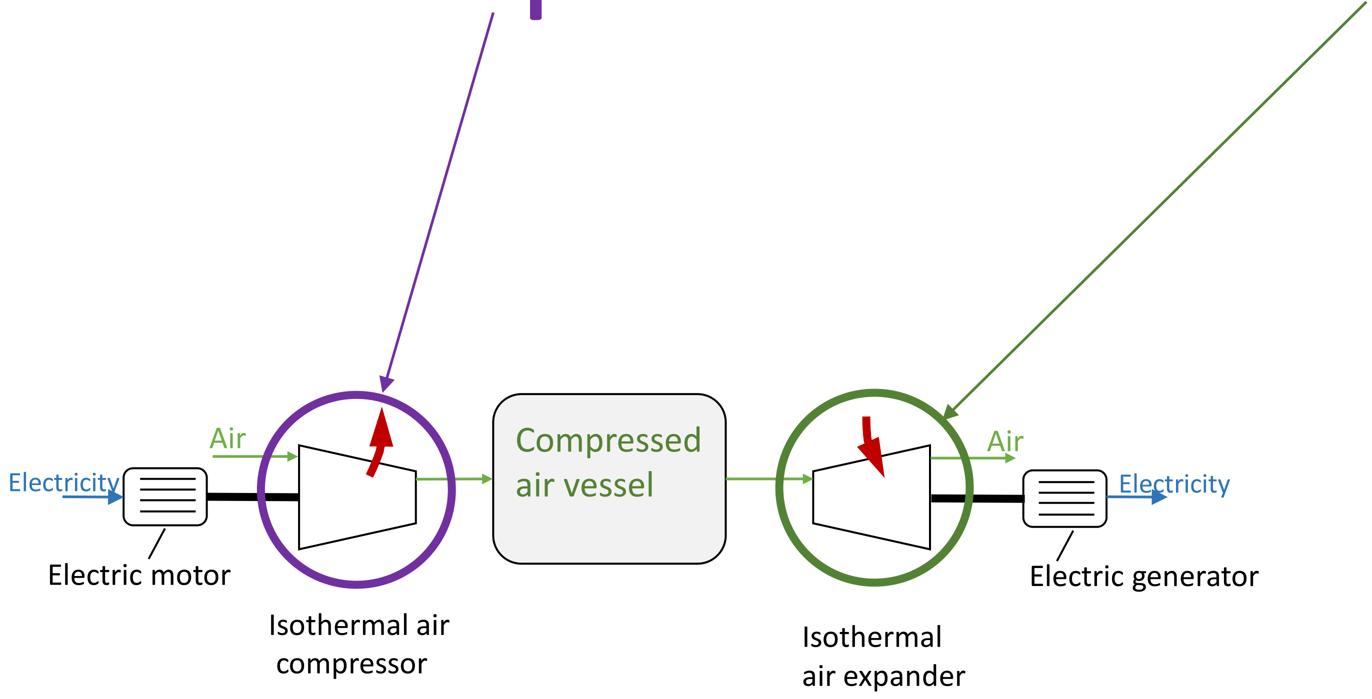
Current status of compressed air energy storage

It can be seen that almost all CAES attempts failed. The only two remaining are Huntorf and McIntosh with 35% efficiency

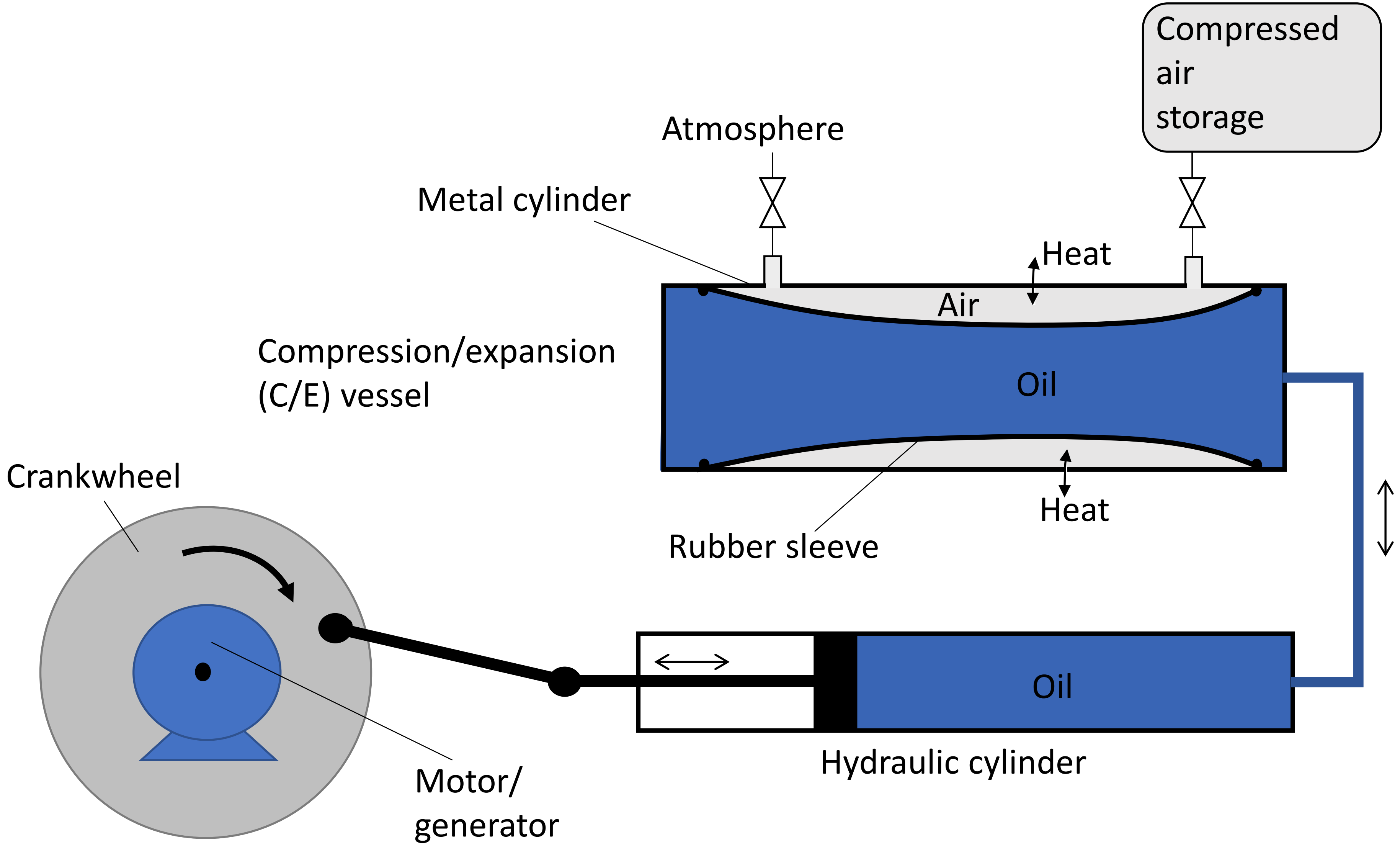


E. Barbour et al., *Why is adiabatic compressed air energy storage yet to become a viable energy storage option?*, iScience **24** (2021).

Isothermal compressor and expander



Isothermal compressed air energy storage (ItCAES):
a patented world-wide and prototype tested (recently) technology



Main features of ItCAES

As a compressor/expander (atmospheric cooling):

- The first commercially viable isothermal compressor/expander
- Thermodynamic efficiency: >98%
- To eliminate global warming:
  - 10 000 units of 300 MW to be built
  - Cost: $150 Billion
  - Steel: 50 million metric tons (annual global steel production: 2 billion tons)
  - Copper: 2 million tons (annual production: 22 million tons)
- However: cannot be used longer than several decades

As an energy storage system:

- The first commercially viable compressed air energy storage technology
- Low cost: ~1 ₵/kWh (battery storage: ~15 ₵/kWh)
- Round-trip efficiency: 85% (similar to batteries)
- Very good recyclability