Nuclear-Powered Direct Air Capture

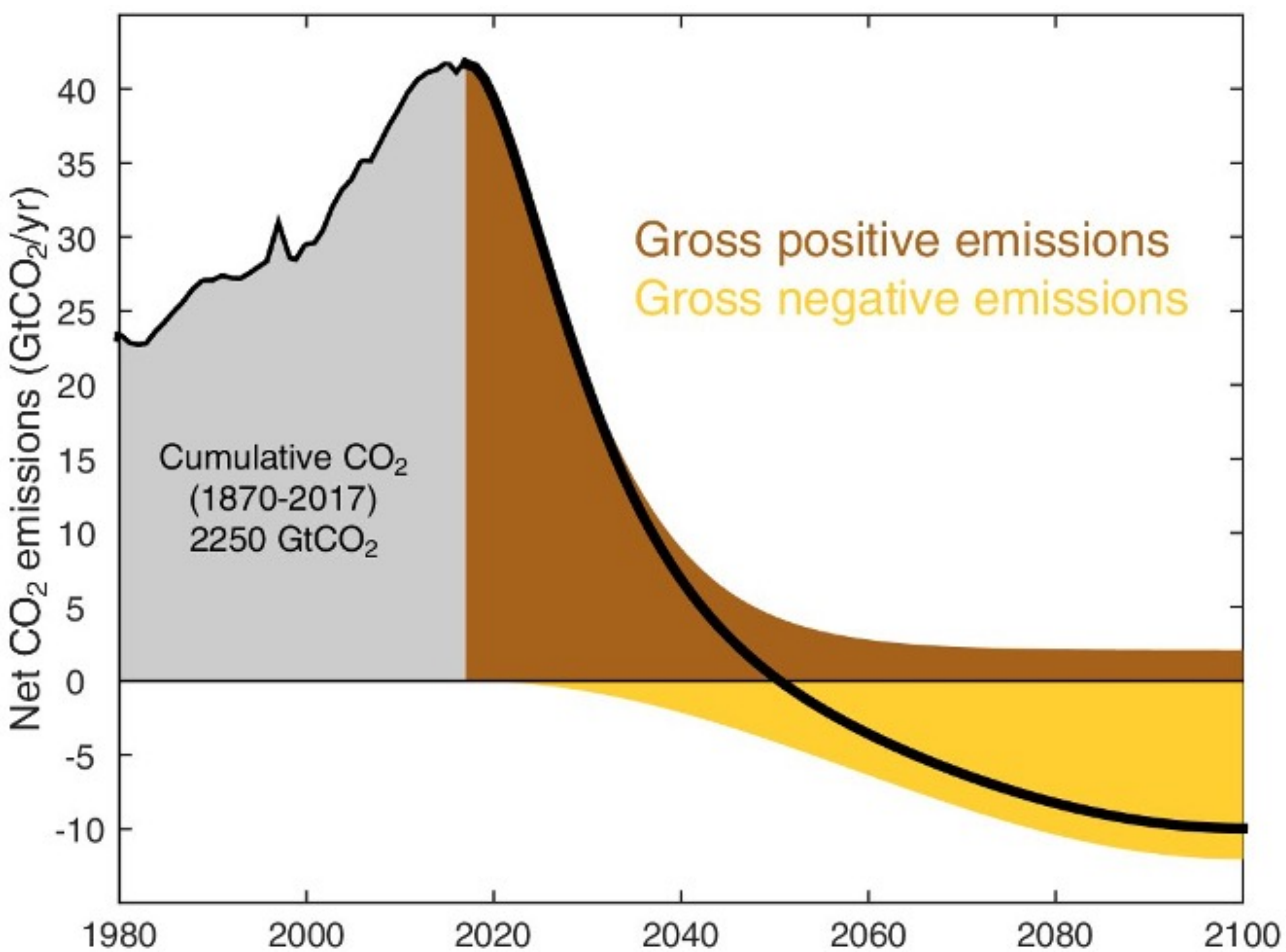
Principles and Options

Dr Staffan Qvist — 2022/01/26
QC Ltd

Negative emissions

- Negative (CO_2) Emissions Technologies (NETs) are needed to keep the global average temperature increase below 2°C *in nearly all integrated assessment models*
- The scale of such negative emissions has been estimated to require extraction of up to 12 Gt of CO_2 per year after 2050 for a <2 °C warming limitation

Typical 1.5-2°C IAM model results



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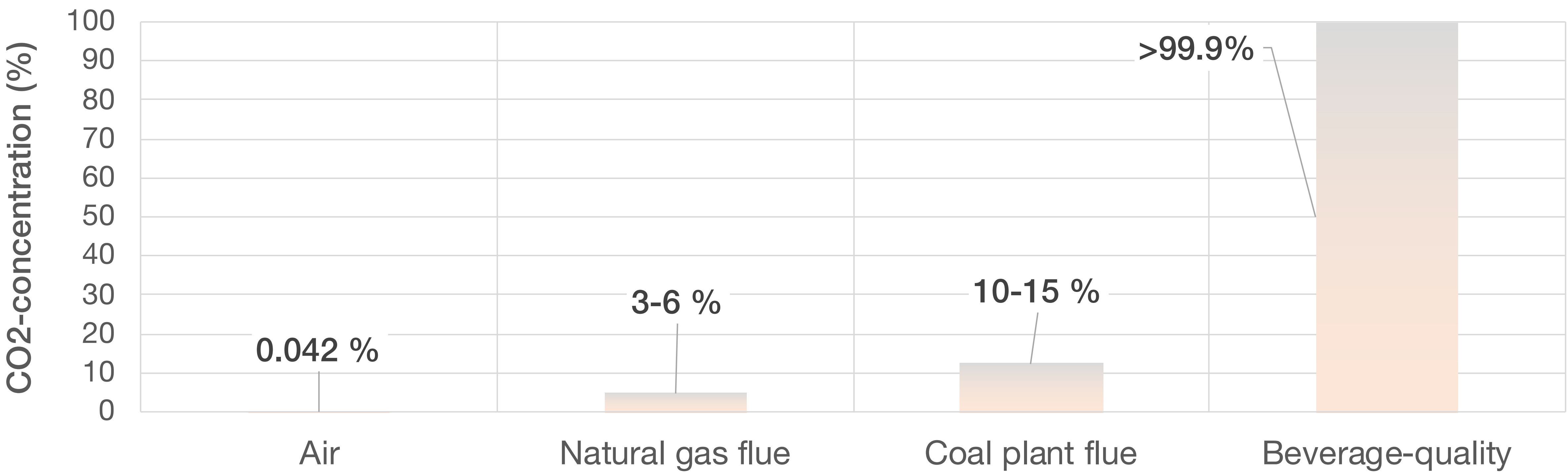
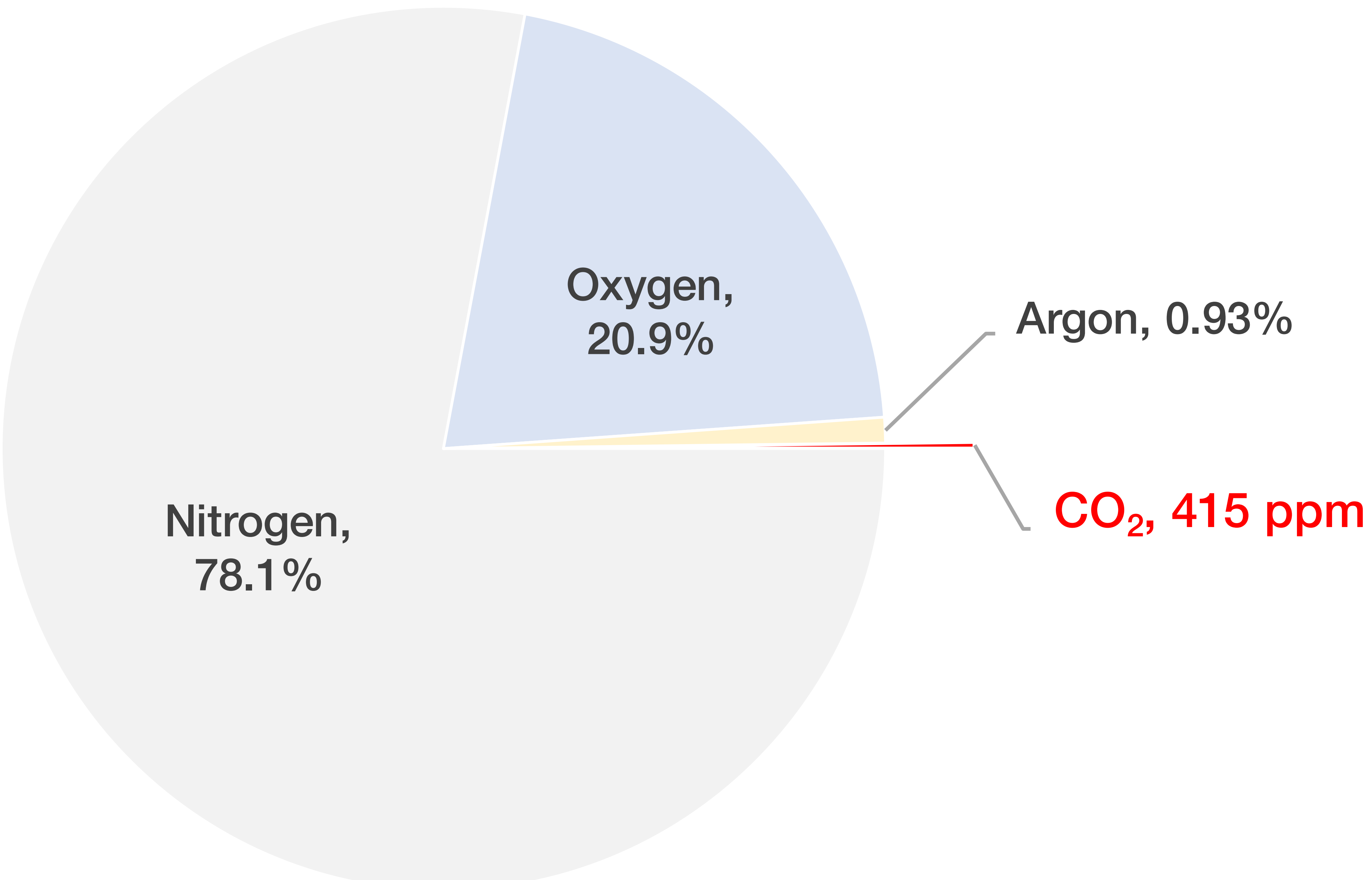
CCS and DAC?

- Direct Air Capture (DAC) can be seen as a type of CCS (Carbon Capture and Storage) or CCU (Carbon Capture and Utilization)
- DAC is distinguished by the concentration of CO_2 in the gas!



Atmospheric air



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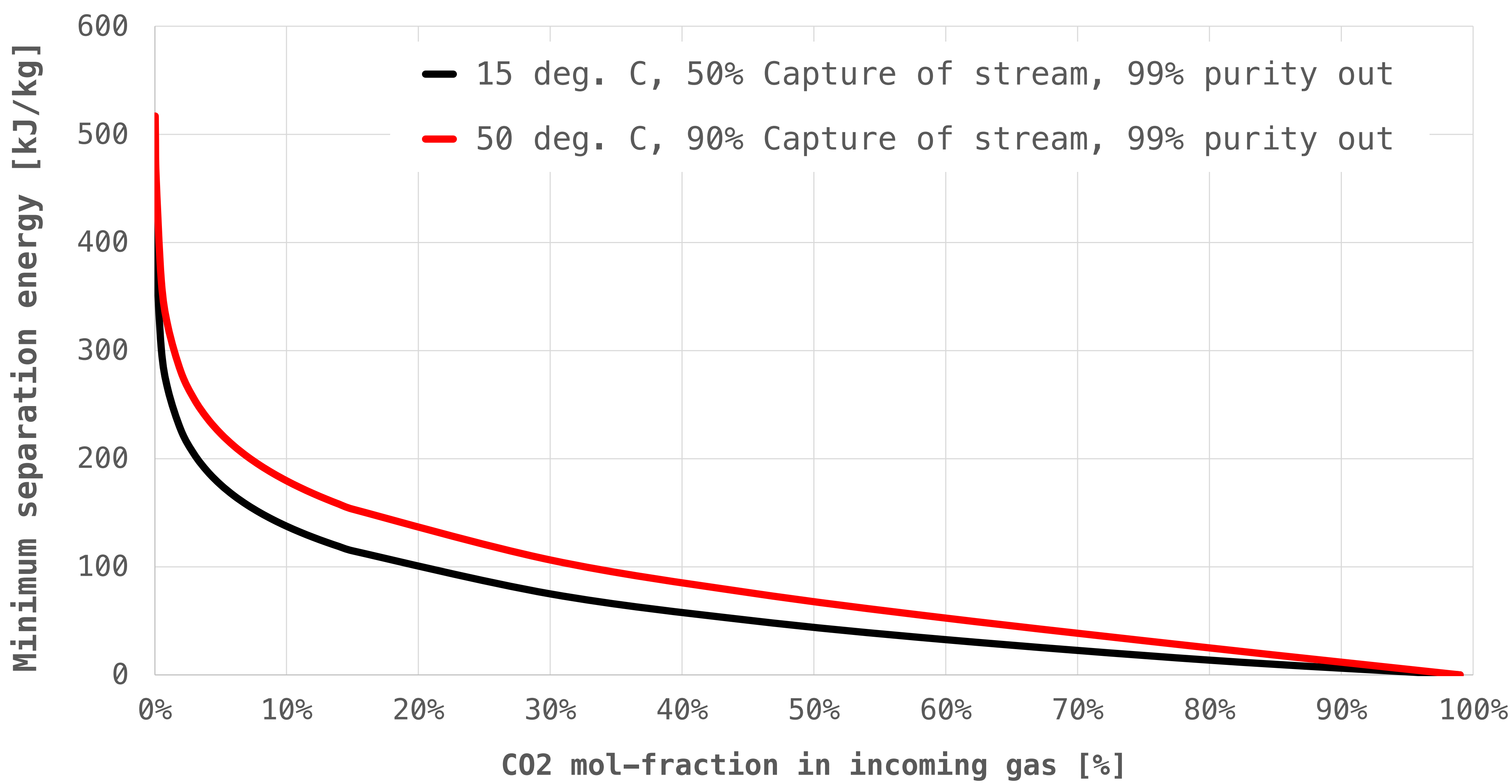
Theoretical separation energy

Minimum theoretical work required to separate CO_2 from air is ~3.5 times higher than from a coal plant flue stack, although concentration differs by a factor of 300



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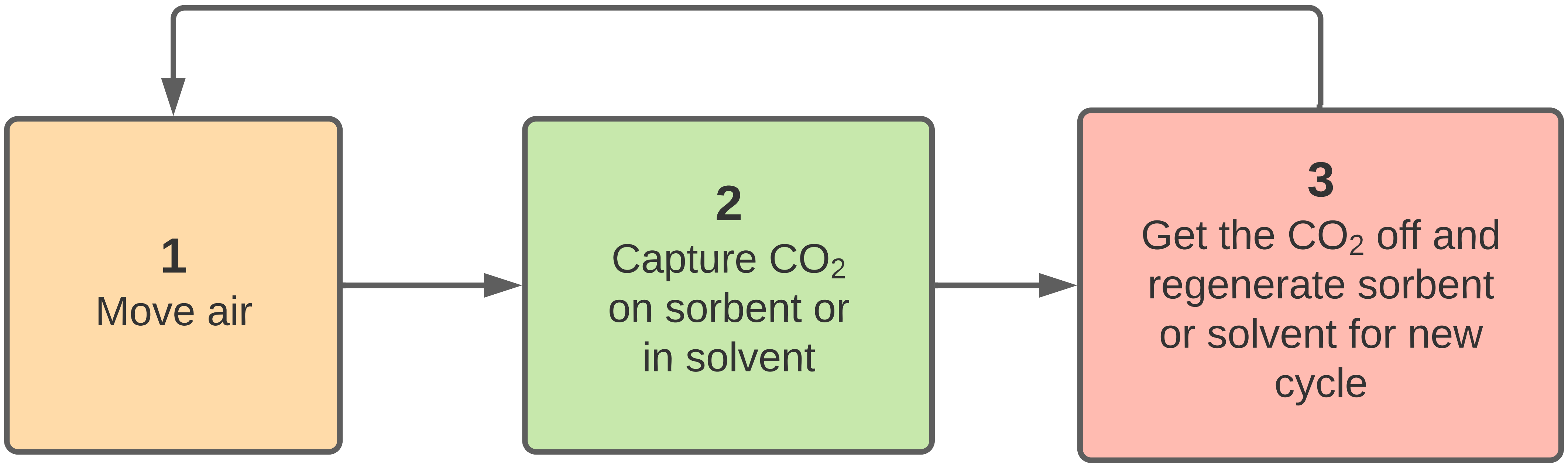
Siting options

- DAC, unlike flue gas carbon capture, is essentially location agnostic!
- However, ambient environmental conditions affect DAC performance, and the proximity to CO_2 storage/pipeline (if this is the preferred option) can be a determining factor economically
- Water vapour competes with CO_2 for the reactive sites on sorbents and adds to the thermal mass that must be heated during regeneration — dry air is better!

Principles of DAC

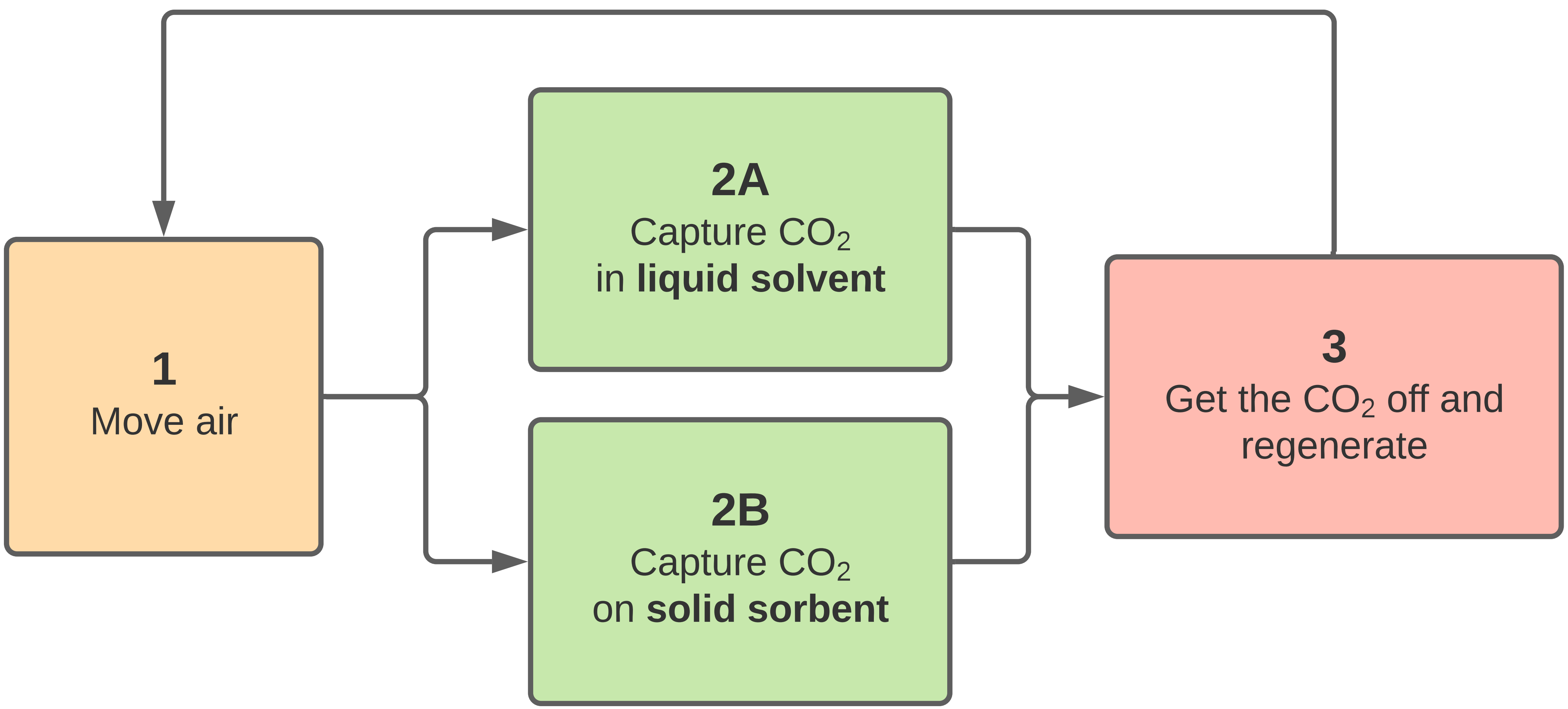
The core process has three main steps



Types of DAC systems

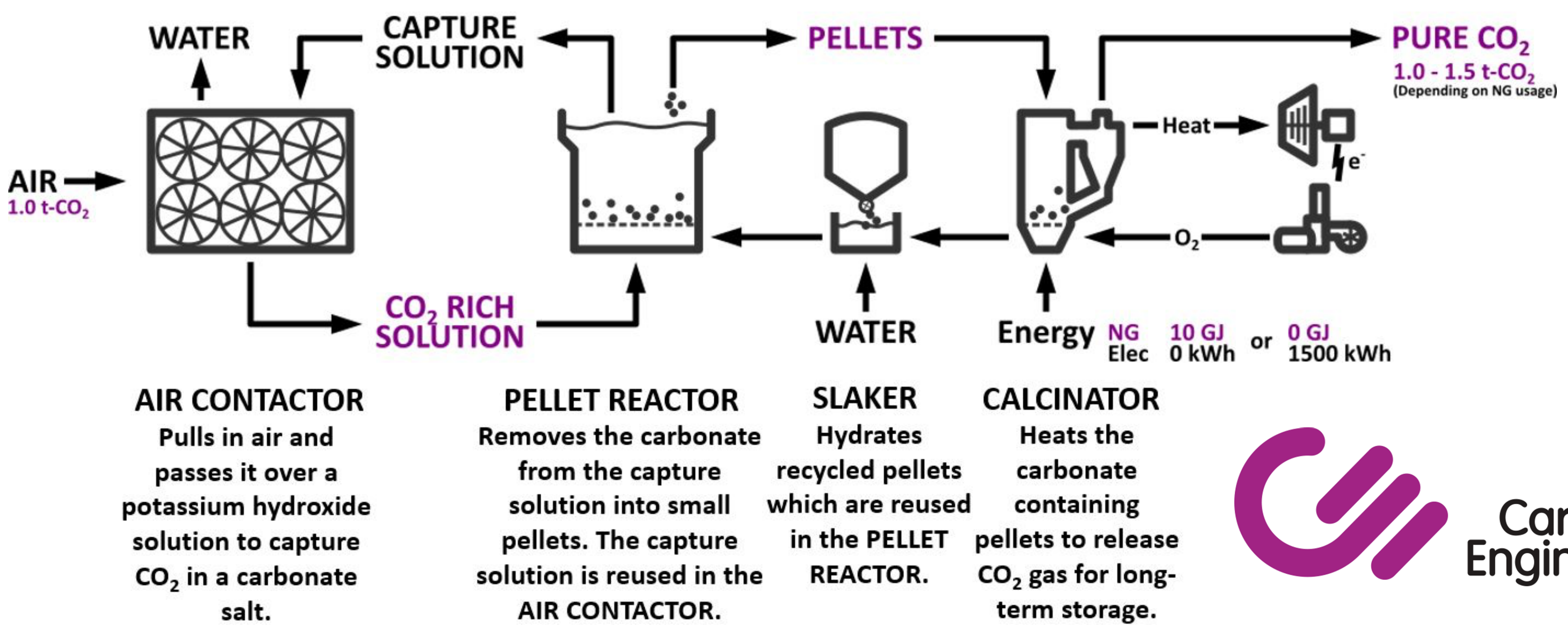
On the very highest level, there are two pathways:

Liquid systems (2A) and Solid systems (2B)



Liquid solvent DAC system

- Solution spearheaded by Carbon Engineering (Canada).
- Regeneration cycle requires heat at 900°C in the calciner for the decomposition of $CaCO_3$ into CaO and CO_2.
- Limits the full heat integration options with nuclear energy



Carbon Engineering

Nuclear + Liquid solvent DAC system

Powered by:

- Electrical power (source-agnostic, so technically uninteresting)

  or..

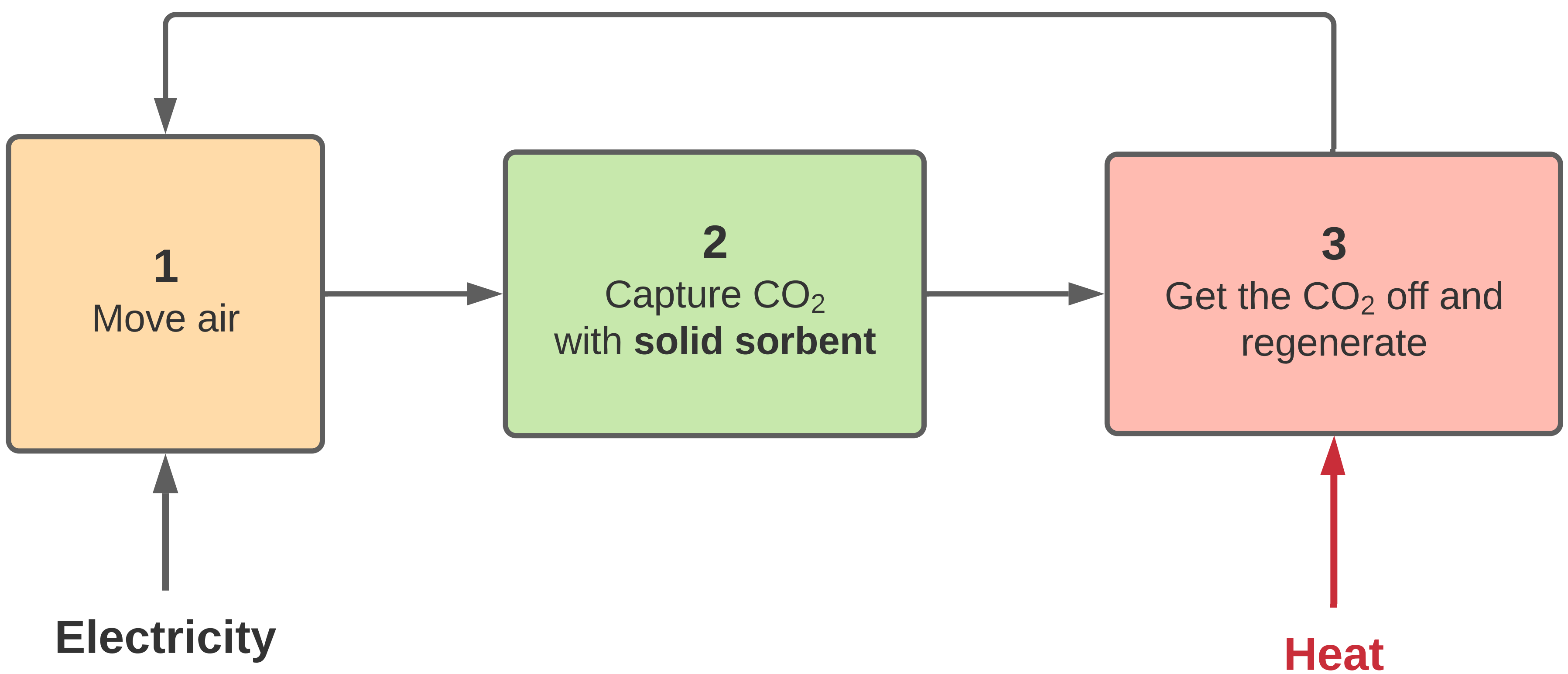
- Heat supplied by high temp gas cooled reactor (HTGR)
  - 950°C coolant outlet could enable 900°C process heat supply

AVR, 1967-1988
950°C out

HTTR, 1999 -
950°C out

HTR-PM, 2021-
750°C out now (900+ possible)

Low-temperature solid adsorbent DAC

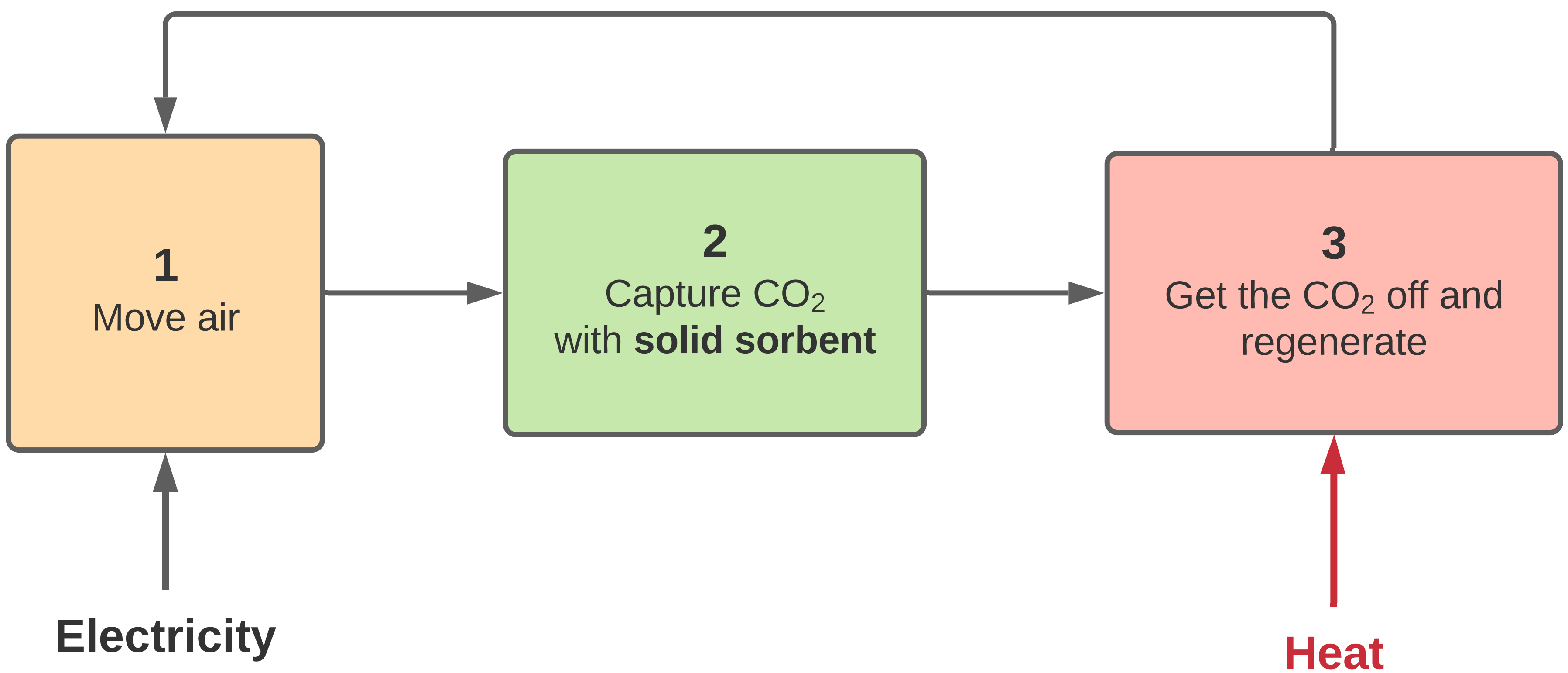


climeworks

Global Thermostat

soletair power

Energy requirements today



Electrical fans

0.5-1.0 MWh
per ton CO_2-captured

100-130°C

2-3.5 MWh
per ton CO_2-captured

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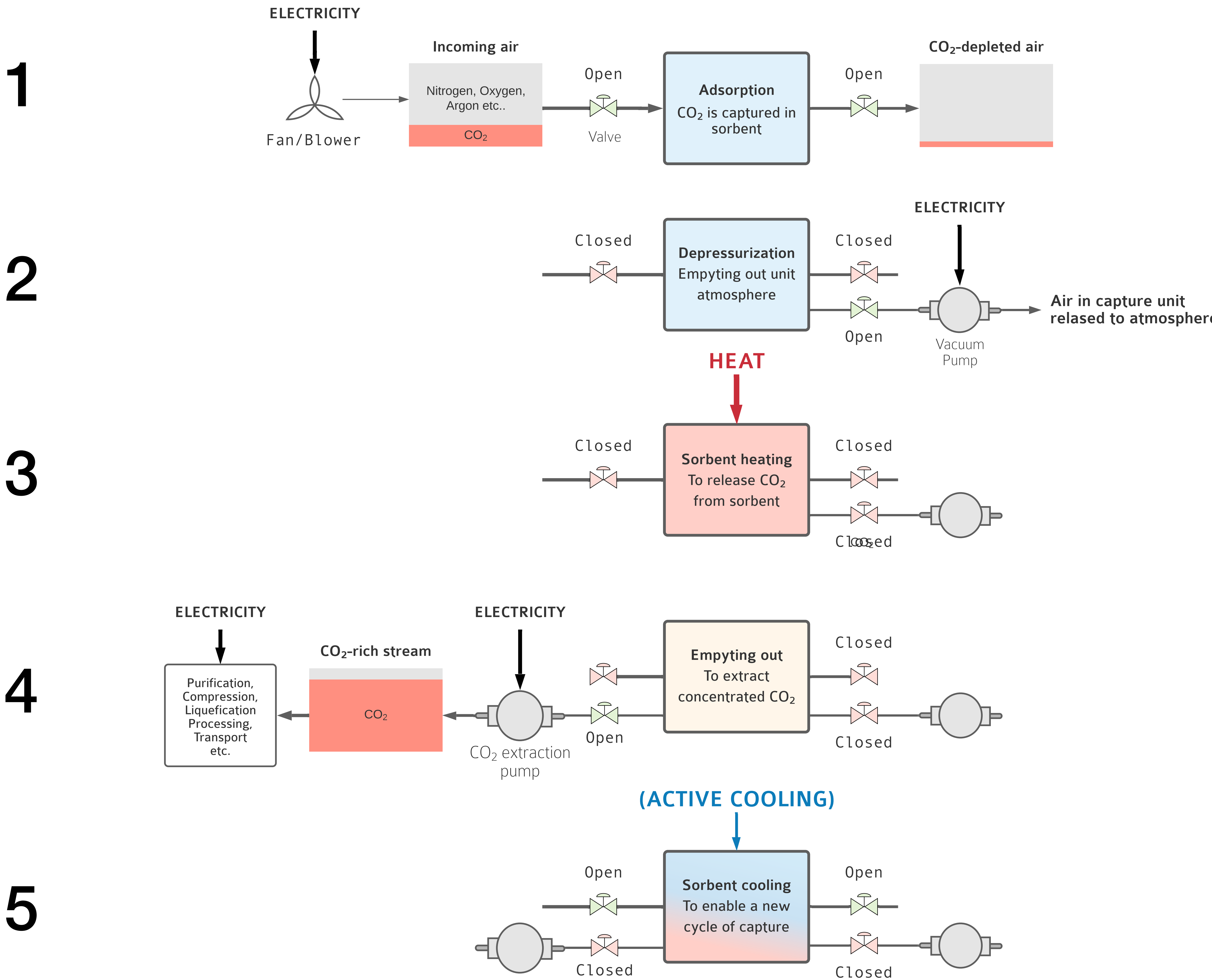


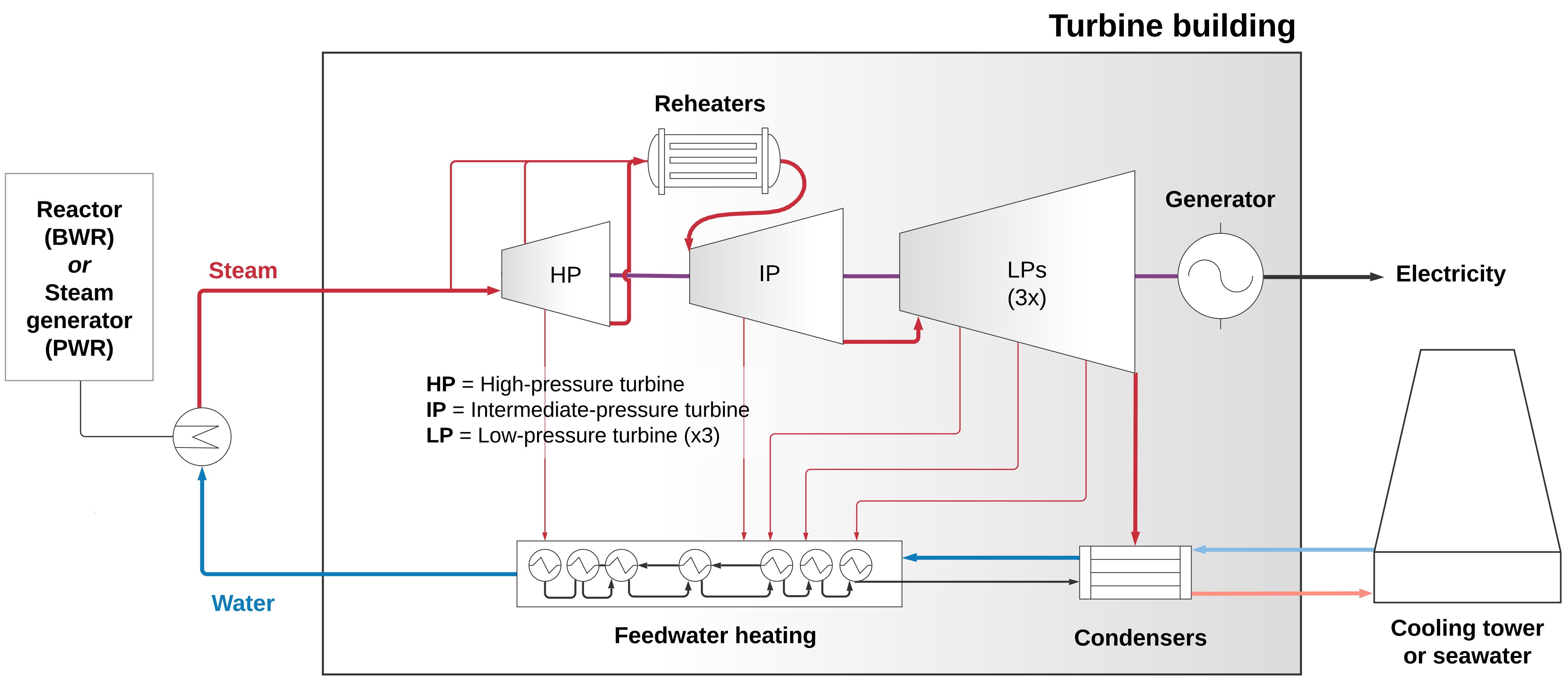
1
ELECTRICITY
Fan/Blower
Incoming air
Nitrogen, Oxygen, Argon etc..
CO_2
Open
Valve
Adsorption
CO_2 is captured in sorbent
Open
CO_2-depleted air
2
ELECTRICITY
Closed
Depressurization
Emptying out unit atmosphere
Closed
Open
Vacuum Pump
Air in capture unit relased to atmosphere
HEAT
3
Closed
Sorbent heating
To release CO_2 from sorbent
Closed
Closed
CO_2
4
ELECTRICITY
Purification, Compression, Liquefication Processing, Transport etc.
CO_2-rich stream
CO_2
ELECTRICITY
CO_2 extraction pump
Open
Empying out
To extract concentrated CO_2
Closed
Closed
(ACTIVE COOLING)
5
Open
Closed
Sorbent cooling
To enable a new cycle of capture
Open
Closed

Nuclear (LWR) powered DAC options

1. **Power current-day solid-adsorbent DAC systems**
   - ✓ Use steam extraction to regenerate solvents

2. **Optimize DAC for nuclear energy integration**
   - ✓ Use steam extraction to regenerate solvents
   - ✓ Move air through system using waste heat

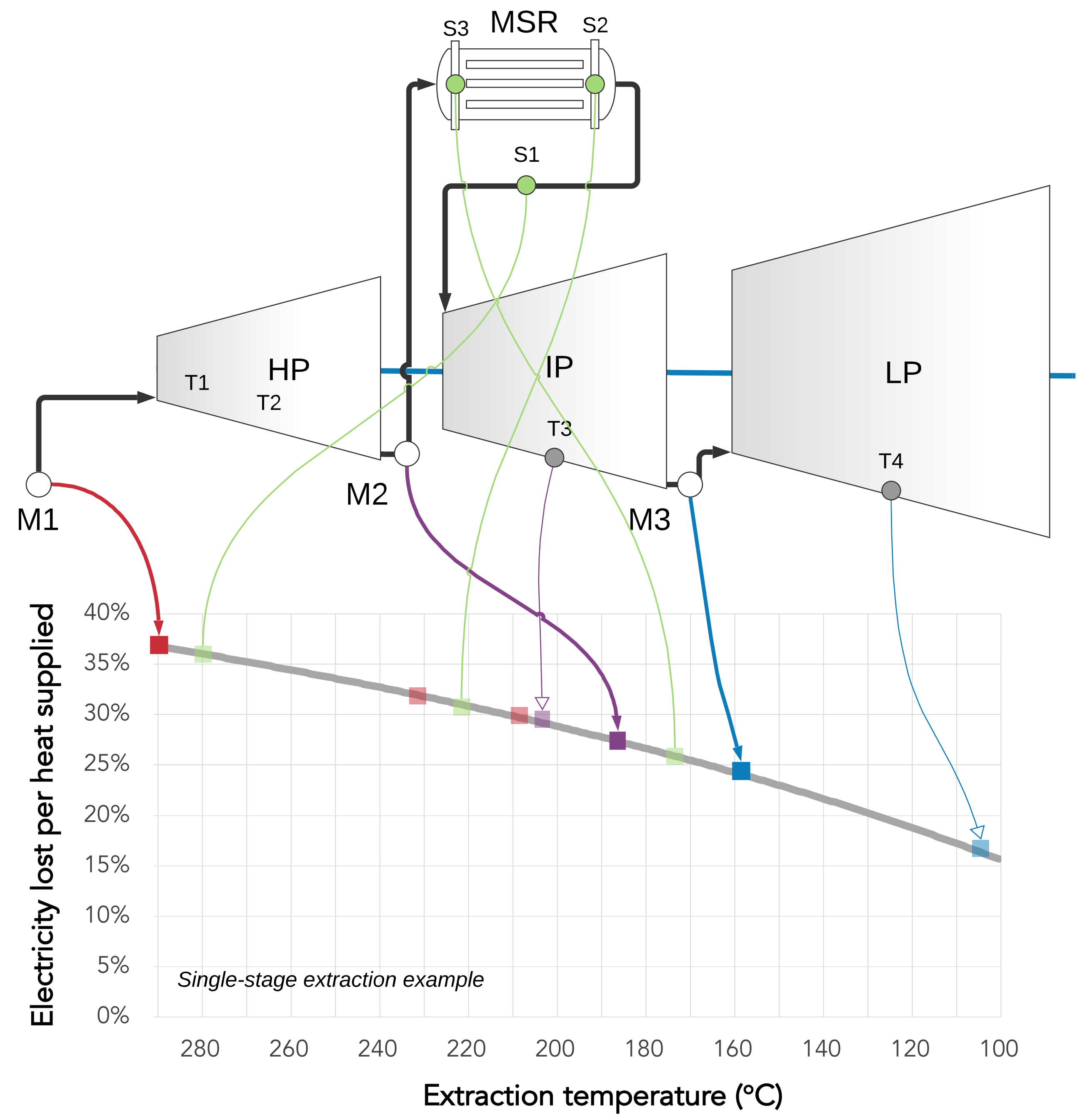
Extracting LWR heat for DAC regeneration



Extracting LWR heat for regeneration

Extracting steam reduced electricity output by:

$$P = \eta \times \frac{(T_R - T_C)}{(T_R + 273.15)}$$



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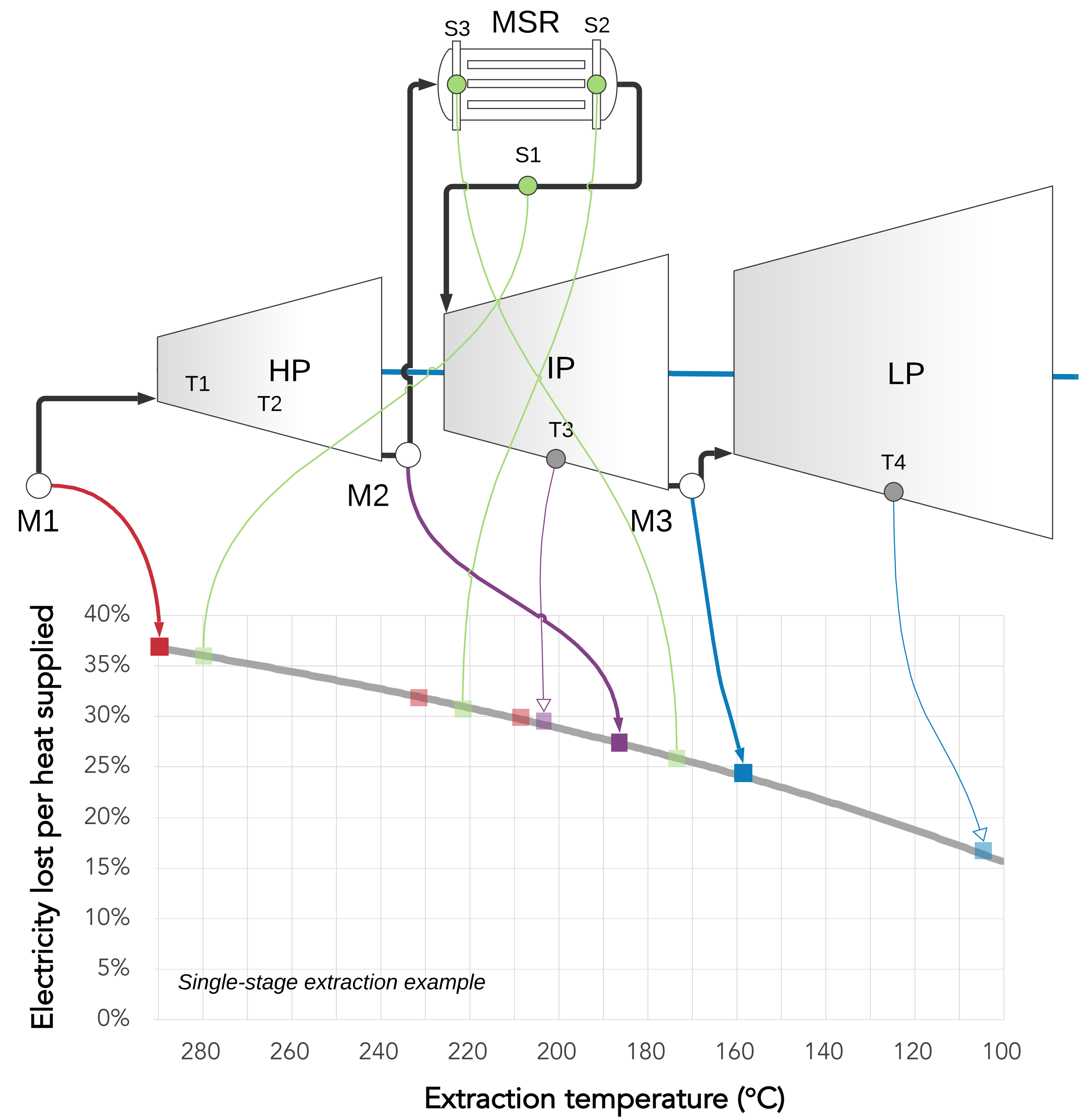
Extracting LWR heat for regeneration

Extracting steam reduced electricity output by:

$$P = \eta \times \frac{(T_R - T_C)}{(T_R + 273.15)}$$

$$P = 0.789 \times \frac{(T_R - 35)}{(T_R + 273.15)}$$



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Extracting LWR heat for regeneration

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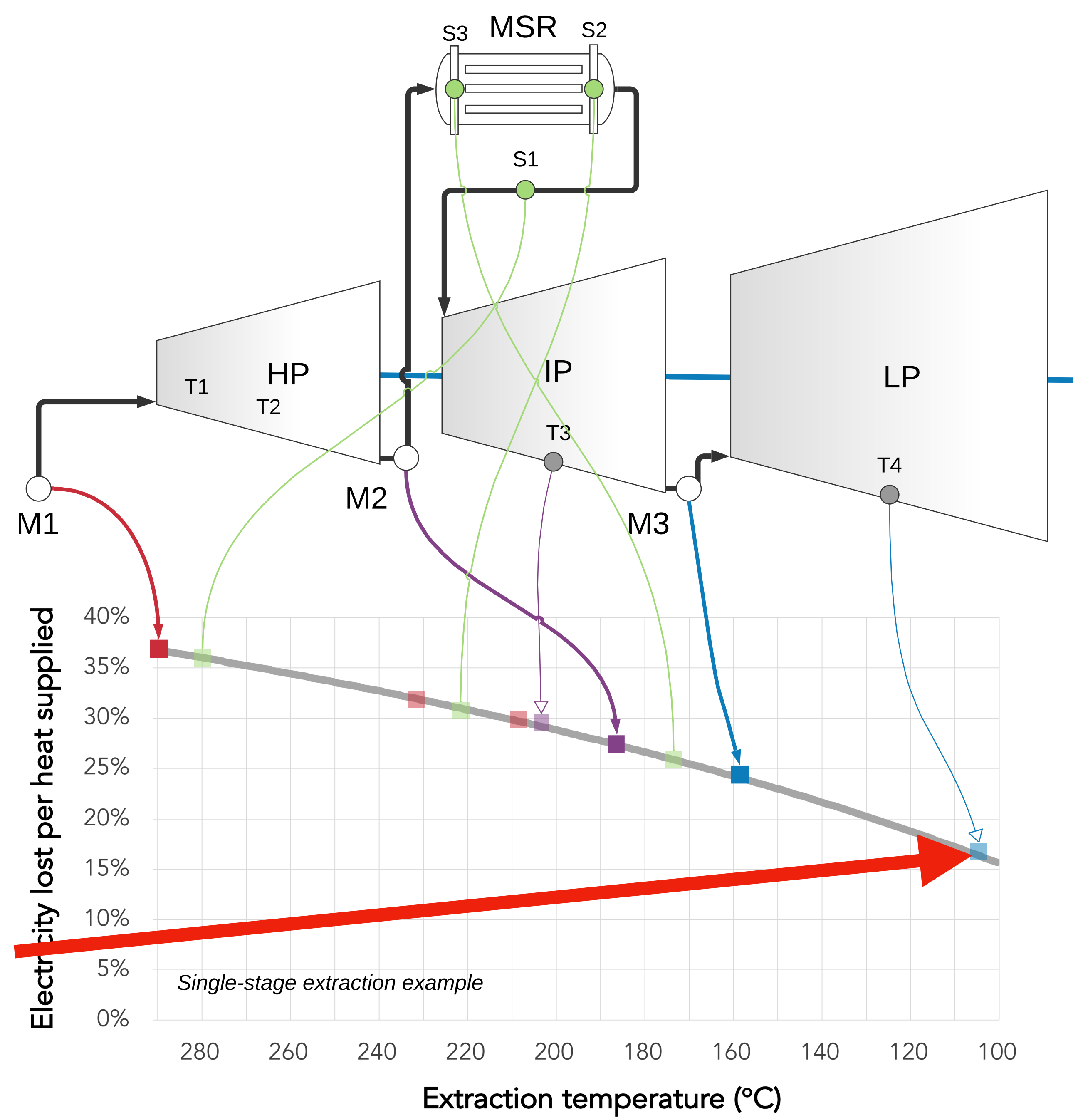
$$P = \eta \times \frac{(T_R - T_C)}{(T_R + 273.15)}$$

$$P = 0.789 \times \frac{(T_R - 35)}{(T_R + 273.15)}$$

$$P = 0.789 \times \frac{(105 - 35)}{(105 + 273.15)} = 0.146$$



1/7th MWh lost per 1 MWh heat supplied!

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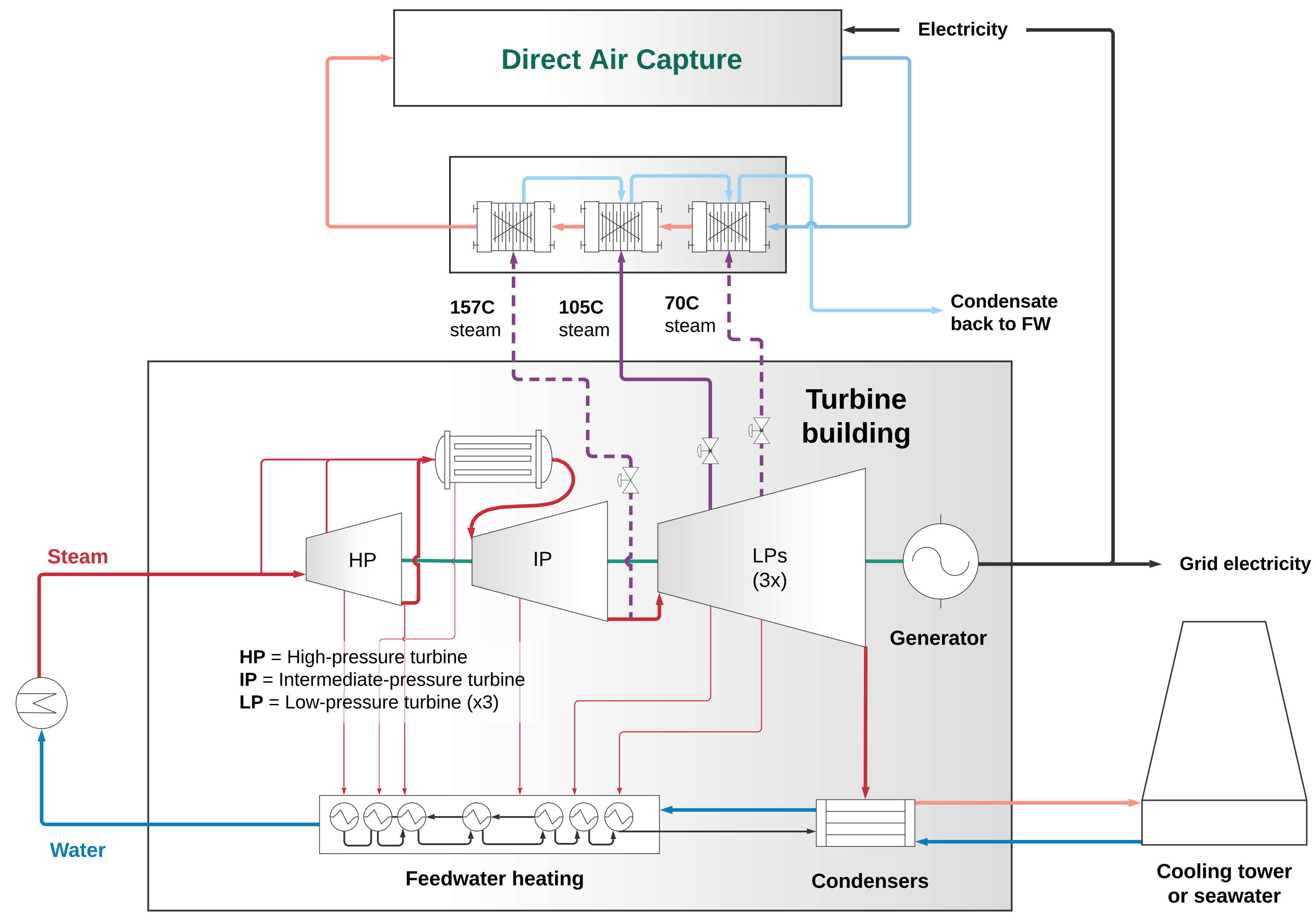
LWR-powered DAC system

- Extract heat out to external condensing HX, return condensate to FW system
- A 3-stage extraction system means losing 0.15 MWh of electricity for each MWh of heat supplied (at 120C)
- Easiest 1-stage extraction point is at the cross-over before the low-pressure turbine stage (0.25 MWh/MWh lost)
- Up to 10% of thermal power can be extracted with minor modifications



Optimized nuclear-DAC system

PROCESS & SORBENT DEVELOPMENT

The University of Nottingham

PROTOTYPE ENGINEERING
& CONSTRUCTION

STRATA TECHNOLOGY LTD

SizewellC
eDF CGN

HOST, UTILITY SUPPLY
& PROJECT MANAGEMENT

INDUSTRIAL MANUFACTURING

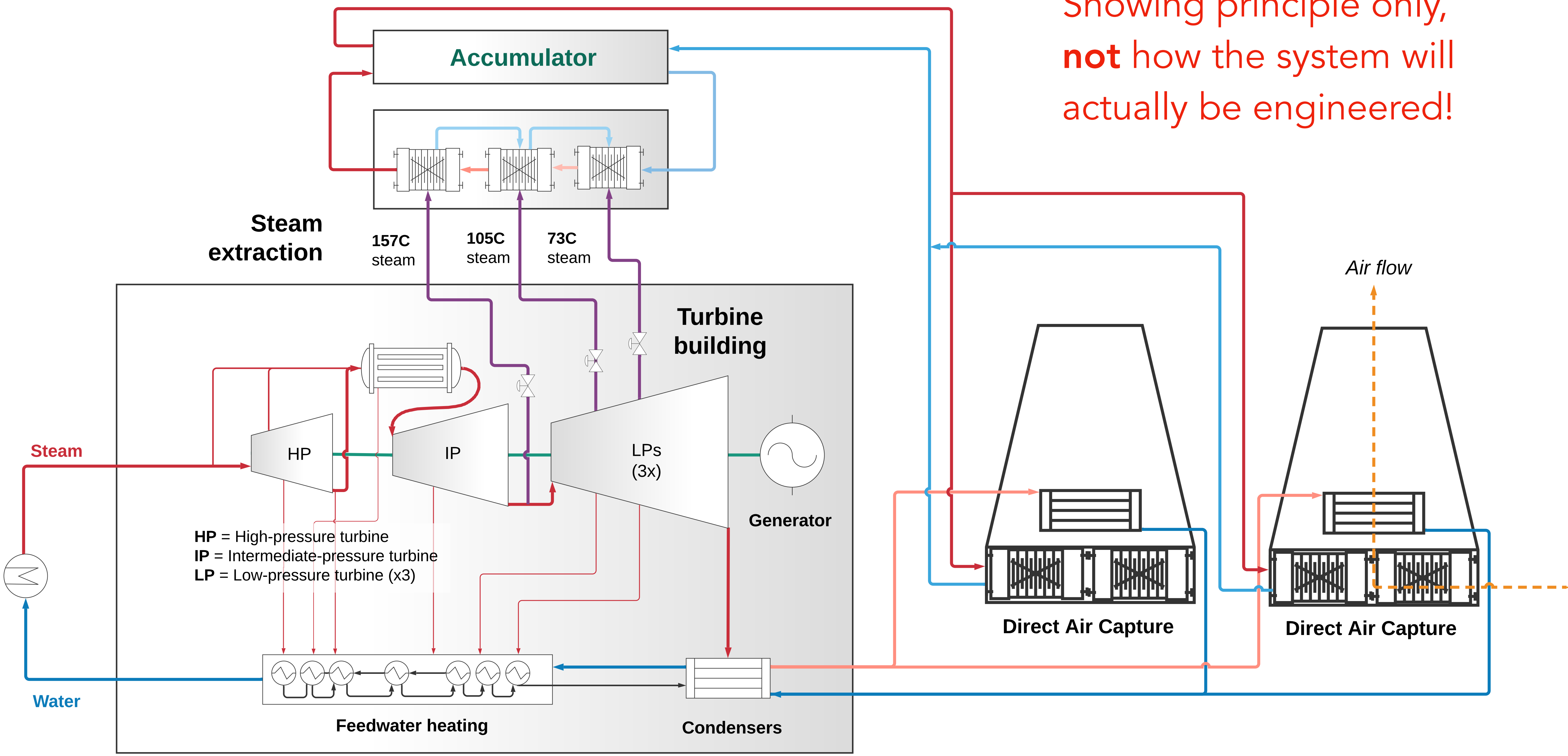
DOOSAN

COMMERCIALIZATION

ATKINS

Principle of integration

Showing principle only, **not** how the system will actually be engineered!



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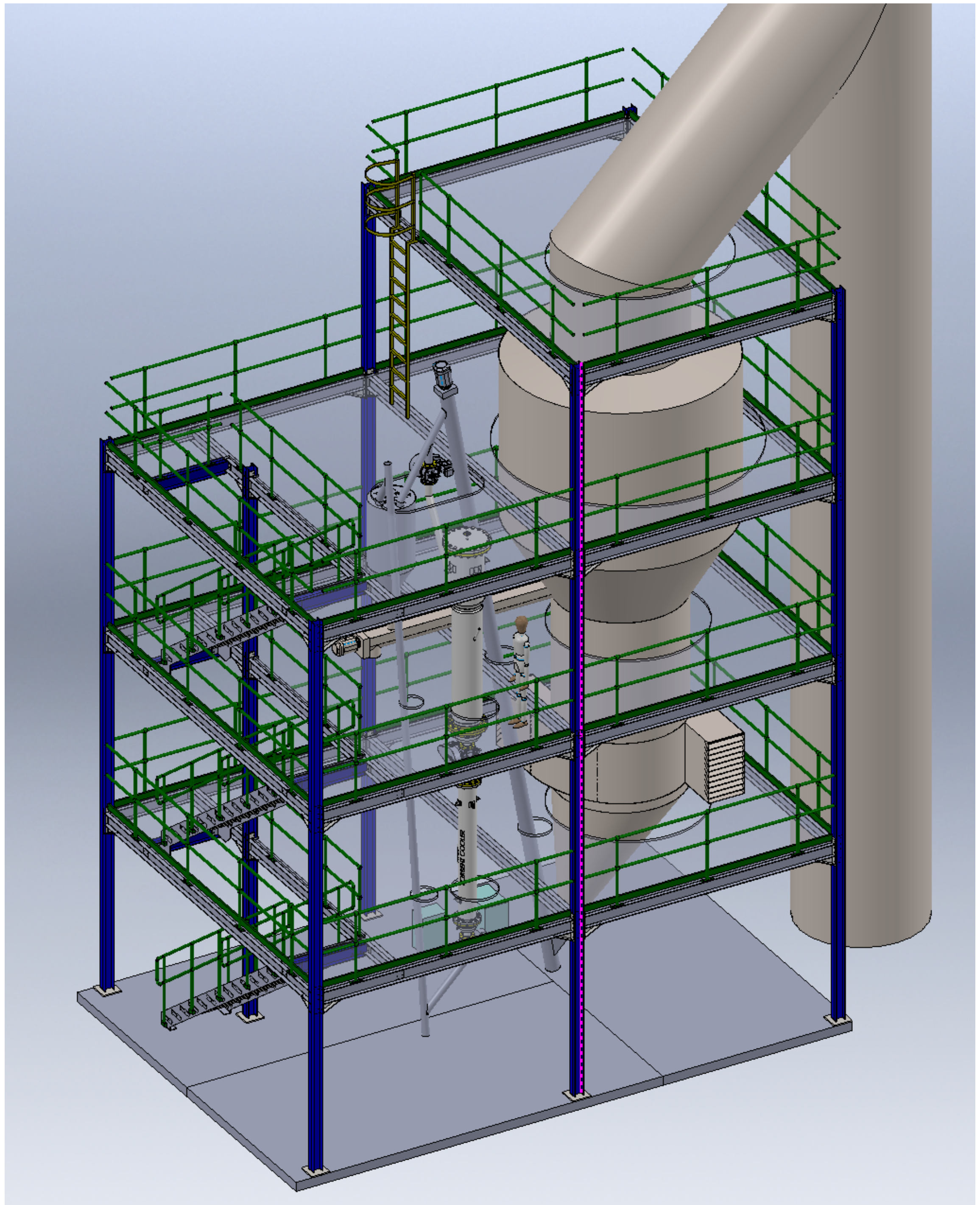
Engineering development

- 100 ton CO_2/year plant designed
- Electrical heating as stand-in for nuclear co-generation for heat to move air (mimicking condenser cooling heat) and heat to regenerate (mimicking steam extraction)
- Winner of UK Government DAC competition, £250k grant first phase, second (build) phase £2m
- **A new standard SMR condenser cooling system?**



DAC economic basics

Three main components

- Cost of DAC equipment
- Cost of electricity supply
- Cost of heat supply

Assumptions for cost of DAC equipment

Year	2020	2030	2040	2050
$CAPEX_{DAC}$ (€/tonCO_2/y)	730	338	237	199
$OPEX_{FIX}$ (€/tonCO_2/y)	29.2	13.5	9.5	8.0
$OPEX_{var}$ (€/tonCO_2)	3	3	3	3

DAC cost floor

Assumptions for *levelized* cost of DAC equipment alone €/tonCO_2 (w. no utility supply) by capacity factor

Year	2020	2030	2040	2050
CF = 100% (Theoretical floor)	94.8	45.5	32.8	28.1
CF = 95% (Grid power)	99.7	47.7	34.4	29.4
CF = 85% (Nuclear dedicated)	111.0	53.0	38.1	32.5
CF = 35% (Onshore wind dedicated)	265.4	124.4	88.2	74.6
CF = 12% (Nordic PV dedicated)	768.3	357.2	251.6	212.0

7% WACC, Asset life: 25 years

Optimized nuclear DAC economics

Reference cost of electricity supply (no modifications):

- €50/MWh

Cost of DAC electricity supply

- 20 kWh/tonCO_2 * €55/MWh ≈ €1/tonCO_2

Cost of DAC heat supply

- Electricity Opportunity Cost +
- Terminal equipment & Upgrades at plant +
- High + Low Temp Heat Transport Equipment Cost +
- Additional operational expenses

≈ €17/tonCO_2

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Comparison economics

Electricity from grid or dedicated renewables

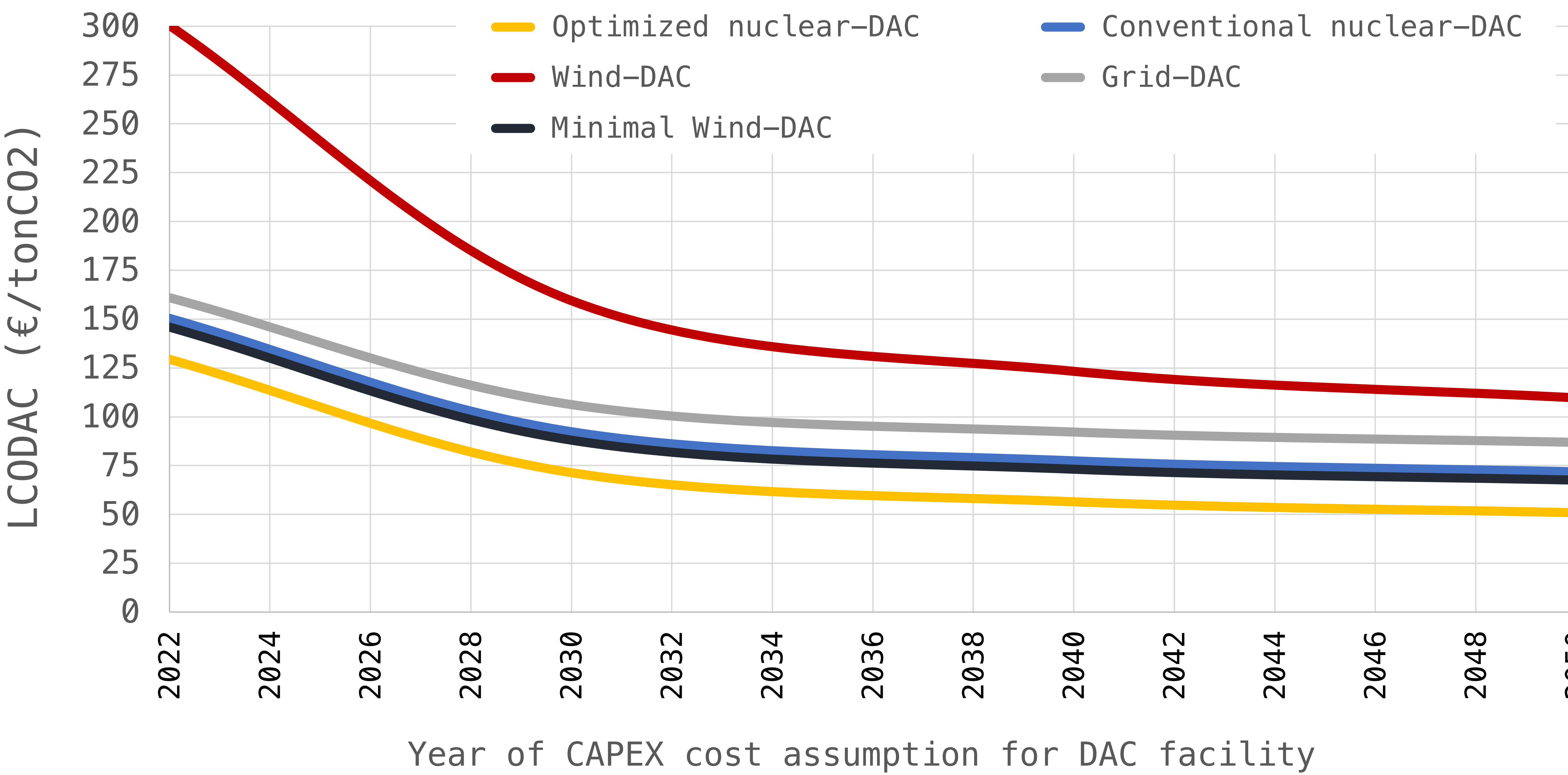
Cost of DAC electricity supply

- 0.4 MWh/tonCO_2 * €25-40/MWh ≈ €10-16/tonCO_2

Cost of DAC heat supply through advanced heat pumps

- 1 MWh/tonCO_2 * €25-40/MWh ≈ €25-40/tonCO_2

Comparative economics



Conclusions

- A nuclear plant can reach capture cost of ~€50/tonCO_2, with life-cycle CO_2-emissions of -160 gCO_2/kWh
- Even at *assumed* far higher LCOE, a nuclear-DAC system has lower LCOD than systems powered by VRE or grid
- A nuclear-optimized DAC system is being developed & commercialised currently, if successful could eventually become a standard SMR condenser cooling system
- Captured CO_2 can form basis (alongside H_2 from effect water electrolysis) for synthetic hydrocarbons

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Sorbents

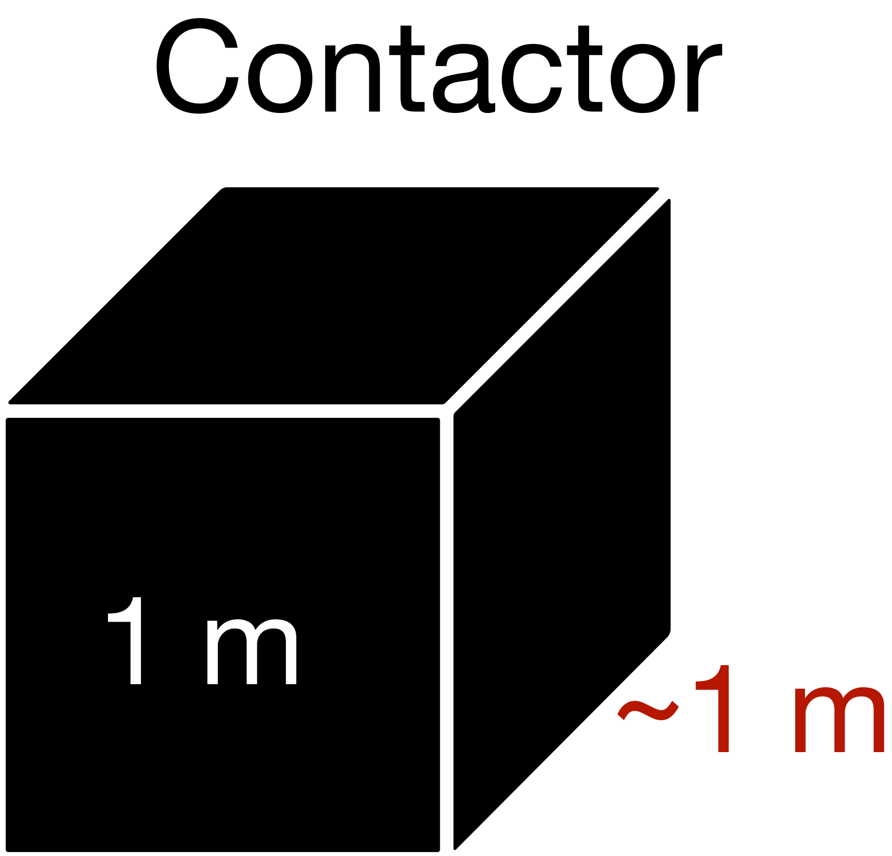
- **Sorbents are chemicals that contain molecules that have affinity for CO_2 and bind to it. Monoethanolamine (MEA) and other amines have been used commercially for this for decades.**
- **Four main factors determine DAC sorbent suitability:**
  - Reactivity (how effectively does it bind CO2)
  - Regeneration energy
  - Degradation rate
  - Cost & Availability
- **Difficult trade-off regarding all four factors!**

How large are "contactors"?

- 1 m^3 of air contains ~0.75 grams of CO_2
- To capture T tons of CO_2 per year, a DAC device that captures X % of the CO_2 in the air passing through it, will need to "process" T / (X * 0.75 g) of air every year.
- If X = 50 % and T = 100 t/y, the value of Y is 8.5 m^3/s.
- This size of the facility depends on the air flow velocity through the system.
- At 1 m/s, the minimum theoretical requirement is 8.5 m^2 of "*intake area*" per 100 t/y, at 4 m/s, just ~2 m^2.
- Systems spends 60-70 % of the year capturing, meaning figures need to be multiplied by ~1.5.

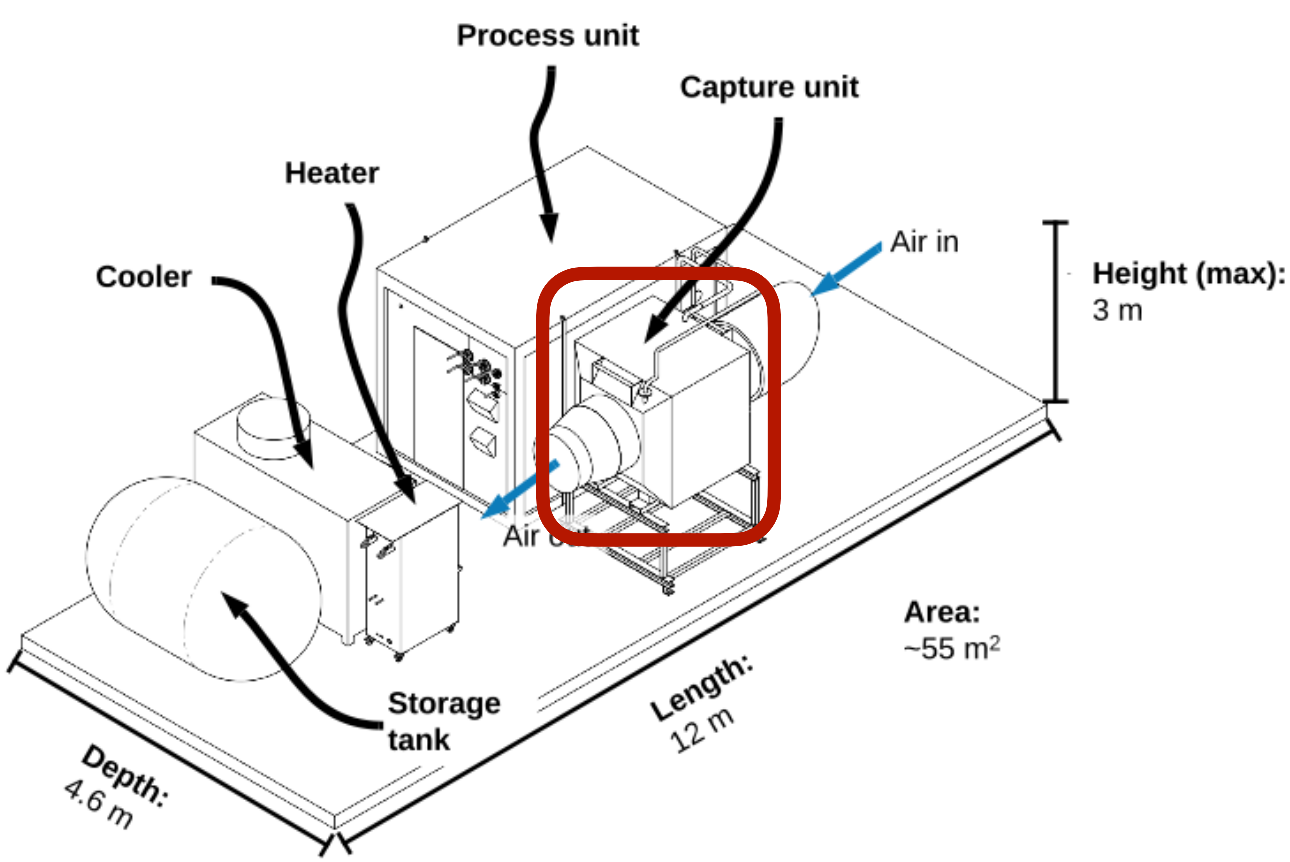
Approximate size of 100 t/y facility

~4-6 x

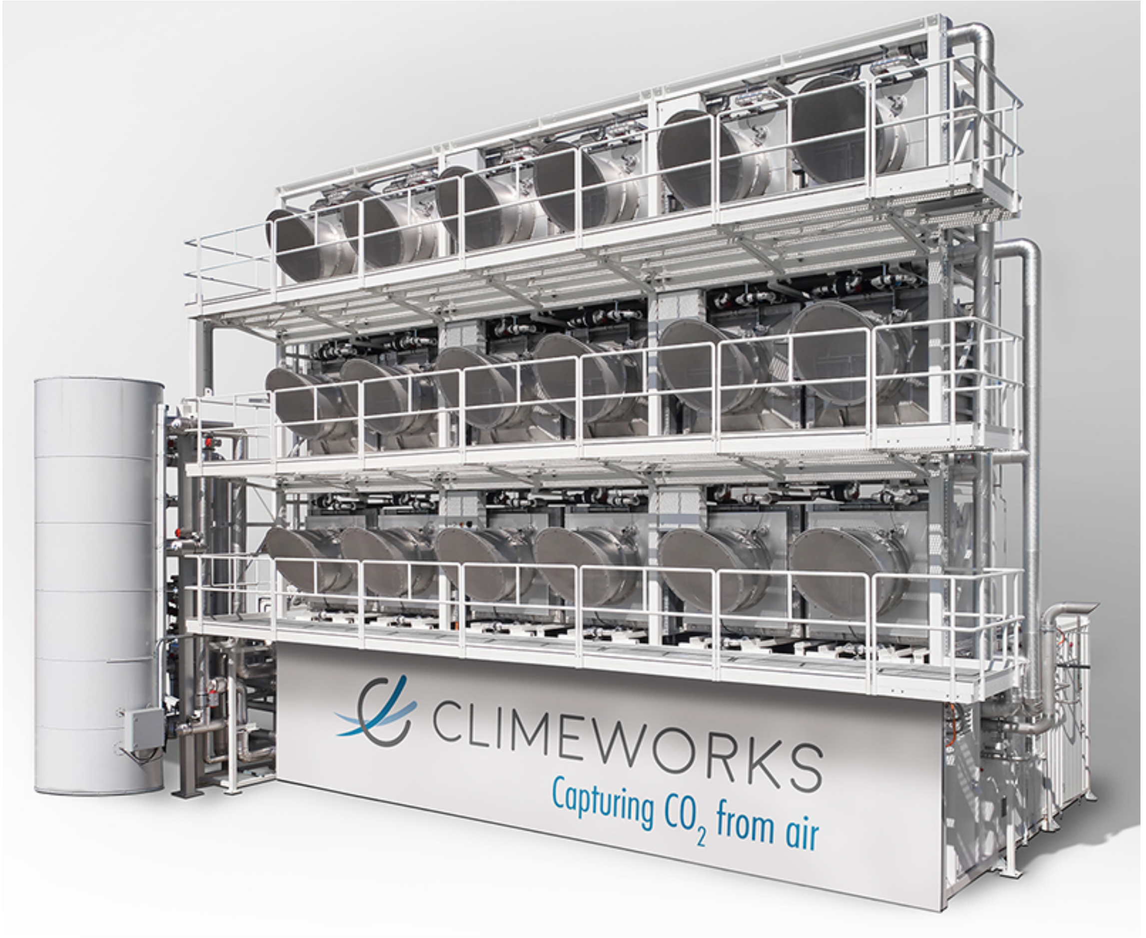


Climeworks size for scale

20 tons/year



500 tons/year



Scaling to 1 MT/y

- Each DAC contactor depletes the air in CO2, i.e they cannot be placed directly behind one another
- ~250 meter downwind separation ensures good air mixing
- 1 MT/y square-shaped plant with no vertical stacking requires ~1 x 1 km of area
- Vertically stacking 5 units (~10 meters high) requires ~0.1 x 1 km area or ~0.5 x 0.5 km square shaped