Pathways to Practical Carbon Capture and DAC

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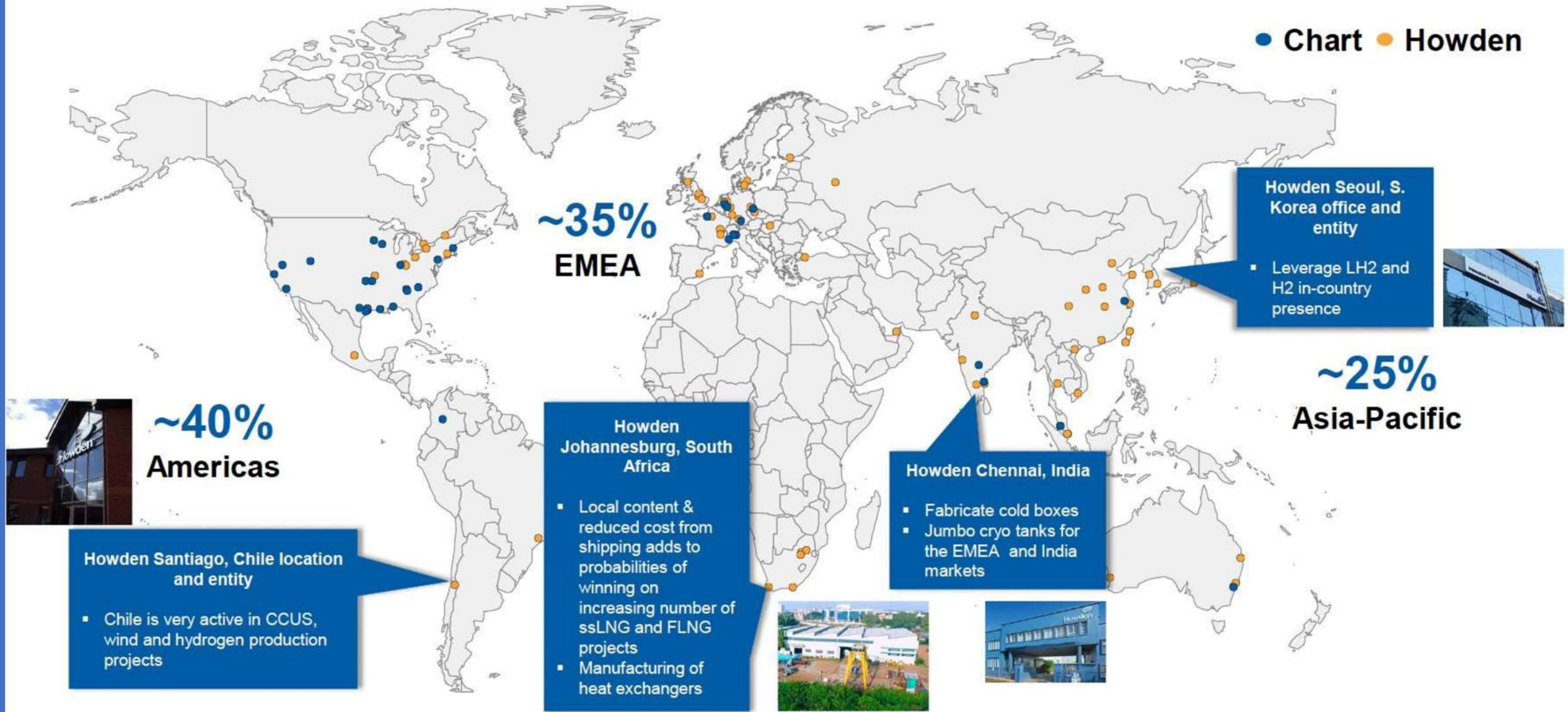
Introduction to Chart Industries and Sustainable Energy Solutions

Chart Industries

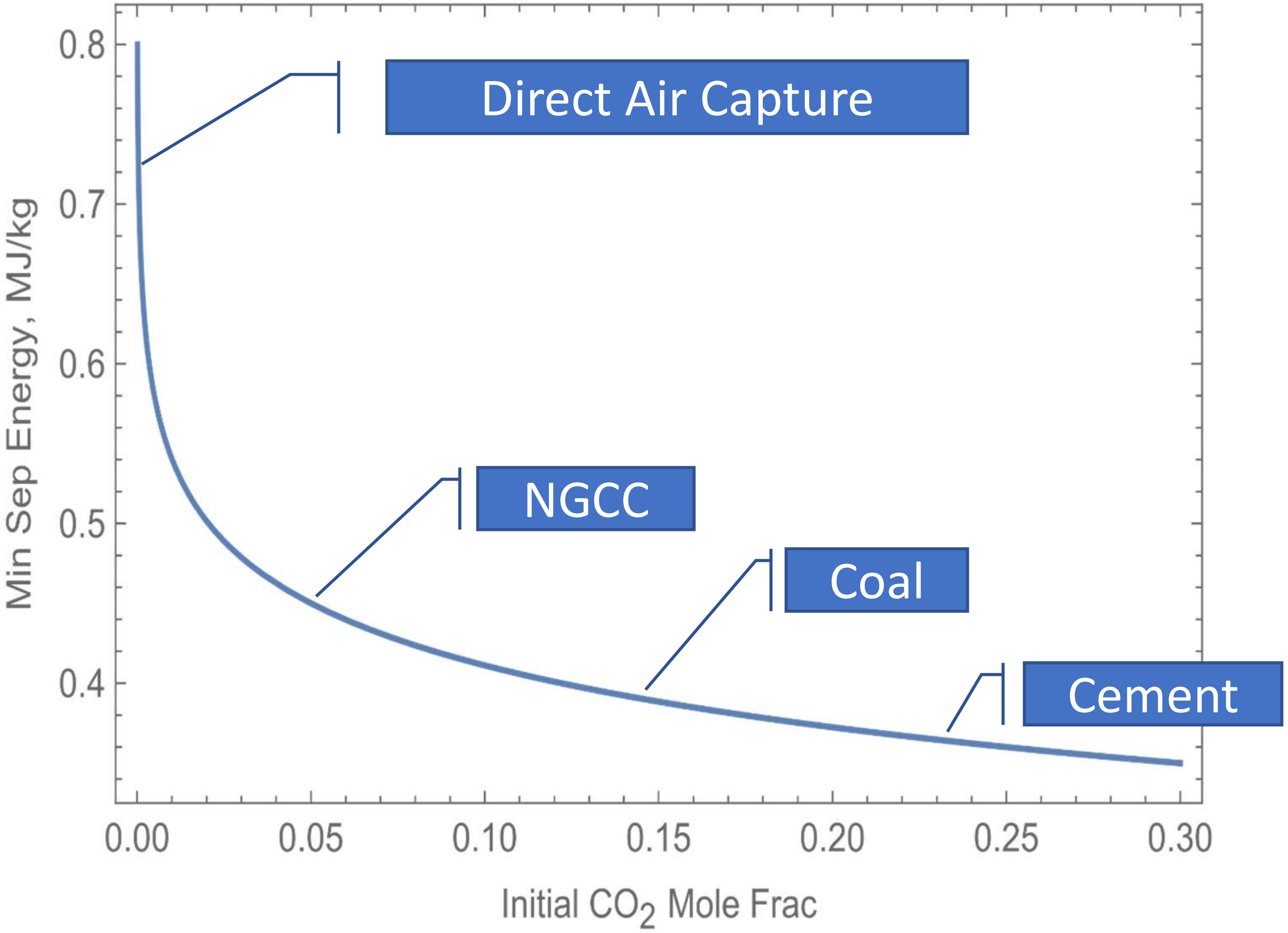
A Global Footprint to Serve Customers Locally



Note: Percentages represent estimated % of revenue on a combined company basis.

Carbon Capture Science for all Technologies

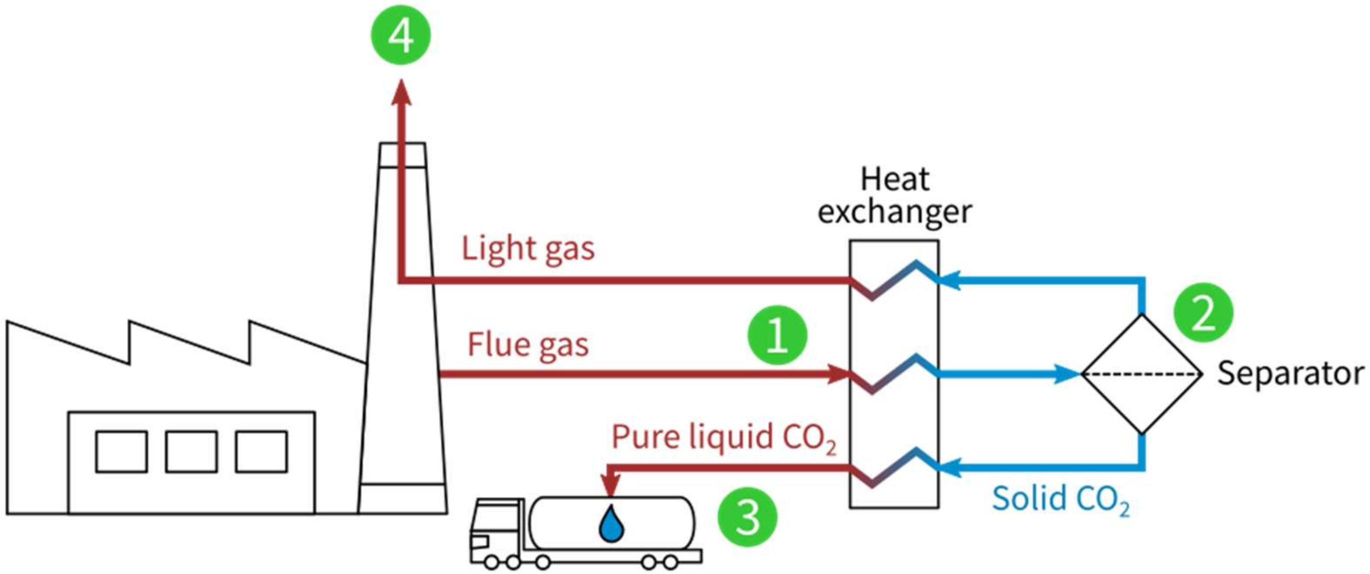
Energy Demand vs Init. Composition



- Min. specific energy demand depends on initial composition in extreme and nonlinear ways.
- Min. specific energy becomes infinite as initial composition approaches zero.
- Differences in real systems exceed these minimum energy differences.

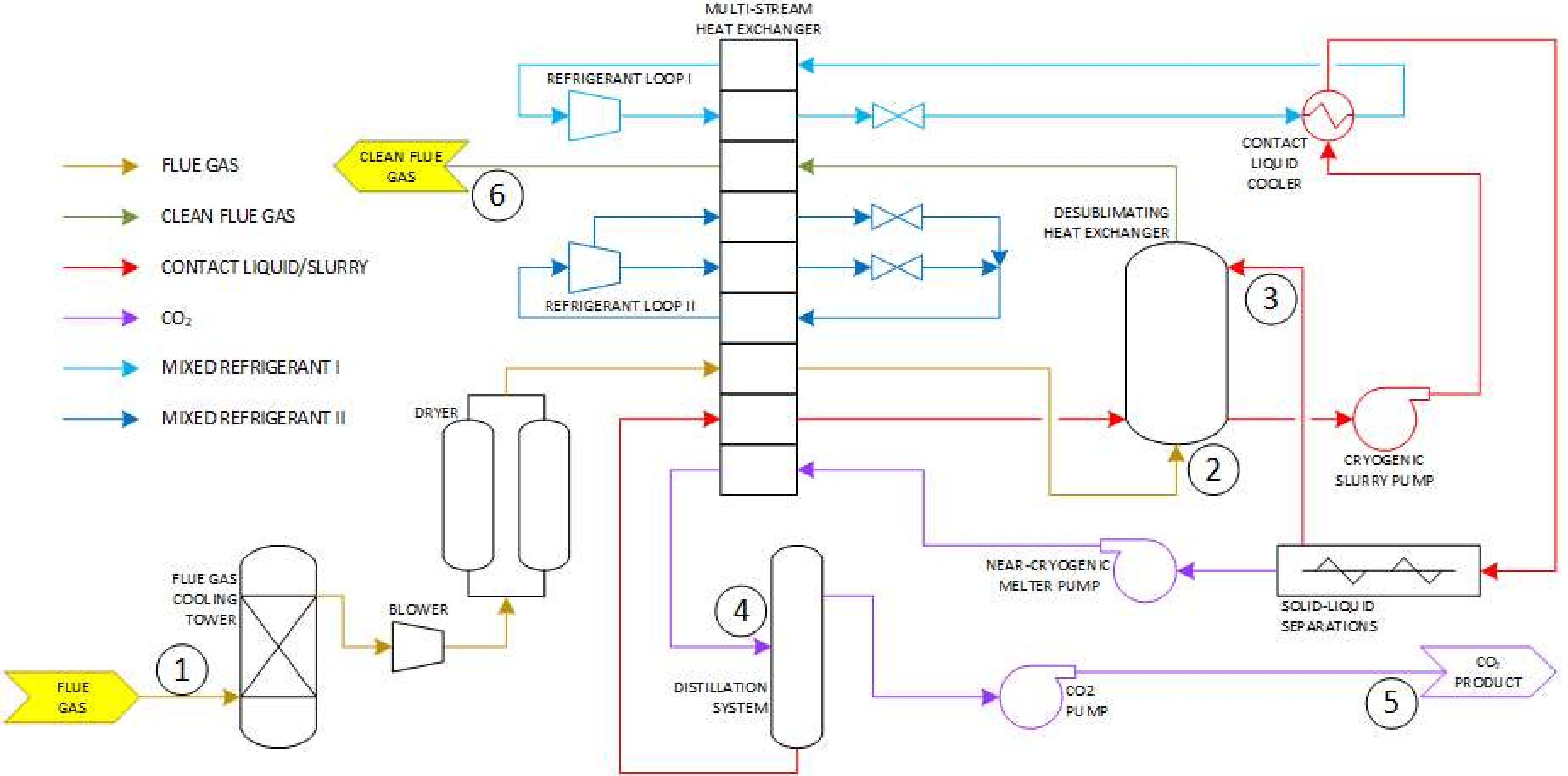
Introduction to Cryogenic Carbon Capture (CCC)

Conceptually Simple Process



1. Flue gas is cooled
2. CO_2 is separated as a solid from the light gases
3. CO_2 is melted and prepared for transport
4. Light gases are reheated and released to atmosphere

CCC Process Flow Diagram



CCC Benefits

Lowest energy and cost retrofit technology

Easiest retrofit carbon capture technology

Produces high-purity, liquid CO_2

Very high capture rates, up to negative emissions (99%+)

Integrated grid-scale energy storage

Independent Validation

"Of all these [carbon capture] processes, I regard the CCC process to have the greatest potential"

-Howard Herzog, MIT Energy Initiative

MITei MIT Energy Initiative

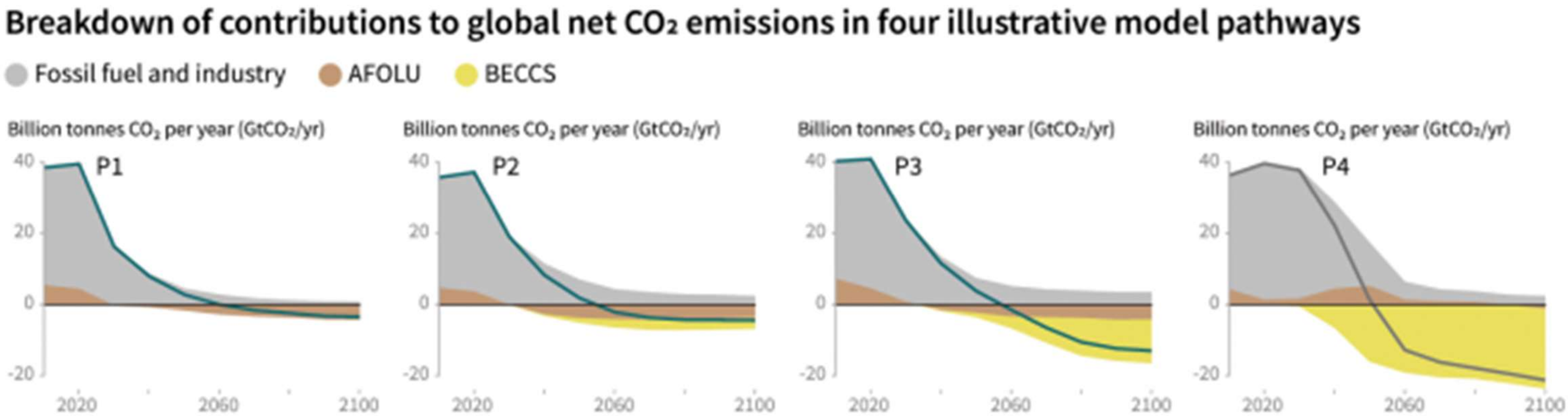
EDISON AWARDS GOLD

R&D 100 55 Years of Invention

EPRI ELECTRIC POWER RESEARCH INSTITUTE

nrg | cosia CARBON XPRIZE

AR6 Summary

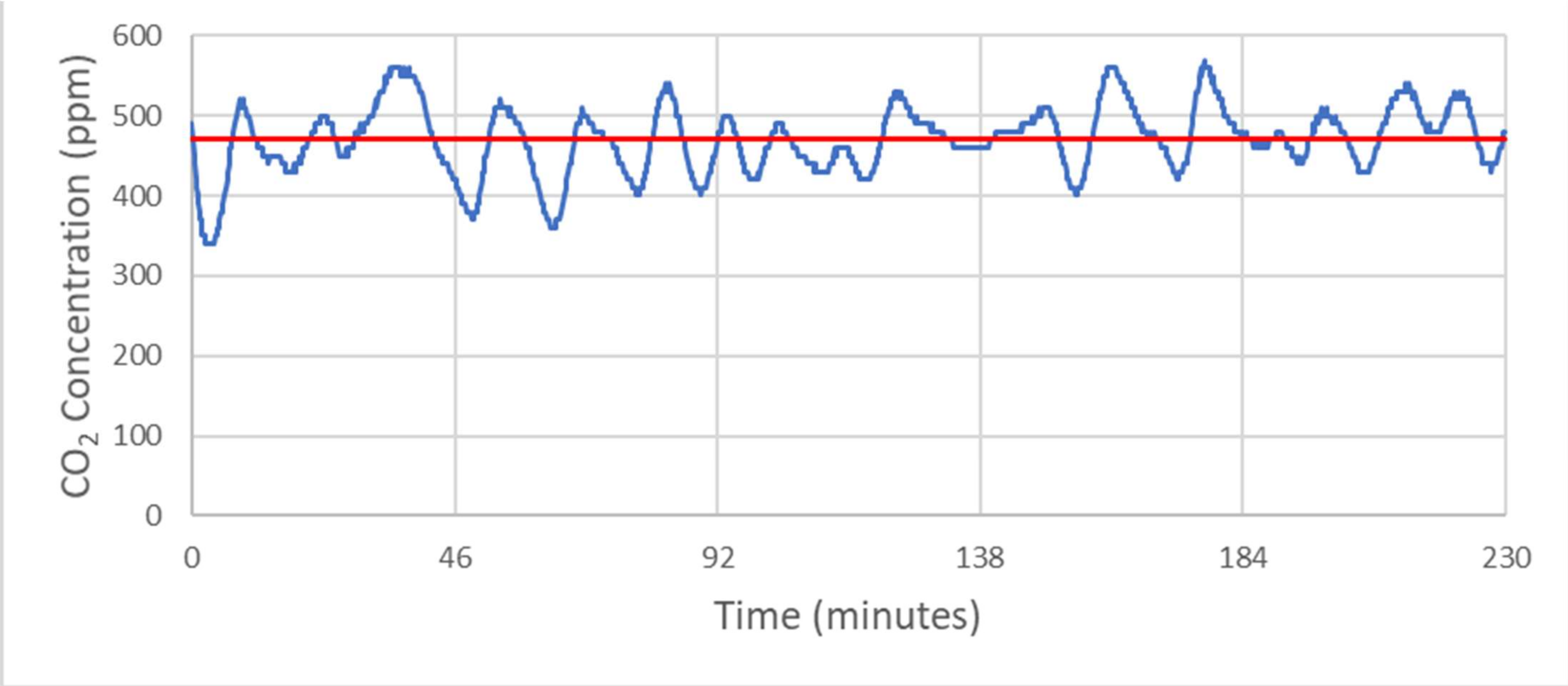


Breakdown of contributions to global net CO₂ emissions in four illustrative model pathways
Fossil fuel and industry
AFOLU
BECCS
Billion tonnes CO₂ per year (GtCO₂/yr)
P1
P2
P3
P4
40
20
0
-20
2020
2060
2100

DAC Technology

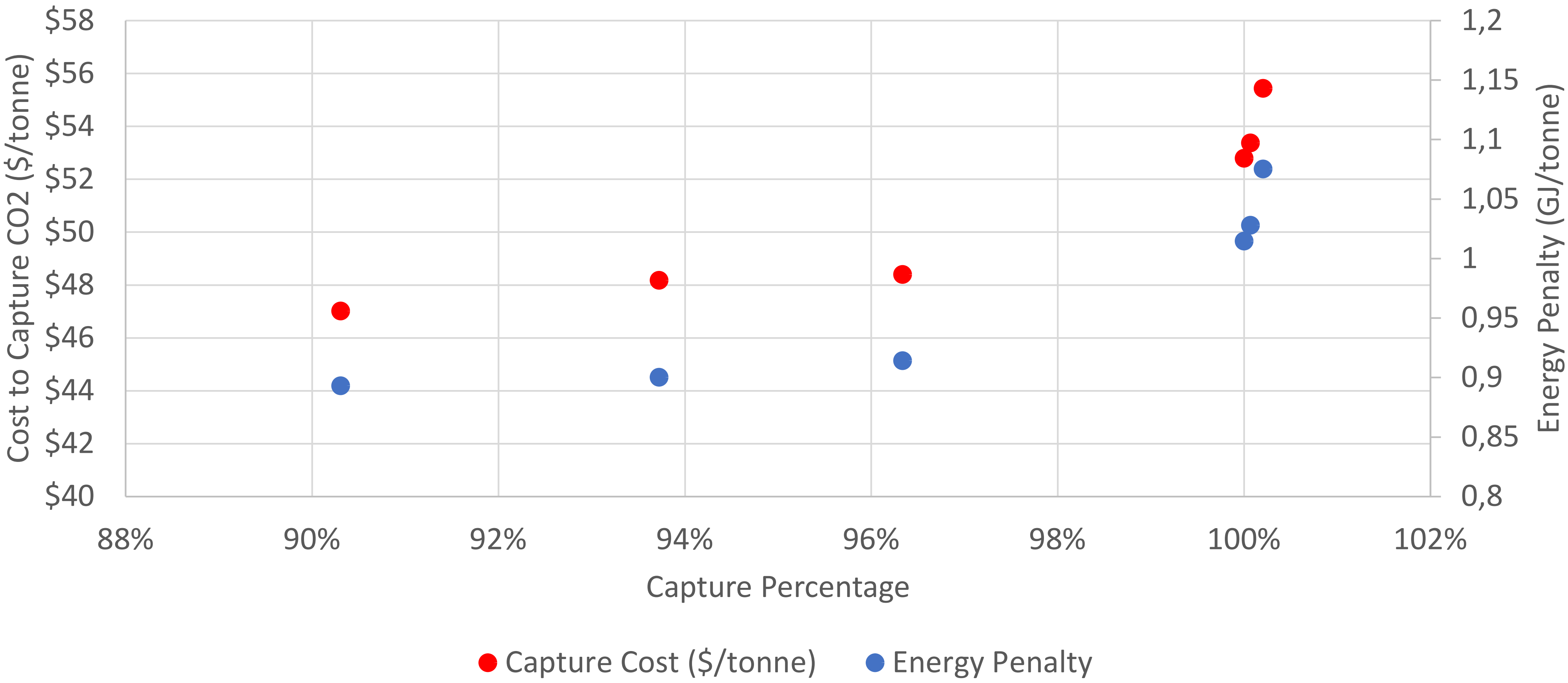
- Depends critically on power supply
  - Coal-powered DAC will likely increase, not decrease, CO_2 emissions – emits 1.2 times as much as captured
  - NG-powered DAC will remove 0.4 t CO_2 for each 1 ton removed.
- Alternative approach is to capture all CO_2 produced from sources and some of the CO_2 that enters with the air (100+% capture).
  - Coal- and NG powered DAC done in this way removes 1 tonne of CO_2 for each tonne removed above the 100% threshold.
  - More importantly, this approach reduces energy demand of DAC by a factor of 4-5 and cost by a larger factor (compared to $1100/tonne for the Iceland Climeworks process – the only process with detailed estimates).
  - Air is already dried and CO_2 is higher in this approach compared to ambient air approach

Skid-scale Demonstration



DAC threshold is greater than 410 ppm because most O_2 has been removed as CO_2 and H_2O

PS DAC Costs



Cost to Capture CO2 ($/tonne)
$58
$56
$54
$52
$50
$48
$46
$44
$42
$40
1,2
1,15
1,1
1,05
1
0,95
0,9
0,85
0,8
Energy Penalty (GJ/tonne)
88%
90%
92%
94%
96%
98%
100%
102%
Capture Percentage
Capture Cost ($/tonne)
Energy Penalty

Conclusions

- DAC accomplished by driving CCC point-source capture to capture all of the process-emitted CO_2 and some of the CO_2 that enters with the air will
  - Reduce DAC energy demand by a factor of 4-5
  - Reduce DAC cost by a factor of 4-5
  - Increase CO_2 concentration in the treated gas by up to 20-30%
  - Dramatically increase effectiveness of DAC powered by fossil fuels
  - Complete the job (prepared pressurized liquid CO_2 for transportation and storage)
  - Eliminate heat demand
  - Enable highly efficient DAC by use of cofired biomass fuels

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