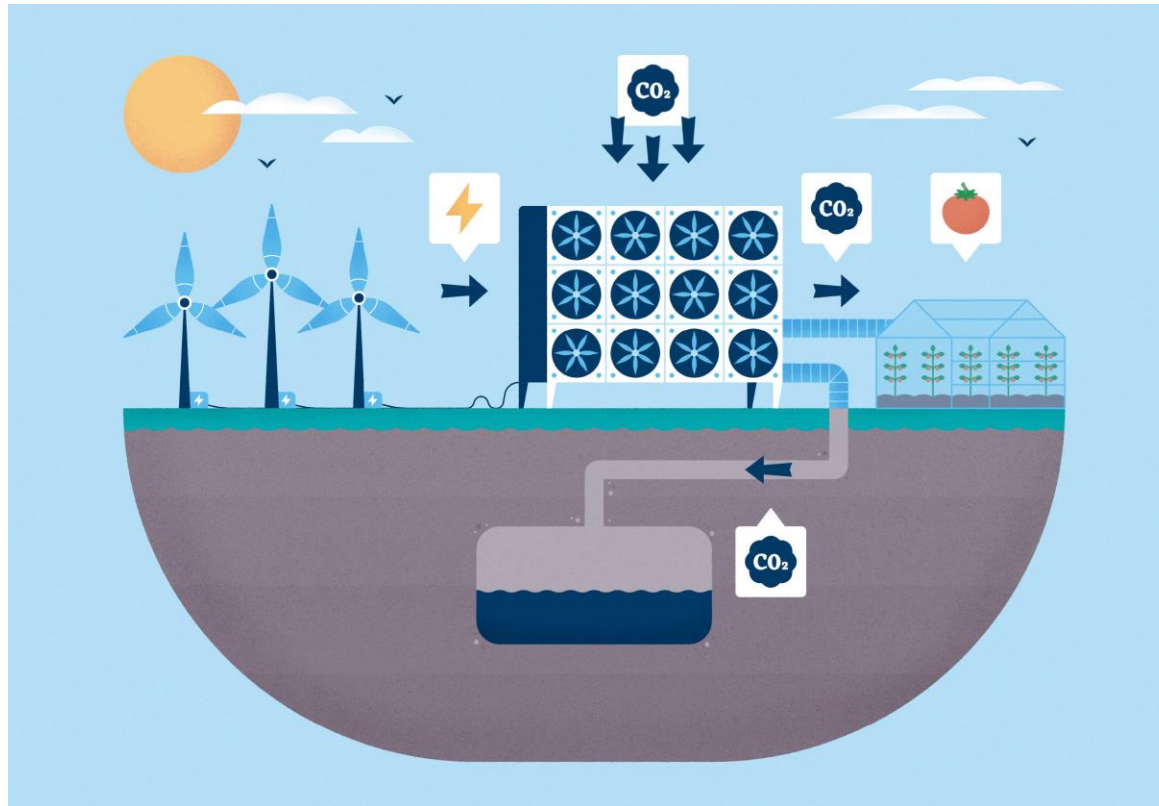


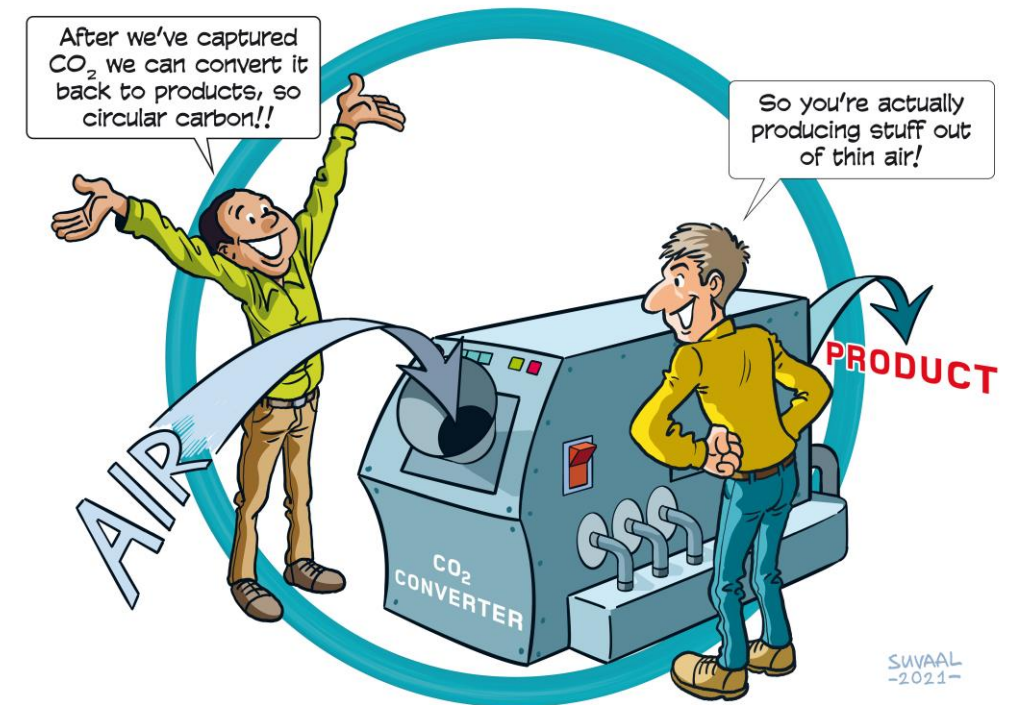
▶ **DIRECT AIR CAPTURE FOR HORTICULTURE APPLICATION**
JASPER ROS
MAY 2022

INTRODUCTION TO DIRECT AIR CAPTURE

Direct use and/or storage pathway



Utilization pathway

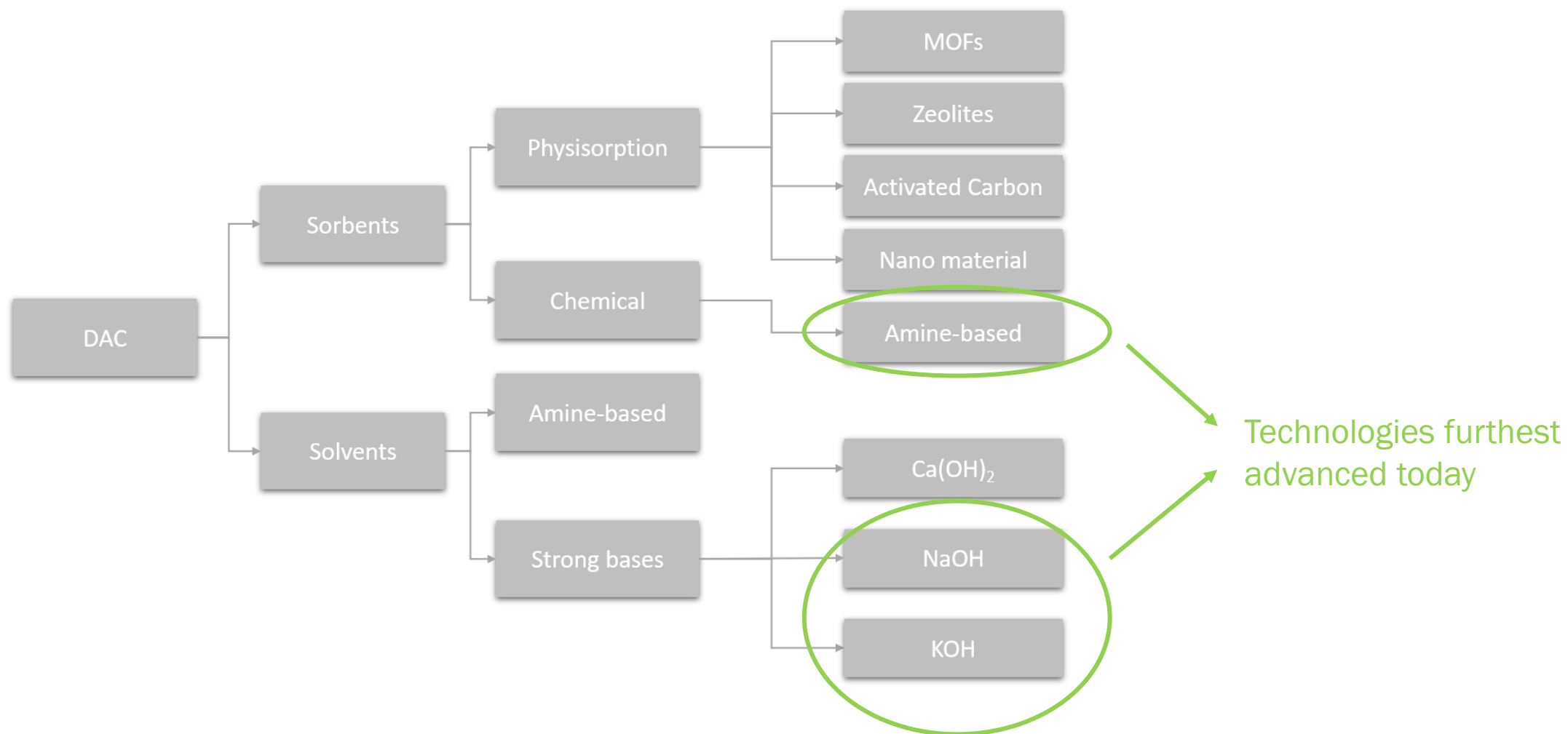


Picture sources:

Left: <https://chinadialogue.net/en/climate/geoengineering-how-to-stop-global-warming-most-controversial-solutions-explained/>. Creator: James Round

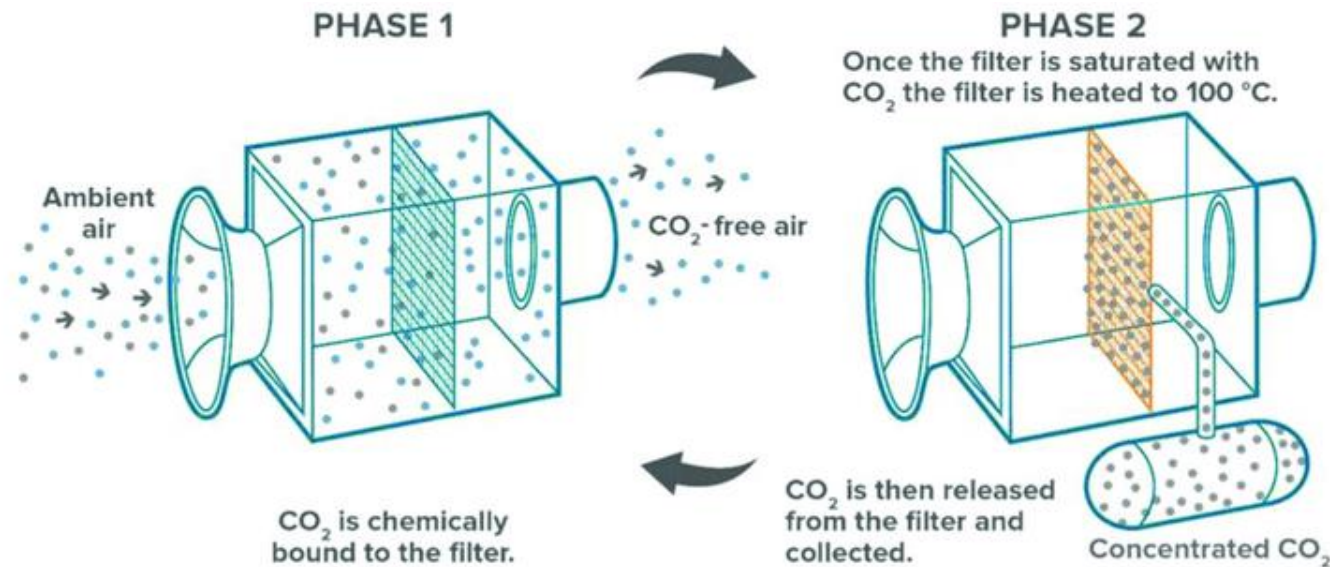
Right: <https://www.tudelft.nl/innovatie-impact/home-of-innovation/innovation-projects/projects-2022/direct-air-capture>

OVERVIEW OF DAC TECHNOLOGY ROUTES



EXPLANATION OF TECHNOLOGY

SORBENT SYSTEMS

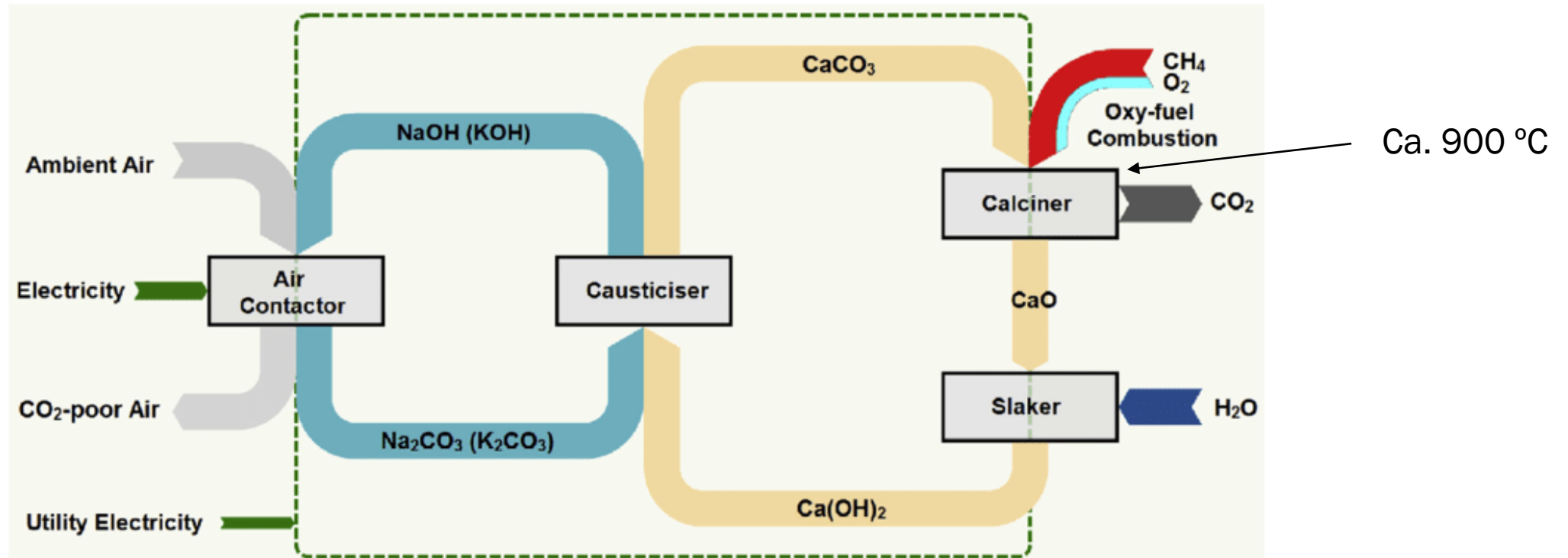


Sorbent based direct air capture is based on adsorption of CO₂ on a solid sorbent at ambient conditions. The CO₂ is released from the sorbent at elevated temperatures (80-120 °C). For greenhouse application this technology seems well suited with respect to scale, temperature requirements and flexibility of the technology.

Picture source:

C. Beuttler, L. Charles, and J. Wurzbacher, "The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions," *Front. Clim.*, vol. 1, 2019, doi: 10.3389/fclim.2019.00010.

EXPLANATION OF TECHNOLOGY SOLVENT SYSTEMS

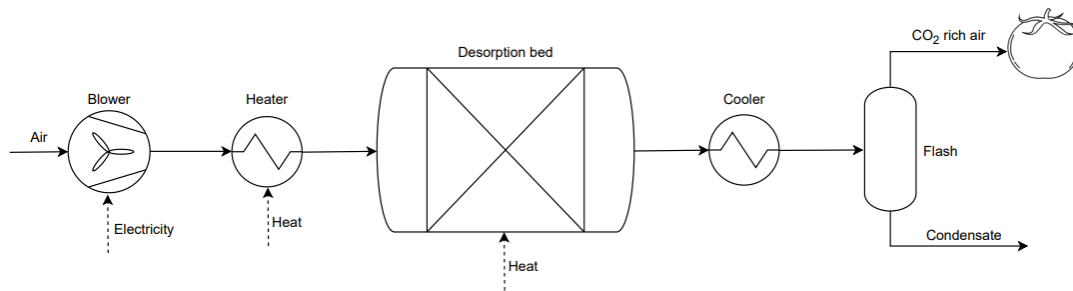


Solvent based direct air capture is based on chemical absorption of CO₂ in a solvent (often KOH or NaOH) at ambient conditions. The CO₂ is then transferred (in)to a calcium carbonate stream, after which the CO₂ is released in a calciner at high temperatures. This technology is especially applicable at larger scale (>100 kton/year) and is less flexible, and seems therefore to be less interesting for the horticulture sector directly.

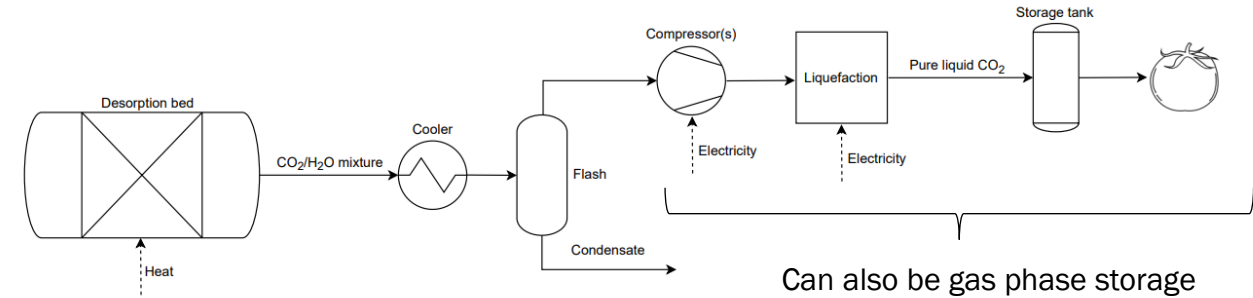
DESORPTION STRATEGY SORBENT SYSTEMS

PURE CO₂ VERSUS ENRICHED AIR PRODUCTION

Example of enriched air route



Example of pure CO₂ route



In normal DAC application, CO₂ is produced as a (near) pure gas, as this specification is often needed for the downstream application. In greenhouses, enriched air could be used since CO₂ is not needed in pure form. However, after technical analysis and talks with the greenhouse owners it is concluded that the pure CO₂ route is also preferred for the horticulture sector

Explanation for advising pure CO₂ route versus enriched air route:

1. Energy demand of both routes in our analysis seems similar. While producing the CO₂ in a lower concentration saves energy from a thermodynamic point of view, a lot of heat is needed in the enriched air route to heat up the incoming gas (which will be mostly lost).
2. In the enriched air route it is not feasible to store the produced CO₂. As greenhouses don't need CO₂ 24 hours per day, it is more convenient to design a system that can store the required CO₂ per day, so that continuous operation of the DAC system can be achieved. this greatly reduces the size (and CAPEX) of the DAC process.
3. The greenhouse owners have stated that it is not convenient to displace the large quantities of product air coming from the enriched air route. Additionally, the effect of this on the greenhouse operation has not been evaluated.

SELECTION FROM CURRENT MARKET (SORBENTS)

CLIMEWORKS – LARGEST PROCESS



Climeworks currently has the biggest sorbent based DAC plant operational in the world, with a capacity of 4 kton CO₂/year. On their website, CO₂ removal is offered at 1000 €/ton CO₂ for individuals.

Picture sources:

Left top: <https://climeworks.com/roadmap/orca>

Right top: <https://www.bloomberg.com/news/features/2021-09-08/inside-the-world-s-largest-direct-carbon-capture-plant>

Right bottom: <https://climeworks.com/subscriptions>

Special Expedition Permanently remove 100 kg of CO ₂ every month EUR 100.-/ month Subscribe now	Discoverer Permanently remove 50 kg of CO ₂ every month EUR 50.-/ month Subscribe now
Explorer Permanently remove 30 kg of CO ₂ every month EUR 30.-/ month Subscribe now	Customized As flexible as your life: Choose different amounts, yearly plans, and company plans here. Start customizing

SELECTION FROM CURRENT MARKET (SORBENTS)

GREENCAP – INTEGRATED GREENHOUSE CONCEPT



Verification of the GreenCap Solutions AS
Environmental Control System

Yield and quality of greenhouse tomatoes

NIBIO REPORT | VOL. x | NO. x | 2021



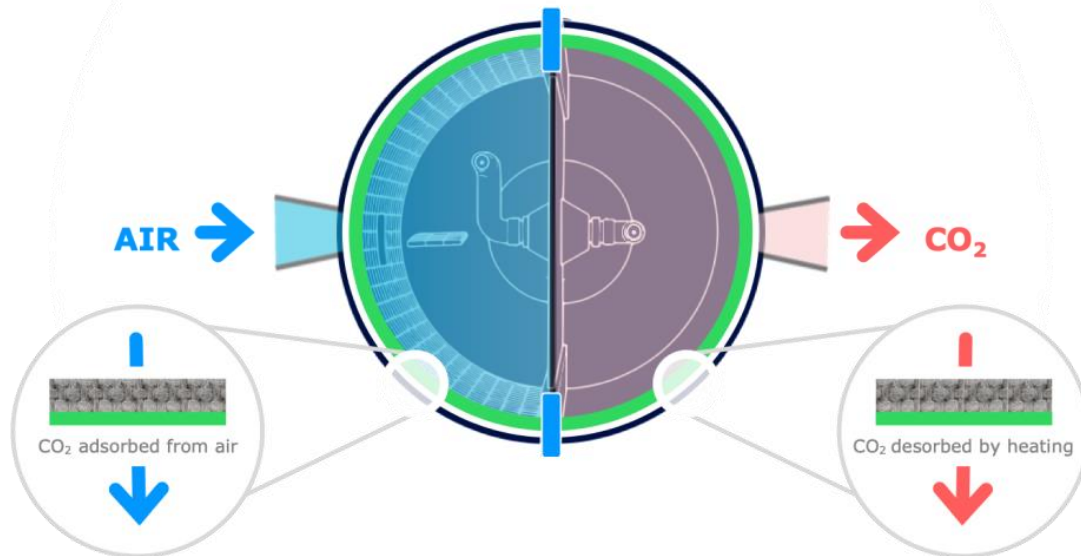
GreenCap has developed a system to combine DAC together with temperature and water control in closed greenhouses. Demonstration has been successful at 0.024 Ha scale. Larger systems are planned to be demonstrated in 2022.

Picture sources:

M. Verheul and H. Maessen, "Verification of the GreenCap Solutions AS Environmental Control System, [Online]. Available: <https://greencap-solutions.com/wp-content/uploads/2021/07/NIBIO-REPORT-Verification-GreenCap-Solutions-AS-Environmental-Control-System-04.07.21.pdf>.

SELECTION FROM CURRENT MARKET (SORBENTS)

CARBYON – NOVEL SORPTION CONCEPT



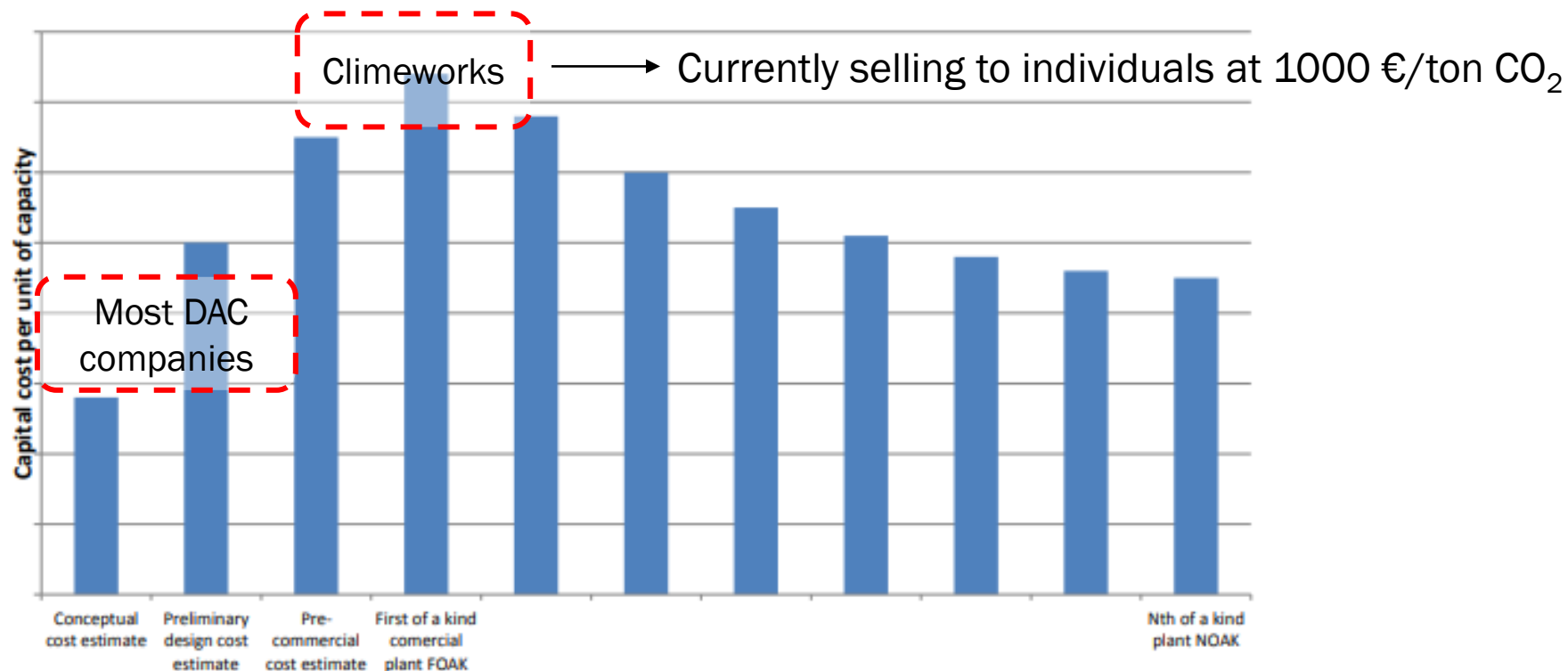
The Dutch start-up Carbyon is working on a novel DAC concept where the CO₂ capture medium is rotated through a cold zone (for capture) and hot zone (for release). This can lead to lower CAPEX costs for the system. Recently, the Carbyon team was awarded with the XPRIZE Milestone Award (1M\$). Publication of prototype results is needed before the technology can be further compared against other technologies.

Picture sources:

Left: <https://carbyon.com/technology/>

Right: <https://innovationorigins.com/en/selected/dutch-co2-capture-company-carbyon-wins-prestigious-international-xprize-milestone-award/>

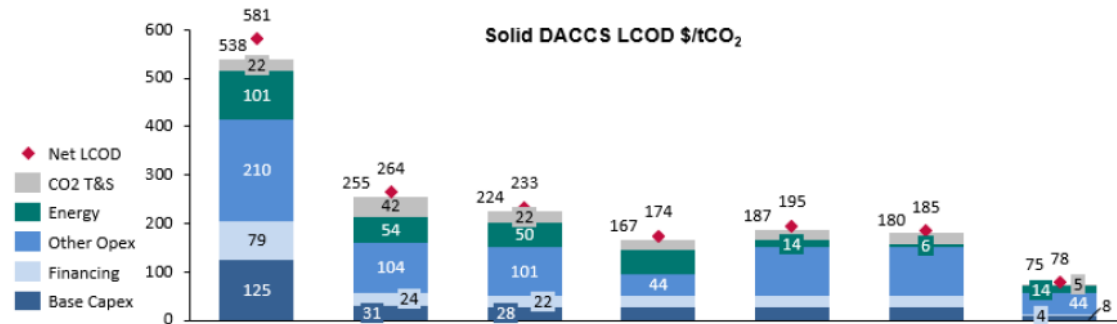
› COST OF DIRECT AIR CAPTURE AS A FUNCTION OF DEVELOPMENT STAGE



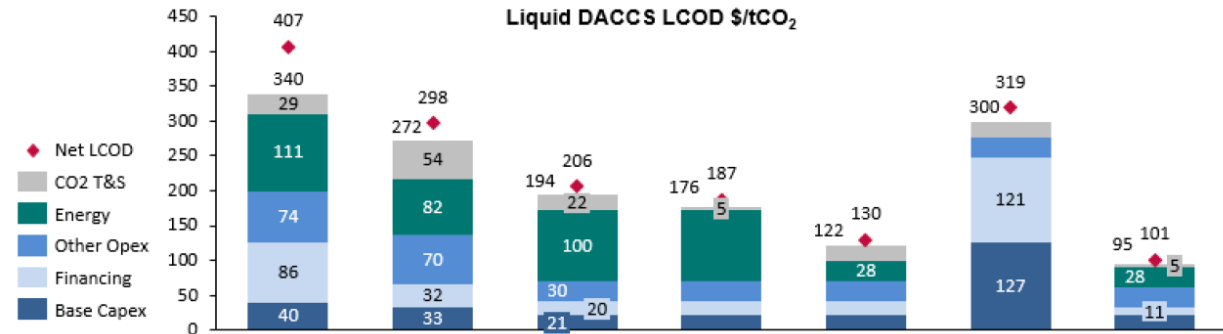
When evaluating the costs of technologies, it is important to look at the maturity of the technology in relation to the cost calculation. A realistic current cost price for first-of-a-kind (FOAK) systems can be taken from Climeworks.

FUTURE COST OF DIRECT AIR CAPTURE

IEAGHG REPORT



Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low-Cost Adsorbent	5- Low-Cost Electricity	6- Low-Cost Energy Hybrid	7- Very Ambitious
Timeline	FOAK 2020s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s	NOAK 2050s
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Hybrid	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Low Sorbent Cost	Base Case	Base Case	Low Sorbent Cost & High Learning Rate
Electricity Source	Solar PV – Base Case (\$68/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Low (\$50/MWh)	Solar PV – Low (\$14/MWh)	Solar PV – Low (\$14/MWh)	Solar PV – Low (\$14/MWh)
Heat Source	Nuclear (\$19/MWh)	Nuclear (\$19/MWh)	-	-	-	Free Waste Heat	-
CO ₂ T&S	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	In Cluster (\$5/tCO ₂)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%



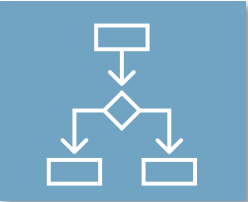
Case	1- Early Hybrid	2- Small Plant	3- Base Electric	4- Low T&S Cost	5- Low-Cost Solar	6- Flexible Operation	7- Very Ambitious
Maturity	FOAK	NOAK	NOAK	NOAK	NOAK	NOAK	NOAK
Technology	Hybrid	Hybrid	Electric	Electric	Electric	Electric	Electric
Capex, Fixed Opex, Consumables	Base Case- Early Plant	Base Case- 100kt/yr Plant	Base Case	Base Case	Base Case	15% Plant Utilisation	Base Case
Electricity Source	Solar PV – Base Case (\$68/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Base Case (\$50/MWh)	Solar PV – Low (\$14/MWh)	Free Solar PV	Solar PV – Low (\$14/MWh)
CO ₂ T&S	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	In Cluster (\$5/tCO ₂)	Base Case (\$22/tCO ₂)	Base Case (\$22/tCO ₂)	In Cluster (\$5/tCO ₂)
Cost of Capital	10%	5%	5%	5%	5%	5%	3%

The IEAGHG has published a report on the current and future expected costs for DAC systems. Cost of a 2020s FOAK systems are estimated between 400-600 \$/ton CO₂, While Nth of a kind systems (NOAK) in 2050 are evaluated between 130 and 300 \$/ton CO₂ (excluding the very ambitious case). Also sorbent based systems are likely the better choice for smaller scale (<100 kton CO₂)/year, while solvent technology seems to perform better at larger scale.

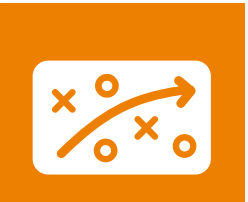
› CONCLUSIONS



Many companies and start-ups are working on direct air capture technology, to reduce the costs and further commercialise the technology



Sorbent based DAC seems to be the best fit technology for the horticulture sector



Pure CO₂ production from the DAC system seems to be the preferred route for application in the horticulture sector



CO₂ captured in the commercial DAC system of Climeworks is current sold to individuals at 1000 €/ton CO₂. For 2050 (NOAK) the cost of DAC is estimated at 130-300 €/ton CO₂



› **THANK YOU FOR
YOUR TIME**

TNO innovation
for life