Direct Air Capture of CO2: A Key Technology for Ambitious Climate Change Mitigation

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Commentary:

Direct Air Capture of CO_2: A key technology for ambitious climate change mitigation

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The Paris Agreement and especially its indicative 1.5°C target pose a dramatic challenge for the energy system, requiring both, unprecedented decarbonisation and at least a limited amount of carbon dioxide removal (CDR) [1]. Direct air capture (DAC) of CO_2 is increasingly expected to emerge as a key technology in the decades to come. As a result, start-ups back DAC with substantial investments and innovation [2], as cost reduction potential is substantial [2,3], and overall efficiency in extracting CO_2 is comparably high [4]. DAC is an enabling technology useful for CDR, first, direct air carbon capture and storage (DACCS) [5] and second, as CO_2 utilisation (DACCU) for fuels in the transport sector, in particular marine, aviation, and chemical industry, where sustainable options are hardly existing [6]. DACCS has not yet been established as a major CDR option [1], for factors like perceived high costs and substantial energy input requirement [7], despite of substantial benefits offered compared to the mainly considered bioenergy carbon capture and storage (BECCS), such as required land area, water demand, technology learning, scalability, and life-cycle aspects [4]. DAC technology is in accordance with the sustainability guardrails for energy systems.

The two main technology routes for DAC considered in this study are the high-temperature (HT) and the low-temperature (LT) desorption processes [2,3]. Additionally, LT moisture swing adsorption is the third route for DAC, which has been excluded from this study due to lack of publicly accessible financial data for a real prototype or pilot plant. Vast majority of all known active companies in the field invest on the LT options [3]. The LT options may lead to lower cost for captured CO_2, and allow to utilise waste heat in the range of 70-100°C, which can further reduce the CO_2 capture cost by about 40%, compared to lack of free waste heat [3]. It may be possible to even use lower temperature levels, but then requiring more heat for thermodynamic reasons. Waste heat might be available from combined heat and power plants, such as geothermal plants or solar thermal power plants, but also from waste incinerators, electrolysers or Fischer-Tropsch synthesis plants. A thermal energy storage as heat buffer may be needed, which is available for comparably low-cost. While the HT route requires water as input, some LT DAC technologies produce water [3]. Water production could be an advantage for integrated systems with water demand, but could increase energy demand for CO_2 regeneration. The HT route could have a faster industrial scaling due to use of more standard components, such as

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calcination. On the other hand, the new technologies used in the LT route could potentially have a higher learning rate which may accelerate the industrial scaling. Keith et al. [2] indicate that levelised cost of CO_2 of 94-232 USD/t_{CO2} may be achievable in near future. A common misperception is that excess electricity of a few hundreds of hours per year from solar or wind plants could be used for DAC, but detailed cost analyses show least cost of captured CO_2 at 6000 to 8000 full load hours per year [3], which requires a constant energy supply incompatible to the previous notion of only excess electricity utilisation.

DAC could become a key technology for climate change mitigation. One study estimates a logistic growth of DAC reaching 1 Gt_{CO2}/a in 2050 [4]. Another study estimates the market potential for DAC at about 7 Gt_{CO2}/a in the energy system and about 8 Gt_{CO2}/a in CDR in 2050 [3]. The first large-scale DACCS implementation study in integrated assessment models (IAMs) is not as optimistic, with about 0.3 Gt_{CO2}/a in 2050, while 30 Gt_{CO2}/a DACCS capacity is achieved in 2080 in a 1.5°C scenario [8]. The DAC deployment level is still too early for market data on the learning rate of the technology, however 10-15% learning rate seems to be realistic, when compared to similar technologies. Fasihi et al. [3] conclude that the realisation of half of this capacity, i.e. 7.5 Gt_{CO2}/a, with 10% learning rate can lead to DAC capital expenditures of 199 to 222 €/t_{CO2}·a, which is equal to levelised cost of direct air capture (LCOD) of 54 €/t_{CO2} (LT), 32 €/t_{CO2} (LT, free waste heat), and 71 €/t_{CO2} (HT) in 2050 for weighted average cost of capital of 7% and the solar and wind condition in the Maghreb region. Such cost levels lead to CO_2 DAC cost shares of about 20% or less for synthetic hydrocarbons [3] and could place DACCS as a major CDR option, also due to good compatibility to a solar, wind and battery dominated sustainable energy system [4,6].

The growth rates required to scale DAC beyond 10 G_{tCO2}/a in 2050 would translate into a compound annual growth rate of the cumulative DAC capacity of around 26% from 2030 to 2050, if 100 Mt_{CO2}/a are installed by 2030. To bring this in comparison, a cumulative DAC capacity of 100 Mt_{CO2}/a necessitates investments of around 32-42 b€ for a learning rate of 10-15%, based on the insights of Fasihi et al. [3]. This investment is comparable to about 34 b€ investment on solar photovoltaics in the 10 years from 1996 to 2005. Later, the solar photovoltaic capacity grew from 5.2 GW in 2005 to 500 GW in 2018, i.e. in 13 years by a factor of 95, comparable to the growth requirement of DAC from 2030 to 2050. The envisaged industrial scaling is hence possible, given clear and ambitious policy targets, and policies that bring investment security at least in the first decade. CDR demand may grow fast beyond 2050 on a level of 10 to 20 Gt_{CO2}/a [9], as it is already too late to avoid massive CDR activities [1]. A DAC system including full renewable energy supply on scale of 1 Gt_{CO2}/a may lead to annual cost of 55 b€ in 2050 according to Breyer et al. [10], with the DAC units contributing 45% of the annual cost, while other components contribute to the rest: solar photovoltaics (16%), batteries (15%), heat pumps (16%), thermal energy storage (7%), others (2%).

Using latest cost considerations based on [3,10] and for solar photovoltaics [11] a global CO_2 DAC cost map for 2050 can be derived (Fig. 1), optimised in full hourly resolution according to [10]. The model includes solar photovoltaics, wind energy, batteries, heat pumps, thermal energy storage and DAC units. Low-cost storage helps to reduce the LCOD. Figure 1 highlights the

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cost potential of DAC for 50 €/t_{CO2} or below in major parts of the word. Since, 1 Gt_{CO2} removal may cost around 45 to 55 b€ annually for year 2050 considerations, as depicted in Figure 1, it is important to rapidly defossilise the global energy system, so that massive cost burden for the future generations can be avoided. Using the same assumptions, based on Fasihi et al. [3] and Vartiainen et al. [11] for the projected cost levels and efficiencies in the year 2040 leads to a cost range of about 55 to 70 b€ annually to capture 1 Gt_{CO2}, and specific cost in 2030 may be around 85 to 100 €/t_{CO2}, based on an industrial scaling substantially below 1 Gt_{CO2}/a. The weighted average cost of capital (WACC) is assumed to be 7%, which may be too high for a common public effort and almost risk-free investments due to governmental decisions. WACC of 5% would reduce the LCOD by further 15%.

Sustainable long-term CO_2 storage requires further financial means [12]. Gaseous CO_2 storage raises concerns about the long-term sustainability, which can be overcome in an additional synthesis step, fulfilling the following criteria: CO_2 converted and stored as a solid compound, which is chemically inert with a very high combustion point, since these requirements avoid the risk of gaseous CO_2 leakages and later reuse or technical accidents involving combustion. Enhanced weathering (EW) as practiced in Iceland [12] such as enhanced rock weathering in the form of permanent geological CO_2 mineralisation in the subsurface fulfills such sustainability constraints for CCS. The CarbFix2 project on Iceland demonstrates that DACCS-EW is a viable option.

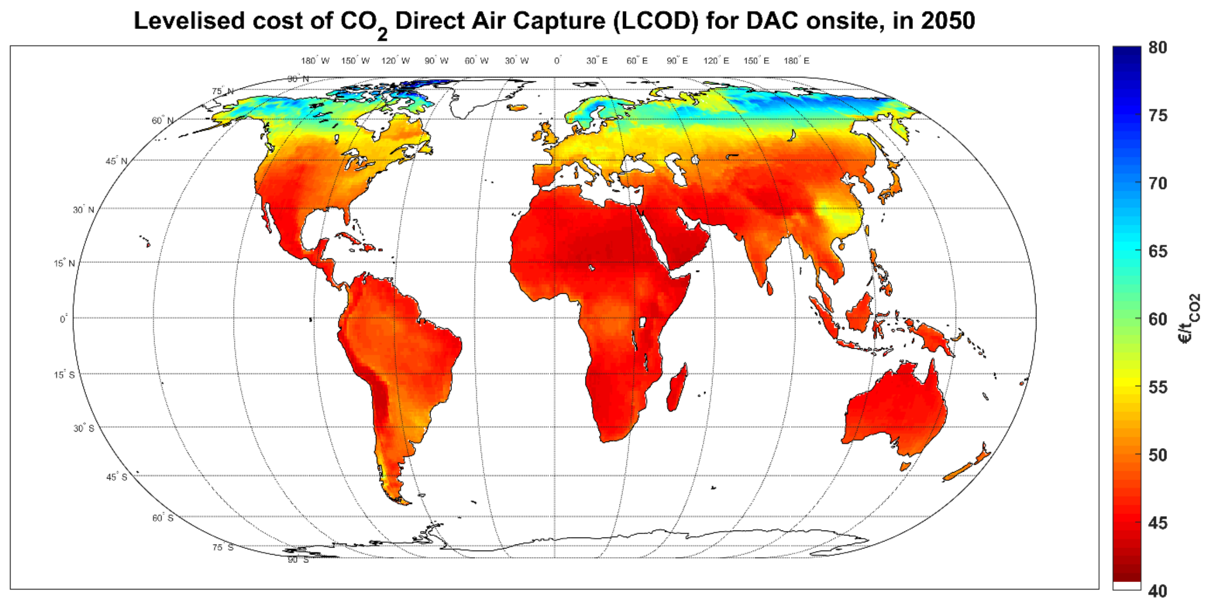

Figure 1. Levelised cost of CO_2 direct air capture projected for the year 2050.
The cost optimisation is calculated in full hourly resolution and based on assumptions in [3, 10, 11].

The two main applications of DAC are carbon capture and utilisation (CCU), which is typically discussed as Power-to-X (PtX) [6], and CDR as carbon capture and storage (CCS), which can be summarised as DACCU and DACCS. A challenge for DACCU and DACCS may be the amount of energy required. To avoid problematic life-cycle GHG emissions from gas-powered DACCU and DACCS, low-cost solar and wind electricity powering DACCU and DACCS will

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be essential to provide affordable and effective synthetic hydrocarbons and carbon sequestration [6]. An alternative would be bioenergy-based routes with CCU and CCS, leading to the much discussed BECCS and more recently discussed BECCU. This route is preferred in most scenarios because of its lower perceived costs. Key challenges of the bioenergy route are high cost, and limited area availability thus limited resource potential of energy crops, low efficiency of the photosynthesis process, and additional water demand [13], to be summarised as limited compatibility with sustainability guardrails. Biomass-based residues and wastes are better suited for BECCU (e.g. waste incinerators with carbon capture and utilisation, or biogas plants with hydrogen-based upgrade to biomethane for CO_2 composition in output gas), due to subsequent CO_2 utilisation for production of synthetic hydrocarbons. The anticipated point source capture costs are competitive to those by DAC. Substantial negative CO_2 emissions in the Gt/a scale require large volume streams of biomass which cannot be provided by bio-waste and residues, and would require energy crops on large scale. Fossil fuel based CCU and CCS options are in massive conflict to the targets of the Paris Agreement and sustainability guardrails, since only point sources can be used, such as thermal plants or industrial sites, but the CO_2 capture efficiency of 80-90% is not sufficient for a zero and net negative GHG emission economy and additional air pollution and emissions still harm people's health and environment. The compatibility of the main energy sources (fossil fuels, bioenergy, solar and wind energy) and the CCU and CCS routes with sustainability criteria is visualised in Figure 2.

	CCU	**CCS**
fossil fuels	fossil CCU (limited to point sources)	fossil CCS (limited to point sources)
bioenergy	BECCU (residues, wastes by-products)	BECCS (energy crops)
solar and wind	DACCU (electricity, optional waste heat)	DACCS (electricity, optional waste heat)

Figure 2. Classification of DAC applications into utilisation (DACCU) and long-term storage (DACCS) and comparison to the bioenergy alternative and fossil fuel reference.
The colour coding indicates compatibility (green) and conflict potential (red) to sustainability limits.

An essential precondition for a continued development and cost-scaling of DAC is sustained investments into the technology, from today onwards. This requires substantial research and development efforts, but in particular a stable market ramp-up for DAC, both for CCU/ PtX applications, but also for CCS/ CDR solutions. Past showed that stable market conditions often coincide with respective regulations. The fundamental learning from the solar photovoltaics case in the 2000s and 2010s is that forward looking policies, in particular the Feed-in Tariff legislation in Germany, a form of regulation, and substantial manufacturing scale-up backed with guarantees, as practiced in China, can accelerate technology deployment and diffusion by decades [14].

Global scenarios of climate change mitigation only reluctantly model DACCS (e.g. Chen and Tavoni [15] and Realmonte et al. [8] as one of the few examples). Instead IAMs prefer BECCS as negative emission technologies. This choice is based on the perceived lower costs of BECCS,

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its ability to generate rather consume energy, and its flexibility to provide fuels for different sectors. It may be also caused by inertia to adopt new options in IAMs, since BECCS has been introduced there much earlier compared to DACCS. Costs assumptions of DACCS originate in the influential report of the National Academy of Science [7]. While these arguments are valid, we here suggest that other dynamics, insufficiently reflected in these models, lead to vastly different outcomes. These involve, life-cycle emissions and land-use costs making BECCS more expensive than estimated; that the LT route of DACCS is less expensive than the HT route originally modelled [7], and that technological learning of modular technologies is mostly ignored. For example, in these models solar photovoltaic cost assumptions in the year 2050 [16] have not been much updated in recent years and are about twice the real present cost [11]. Such higher electricity cost is a further burden for DACCS. The IAMs still reflect technology development with only insufficiently reflecting technological learning by modular and granular technologies. The case of solar photovoltaics, also relevant as low-cost energy input for DACCS, shows that such policies can accelerate the development by more than three decades. This analogy may show the way how responsible and forward looking policies for DAC may offer a powerful climate mitigation technology, faster than expected by most experts in the field.

The relatively young research field of DAC technology still exhibit several research questions, which are not yet addressed well. Sorbents with high CO_2 capacity, easily regenerable, favourable kinetics and long lifetime need more development. In addition, the DAC performance under different weather conditions and integration of DAC to systems with abundant waste heat needs to be demonstrated. Life-cycle assessment studies for DAC [17] are still very limited and require more attention. A detailed global inventory of all CO_2 point sources, which would be still available under strict sustainability criteria, such as cement mills, pulp and paper plants and waste incinerators, is required, since such sources can be used first for CCU processes. The remaining CO_2 raw material demand for hydrocarbon-based fuels and chemicals can be covered by DAC. The learning rate of DAC is not yet understood well, but has a substantial impact on DAC cost projections [3]. Technologically detailed, and temporally and geo-spatially highly resolved studies for the impact of BECCS and DACCS on the energy system are missing. More research is needed for the feasibility and economics of large-scale carbon storage in solid form, in particular fulfilling the constraints of being chemically inert and a high combustion point.

The 1.5°C target of the Paris Agreement may not be ambitious enough for a true sustainable re-balancing within the limits of our planet, which may lead to a revised target of 1.0°C equivalent to 350 ppm CO_2 in the atmosphere [18]. Latest research results indicate that an energy transition towards a highly renewable energy system could be achieved in a cost-neutral pathway, which will enable broadly available sustainable power supply for DACCS. In case humankind would like to advance the targets of the Paris Agreement, DAC technology would become even more important. Importantly, a low-energy demand scenario is modeled in accordance with stabilising temperatures at 1.5°C [1]. If in addition a scalable negative emission technology can deliver CO_2-sequestration at costs of less than 100 USD/t_{CO2}, it becomes feasible to imagine trajectories that reduce temperatures to 1°C until 2100 to 2150. Such a

highly ambitious target is in line with the global Fridays for Future movement of the youth all around the world, based on scientific insights. However, as there is no guarantee that DACCU and DACCS will be deployed, and without considerable environmental risks, all other mitigation levels, including demand-side solutions, still require strong policy support and are indeed a precondition for such ambitious targets.

DAC technology is identified as a central technology for ambitious climate change mitigation, comparable to solar photovoltaics, wind energy, batteries and electrolysers. Immediate and continued market ramp up is key for a fast, comprehensive and beneficial impact of DAC on the energy transition and climate change mitigation ahead.

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