MITIGATION OF GLOBAL WARMING
BY DIRECT COOLING OF THE ATMOSPHERE

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The problem (we all know that)

\[ \frac{dT}{dt} \approx 0.018^\circ C/year \]
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: \(1006 \text{ J/kgK}\)

Atmosphere: \(5.15 \times 10^{18} \text{ kg}\)

\[Q = mC\Delta T = 0.94 \times 10^{20} \approx 10^{20} \text{ J/year}\]
By how much the ocean will warm?

\[
\Delta T = \frac{Q}{mc} = 0.000018^\circ C/\text{year}
\]

Ocean: \(1.4 \cdot 10^{21}\) kg

Ocean water: 3850 J/kgK

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

1000 times less than air
Amount of heat introduced to the ocean

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

\[ 1.5 \times 10^{22} \text{ J} \]

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

\[ 10^{20} \text{ J} \]

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:**

- $T_{\text{cooling water}} < T_{\text{ambient air}}$
- Energy needed for pumping air; water

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**Diagram:**

- Ambient air
- Cooled air
- Cooling water in
- Cooling water out

**Graph:**

- Depth (m)
- Temperature (C)
- Ocean temperature
- Air temperature
- For Tropics
2. Atmospheric cooling by compression/expansion

**Gas compression:** Heat is generated

- **Isothermal air compressor**
- **Compressed air vessel**
- **Heat to water or land**
- **Electric motor**
- **Electric generator**

**Gas expansion:** Heat is consumed

- **Isothermal air expander**
- **Heat from the atmosphere**

**Requirements:**
- $T_{\text{cooling water}} < T_{\text{ambient air}}$
- Energy needed for pumping air; water

Electricity flows from the electric motor to the isothermal air compressor, then to the compressed air vessel. Heat is generated when the air is compressed. The compressed air then goes to the isothermal air expander, where heat is consumed. The heat is then directed to water or land, or to the atmosphere. Electricity is also generated from the electric generator.
2. Atmospheric cooling by compression/expansion

Gas compression: Heat is generated

Heat to water or land

Compressed air vessel

Electric motor

1 kW electricity

1 kW heat

Isothermal air compressor

Air

Gas expansion: Heat is consumed

Heat from the atmosphere

Isothermal air expander

Electric generator

1 kW electricity

1 kW heat

Requirements:
- $T_{\text{cooling water}} < T_{\text{ambient air}}$
- 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 **intrinsic energy storage**!
2.3. Compression/expansion with power generation

\[ \eta = \frac{T_{\text{expansion}} - T_{\text{compression}}}{T_{\text{expansion}}} \]

**Requirement:**
- \( T_{\text{cooling water}} < T_{\text{ambient air}} \)

![Diagram of compression/expansion with power generation](image)
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