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Techno-economic assessment of CO_2 direct air capture plants

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ABSTRACT

CO_2 direct air capture (DAC) has been increasingly discussed as a climate change mitigation option. Despite technical advances in the past decade, there are still misconceptions about DAC's current and long-term costs as well as energy, water and area demands. This could undermine DAC's anticipated role in a neutral or negative greenhouse gas emission energy system, and influence policy makers. In this study, a literature review and techno-economic analyses of state-of-the-art DAC technologies are performed, wherein, DAC technologies are categorised as high temperature aqueous solutions (HT DAC) and low temperature solid sorbent (LT DAC) systems, from an energy system perspective. DAC capital expenditures, energy demands and costs have been estimated under two scenarios for DAC capacities and financial learning rates in the period 2020 to 2050. DAC system costs could be lowered significantly with commercialisation in the 2020s followed by massive implementation in the 2040s and 2050s, making them cost competitive with point source carbon capture and an affordable climate change mitigation solution. It is concluded that LT DAC systems are favourable due to lower heat supply costs and the possibility of using waste heat from other systems. CO_2 capture costs of LT DAC systems powered by hybrid PV-Wind-battery systems for Moroccan conditions and based on a conservative scenario, without/with utilisation of free waste heat are calculated at 222/133, 105/60, 69/40 and 54/32 €/t_{CO2} in 2020, 2030, 2040 and 2050, respectively. These new findings could enhance DAC's role in a successful climate change mitigation strategy.

1. Introduction

The problem of global warming caused by greenhouse gas (GHG) emissions, mainly carbon dioxide (CO_2), has reached dangerous levels. CO_2 concentration in the atmosphere has rapidly increased from 280 ppm in the pre-industrial era to 403 ppm in 2016, with an annual growth rate of 2 ppm (IEA, 2017). The Paris Agreement aims to mitigate climate change and keep temperature rise well below 2 °C and preferably 1.5 °C in comparison to the pre-industrial age by united efforts of all countries (UNFCCC, 2015). To achieve this goal, along with sharply cutting anthropogenic GHG emissions, actions are needed for active CO_2 removal by implementation of Negative CO_2 Emissions Technologies (NETs) (Kriegler et al., 2017; Rogelj et al., 2018).

A range of options are available for CO_2 emissions removal. CO_2 emissions can be captured at point sources such as flue gases from conventional power plants or non-energetic sectors such as cement plants. However, some plants are too old and cannot be retrofitted. Moreover, even in plants with CO_2 removal systems, not all emissions are captured as the average capture rates are in the range of 50–94% (Leeson et al., 2017). On the other hand, it is not possible to directly capture CO_2 emissions produced by long-distance aviation and marine transport. Large amount of small emitters, such as in the transport sector, which account for 50% of global GHG emissions, are just impossible to neutralise by conventional CO_2 capture applications (Seipp et al., 2017). These facts lead to the undeniable necessity of finding additional solutions that are capable of capturing CO_2 independent of origin and location.

Another approach for climate change mitigation is capturing CO_2 directly from the atmosphere. Hitherto, plants have been doing it naturally to some extent. Nonetheless, they cannot keep up with the increasing anthropogenic emissions (Goeppert et al., 2012). Afforestation, bioenergy with carbon capture and storage (BECCS) and enhanced weathering were introduced to reduce CO_2 concentration in the atmosphere (Williamson, 2016). However, their commercial feasibility is limited, as all of these measures are associated with risks. Large-scale BECCS and afforestation threat biodiversity, water and food security, as both are characterised by

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Nomenclature

BECCS	Bioenergy with Carbon Capture and Storage
capex	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
COP	Coefficient of Performance
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
FLh	Full Load hours
GHG	Greenhouse Gas
HT	High Temperature
LCOD	Levelised Cost of CO_2 Direct Air Capture
LT	Low Temperature
MOF	Metal Organic Frameworks
MSA	Moisture Swing Adsorption
NET	Negative Emission Technology
opex	Operating Expenditures
PSCC	Point Source Carbon Capture
PtG	Power-to-Gas
PV	Photovoltaic
RE	Renewable Energy
SNG	Synthetic Natural Gas
TSA	Temperature Swing Adsorption
TVSA	Temperature Vacuum Swing Adsorption
WACC	Weighted Average Cost of Capital

Subscripts

el	electricity
fix	fixed
p	peak
th	thermal
var	variable

huge land requirements (Smith et al., 2016). Enhanced weathering provokes rising pH values in rivers and changing the chemistry in oceans (Kohler et al., 2010). Besides afforestation/reforestation, BECCS and enhanced weathering, the full portfolio of NETs also includes biochar, ocean fertilisation and soil carbon sequestration (Fuss et al., 2018; Minx et al., 2018), which may have to be applied in a portfolio of NETs for effective climate change mitigation (Bui et al., 2018).

CO_2 Direct Air Capture (DAC), besides BECCS, is the other option for capturing CO_2 from the atmosphere, diluted gases and distributed sources of carbon via industrial processes (Broehm et al., 2015; Goeppert et al., 2012; Lackner, 2009). DAC is a relatively new and innovative technology in early commercial stages (Nemet et al., 2018), which in a long term perspective, along with conventional technologies, can help humankind to control and mitigate climate change (Keith, 2009; Sanz-Pérez et al., 2016).

In this paper, a techno-economic assessment of the main CO_2 direct air capture technologies, from an energy system point of view, has been carried out. The remaining sections of the paper are as follows: Section 2 describes the methodology. In section 3, a literature review has been carried out. In section 4, available technologies have been described and the collected techno-economic data is categorised and summarised in the form of tables. The final model of main technologies in 2020 are introduced. Later, DAC capital expenditures, energy demands and costs have been estimated under two scenarios for DAC capacities and financial learning rates in the period 2020 to 2050 and sensitivity analyses for the most valuable parameters are done. Further, DAC's area and water demands, as well as CO_2 compression, transport and storage are presented. In section 5, relevance of DAC with respect to the Paris Agreement, as well as benefits and challenges of the main DAC technologies are discussed. Later, more factors on the final costs of large-scale DAC systems are examined and results are compared to projections from companies or literature. Moreover, a cost comparison to point source carbon capture (PSCC), as one of the competing technologies is performed. In addition, the cost share of CO_2 DAC in power-to-gas systems has been investigated. Finally, conclusions are drawn in section 6.

2. Methodology and data

An extensive review has been performed considering literature published from the early 2000s to the present time that are relevant to this research. Research was conducted in the following manner: data gathering via such platforms as ScienceDirect, Scopus, Google Scholar, ResearchGate, official websites of companies and international agencies such as Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA). The following keywords were used: CO_2 capture plant, CO_2 capture methods, CO_2 scrubbing, CO_2 separation, direct air capture, cost of CO_2 capturing, carbon capture start-up companies and atmospheric CO_2 capture.

A database of relevant data has been created from all the reviewed publications, for further analyses. Recalculation and aligning of the findings were conducted. All parameters are presented on a comparable scale for classification of all available technologies and to deliver the final models, including long-term estimations. A sensitivity analysis of the most valuable variables is performed.

Cost numbers from different years presented in USD are converted to euros by using a fixed exchange ratio of 1.33 USD/€, as the long term average exchange rate. As an exception, cost numbers from Keith et al. (2018) and values in other currencies are converted to euros based on exchange rates of the corresponding year.

equations (1)–(4) below have been used to calculate the levelised cost of electricity (LCOE), the levelised cost of heat (LCOH) and the levelised cost of CO_2 DAC (LCOD). Abbreviations: capital expenditures, *capex*, annuity factor, *crf*, annual operational expenditures, *opex*, fixed, *fix*, variable, *var*, annual CO_2 production of DAC plant, $Output_{CO2}$, full load hours per year, *FLh*, electricity demand of DAC plant per t_{CO2} produced, $DAC_{el.input}$, heat demand of DAC plant per t_{CO2} produced, $DAC_{heat.input}$, fuel costs, *fuel*, efficiency, η, coefficient of performance of heat pumps, *COP*, weighted average cost of capital, *WACC*, lifetime, *N*.

A WACC of 7% is used for all the calculations in this study.

$$LCOE = \frac{Capex \cdot \mathrm{crf} + Opex_{fix}}{FLh} + Opex_{var} + \frac{\mathrm{fuel}}{\eta} \tag{1}$$

$$LCOH = \frac{Capex \cdot \mathrm{crf} + Opex_{fix}}{FLh} + Opex_{var} + \frac{\mathrm{fuel}}{\eta} + \frac{LCOE}{COP} \tag{2}$$

$$LCOD = \frac{Capex_{DAC}\cdot \mathrm{crf} + Opex_{fix}}{Output_{CO_2}} + Opex_{var} + DAC_{el.input}\cdot LCOE + DAC_{th.input}\cdot LCOH \tag{3}$$

$$\mathrm{crf} = \frac{\mathrm{WACC}\cdot(1+\mathrm{WACC})^{N}}{(1+\mathrm{WACC})^{N}-1} \tag{4}$$

Maturity level of technologies is also taken into consideration, as the focus of this research is on pilot and commercial-scale technologies, while the theoretical and laboratory-scale studies have been included as well.

Cost and technical trends based on technology evolution over 20 years of active research and development are identified. As a result, up to date data is used for the long-term estimation of key parameters for the time periods 2020 to 2050 in 10-year steps, based on adapted learning rates.

3. Literature review

The first application of capturing CO_2 from ambient air was introduced in the 1930s in cryogenic air separation plants and later it found its application in life support systems of manned closed systems such as space stations and submarines (House et al., 2011). The first systems dated back to 1965 were not regeneratable (Isobe et al., 2016). Whereas, modern space shuttles are all equipped with regeneratable Carbon Dioxide Removal Assembly (CDRA) that helps to maintain habitable environment for crewmembers (NASA, 2006).

Due to ultra dilute concentration of CO_2 in the atmosphere, chemical sorbents with strong binding characteristics became widely discussed in literature. An aqueous solution of strong bases is used in conventional PSCC technologies and many researchers have investigated its applicability to DAC. Keith et al. (2006) analysed physical and economic limits of BECCS and aqueous solution-based DAC and concluded the second option to be feasible in the near term. However, high-grade (900 °C) heat demand of aqueous solution-based DAC could limit the options for heat source and increase the costs. Baciocchi et al. (2006) tried to optimise the system based on the same chemical solution and applied two different calcium carbonate precipitators. Zeman (2007) was one of the first who proposed the same approach on an industrial scale. In addition, he has benchmarked the system with two previous studies on thermodynamic levels. Stolaroff et al. (2008) discussed optimisation of energy demand and possible reduction of final costs by improving the contactor part. The extensive report of American Physical Society (APS) by Socolow et al. (2011) compared post-combustion CO_2 capture methods to DAC systems based on the work of Baciocchi et al. (2006). Zeman (2014) investigated the APS report and proposed a reduction in final costs of avoided CO_2 by using low-carbon electricity and minimising plastic packing materials of the contactor part. Li et al. (2015) investigated the optimal operation of the system proposed in the early work of Zeman (2007) by using wind power and battery as the energy inputs. All the above mentioned works applied different approaches to improve the performance of aqueous alkaline solution, in particular sodium hydroxide; whereas, Nikulshina et al. (2009) presented a single-cycle system carrying out continuous removal of CO_2 via serial CaO-carbonation at higher temperatures (of about 365–400 °C) and $CaCO_3$-calcination at 800–876 °C, powered by concentrated solar power (CSP). Mahmoudkhani and Keith (2009) suggested a novel approach to avoid calcium carbonate in the loop, by using Sodium Tri-Titanate. The technique requires 50% less high-grade heat than conventional causticisation and the maximum temperature required is reduced by at least 50 K, from 900 °C to 850 °C. Holmes and Keith (2012) and Holmes et al. (2013) suggested potassium hydroxide (KOH) as a non-toxic solution and discussed the results of laboratory-scale and prototype tests of improved contactor parts. Keith et al. (2018) provided a detailed techno-economic analysis of a 1 Mt_{CO2}/a design based on a real pilot plant for the first time.

Another major group of scientific publications are focused on systems based on adsorption process. Temperature swing adsorption (TSA) is the main DAC method in this category, described by Kulkarni and Sholl (2012) and Sinha et al. (2017). Unlike typical aqueous solution-based systems, the regeneration in solid sorbent DAC happens at relatively lower temperatures (80–100 °C), which is cheaper to produce or could be available as waste heat from some industrial plants, such as combined heat and power plants, power plants with cooling tower, pulp and paper mills, steel or glass making plants, or waste heat from exothermic synthetic fuels production processes. Choi et al. (2011a; 2012) examined modified sorbents with higher CO_2 uptake capacity and higher stability in dry conditions. Roestenberg (2015) introduced a LT DAC design based on non-amine sorbent and separate adsorption and desorption units for increasing the plant's utilisation rate, evaluated costs of small-scale and large-scale systems and considered heat supply from methanol synthesis plant coupled to the DAC unit. Derevschikov et al. (2014) suggested using composite solid sorbent for DAC and using renewable energy (RE) to produce methane on site. Ping et al. (2018a) introduced a system with full cycle of less than 30 min. Moisture swing adsorption (MSA) is the other method in this category in which the regeneration happens by moisturising of CO_2-rich sorbent. Lackner (2009) examined the possibility of MSA CO_2 capture on amine-based ion-exchange resin at low temperatures (45 °C). Later, Goldberg et al. (2013) studied the combination of this system with wind energy and offshore geological storage.

Radical methods have been suggested for DAC by some researchers. Eisaman et al. (2009) examined electrochemical CO_2 capture. Freitas (2015) suggested the use of nanofactory-based molecular filters and claimed that these methods are able to bring the final capture costs down to 13.7 €/t_{CO2} (18.3 USD/t_{CO2}). Seipp et al. (2017) introduced a rather novel approach based on crystallisation of CO_2 molecules with a guanidine sorbent with low temperature requirements of 80–120 °C. Despite promising preliminary results, deeper investigations and possible pilot plants are needed for a better evaluation of these approaches.

In addition, several papers have presented an overview of available technologies. Simon et al. (2011) analysed LCOD of a generic DAC based on capture devices, energy supplies, footprint, water use and sequestration costs. Goeppert et al. (2012) discussed capturing CO_2 from point sources, raised the question as to why DAC is needed, summarised and discussed all available technologies on a technical level and listed active companies. It is concluded that DAC is indispensable for stabilising climate change. In addition, it points out that even though CO_2 concentration in the atmosphere is about 250–300 times less than concentrated sources, the theoretical energy demand by DAC is only 2–4 times higher. However, the vast range of projected overall costs of CO_2 DAC can become clearer only after the construction of pilot plants. The detailed numerical analyses by Wilcox et al. (2017) confirm the comparison on minimum work of carbon capture from atmospheric and concentrated sources by Goeppert et al. (2012), however, they show that the ratio of the real work demand of carbon capture from atmosphere to concentrated sources could be higher. On the other hand, it indicates that even though the minimum work of separation form ambient air slightly increases by aiming for higher CO_2 capture rates, the real work demand significantly decreases at higher capture rates. Broehm et al. (2015) divided all available technologies into three groups (aqueous solutions of strong bases, amine adsorptions and inorganic solid sorbents), compared them based on critical criteria such as energy demand and economic estimation, addressed limiting factors such as land and potential location options, associated emissions and water losses. In order to provide more details of the technology, Broehm et al. (2015) closely analysed two case studies, one based on Socolow et al. (2011) technology and the other based on the results achieved in private commercial companies. He pointed out that success of DAC does not only depend on the technical and economic performance, but also depends on external factors such as market demand for CO_2, development of synthetic fuels and supporting technologies such as storage. A broad comparison of all techniques capturing CO_2 from ambient air was done by Williamson (2016), where strengths and limitations of all possible applications were pointed out.

Several companies are active in the field of CO_2 DAC, which are shown in Fig. 1. Carbon Engineering, established in 2009 by Keith in Squamish, Canada (Carbon Engineering, 2018a), is the only detected company active in high temperature (HT) aqueous solution-based DAC. The company is partly funded by Bill Gates (Carbon Engineering, 2018a). The 1 t_{CO2}/day demonstration plant was introduced in October 2015 and the current goal of the company is to establish broad commercial deployment of synthetic fuels production based on their DAC technology (Carbon Engineering, 2018b). At a large scale, the company expects to achieve costs of 75–113 €/t_{CO2} captured, purified, and compressed to 150 bar (Carbon Engineering, 2018c). Climeworks, founded by Gebald and Wurzbacher in 2009 in Zurich, Switzerland (Climeworks, 2018a), is the most well-known low temperature (LT) solid sorbent-based DAC company. In 2014, in a partnership with Audi and Sunfire, the company launched a pilot plant in Dresden that captures 80% of CO_2 molecules from air passing through the system and converts them into synthetic diesel (Audi, 2015). In 2017, the company commissioned another commercial scale DAC plant in Switzerland that provides CO_2 for a nearby-located greenhouse. In the same year, another DAC unit has been installed in Iceland to permanently fix air captured CO_2 in a mineralisation process 700 m underground (Climeworks, 2017). This is the world's first direct air carbon capture and storage (DACCS) system coupled to enhanced weathering, which may evolve to be a major NET option (Fuss et al., 2018; Minx et al., 2018). The company is targeting production costs of about 75 €/t_{CO2} for large-scale plants (Climeworks, 2018b). Global Thermostat, formed in 2010 by Eisenberger in New York, USA, is the other LT DAC company, with its multifunctional technology capable of capturing CO_2 from both the atmosphere as well as point source emissions (Global Thermostat, 2018a). Major technological know-how, particularly in the field of catalysts is licensed from Georgia Institute of Technology (Global Thermostat, 2018b; Sanz-Pérez et al., 2016). The company already has pilot and commercial demonstartion plants operating since 2010 at SRI International in Menlo Park, California (Ping et al., 2018a). The modular units can utilise waste heat at 85–95 °C for CO_2 regeneration and have a capacity of 40 000 t_{CO2}/a. The company has announced ambitious plans to deliver CO_2 at a cost of 11–38 €/t_{CO2} (Kintisch, 2014). Antecy, founded in 2010 by O'Connor in Hoevelaken, Netherlands, is the other European LT DAC company (Antecy, 2018) that requires moderate temperatures of 80–100 °C for CO_2 regeneration. After laboratory tests and completing commercial-scale designs, in cooperation with Shell, the company is ready for the implementation of a pilot plant (Roestenberg, 2015). Oy Hydrocell Ltd is a Finnish company founded in 1993 that has provided a DAC system to VTT Technical Research Center of Finland (Hydrocell, 2018; Elfving et al., 2017). The 1.387 t_{CO2}/a system is packed in a standard shipping container and is fully portable. By using temperature vacuum swing adsorption (TVSA), at 70–80 °C, it has the lowest regeneration temperature among detected technologies, which widens the options for applicable waste heat sources (Bajamundi, 2015; Bajamundi et al., 2018). Other DAC companies are Skytree and Infinitree, however their disclosed information is very limited. Skytree, founded in 2008 and located in Amsterdam, Netherlands, commercialises a CO_2 capturing technology based on electrostatic absorption and moisturising desorption, as a spin-off of the European Space Agency (Ishimoto et al., 2017; Skytree, 2018). Infinitree, founded in 2014 and located in Huntington, New York, utilises an ion exchange sorbent material in a moisture swing process (Infinitree, 2018). Early niche markets for Skytree and Infinitree are urban farming projects for which they provide CO_2 for faster growth of plants.

4. Results

4.1. Description of technologies

Basic air capture models consist of contacting area, solvent or sorbent and regeneration module. Contacting area exposes sorbent to ambient air and facilitates airflow through the model, increasing

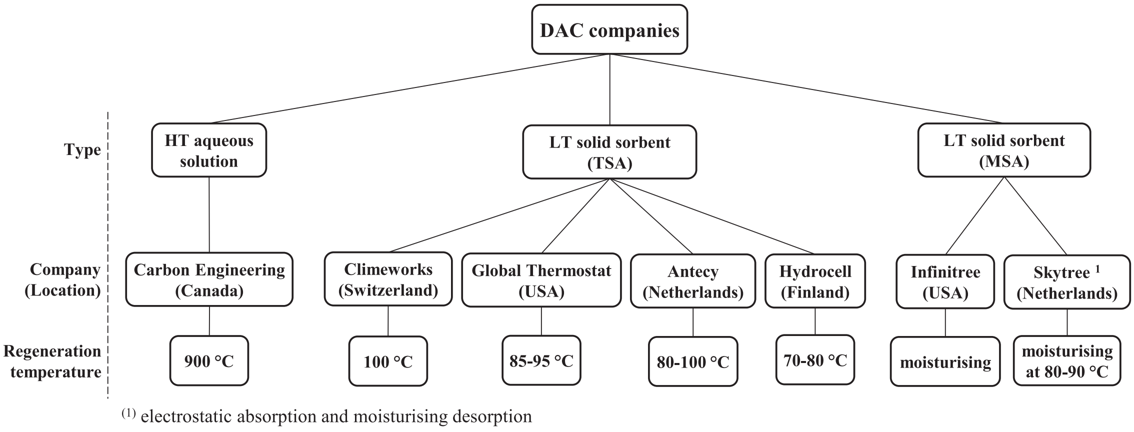

Fig. 1. Companies active in the field of CO_2 DAC. Abbreviations: high temperature, *HT*, low temperature, *LT*, moisture swing adsorption, *MSA*, temperature swing adsorption, *TSA*.

the absorption or adsorption of CO_2 molecules. Solvent or sorbent must be easy to handle, resistant to contamination and should not vanish during the process, as its properties determine the whole process. The main DAC systems are described below.

4.1.1. High temperature (HT) aqueous solution

Aqueous solution consists of two cycles that can happen simultaneously. The basic example of the approach is illustrated in Fig. 2. In the first cycle, known as absorption, ambient air is brought into contact with sprayed sodium hydroxide (NaOH) as the solvent in the absorption column, with the aid of fans or natural airflow. CO_2 molecules react with NaOH and form a solution of sodium carbonate (Na_2CO_3) (Eq. (5)). The absorption happens at room temperature and ambient pressure. This solution is transported to the regeneration cycle and CO_2 depleted air leaves the column.

In the second cycle, known as regeneration, Na_2CO_3 is mixed with calcium hydroxide ($Ca(OH)_2$) in the causticiser unit, where solid calcium carbonate ($CaCO_3$) is formed and NaOH is regenerated (Eq. (6)). NaOH is sent back to the contactor and ready to start another absorption cycle. Meanwhile, in the most energy intensive step, $CaCO_3$ is heated up to around 900 °C in the kiln (calciner unit) to release CO_2. As shown in Table 1, according to literature and based on the level of heat integration, the overall heat demand is in the range of 1420–2250 kWh_{th} per ton CO_2. The outputs of this reaction are calcium oxide (CaO) and a pure stream of CO_2 (Eq. (7)). CO_2 is collected and CaO is mixed with water in the slaker unit for $Ca(OH)_2$ regeneration (Eq. (8)).

$$\text{contactor} \quad 2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \tag{5}$$

$$\text{causticiser} \quad Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3 \tag{6}$$

$$\text{calciner} \quad CaCO_3 + \text{heat} \rightarrow CaO + CO_2 \tag{7}$$

$$\text{slaker} \quad CaO + H_2O \rightarrow Ca(OH)_2 \tag{8}$$

Besides heat, the system also needs electrical power for blowing air through the contactor, spraying the aqueous and moving solutions from one unit to another. In literature, this electrical power is presented to be in the range of 366–764 kWh_{el} per ton CO_2 (Table 1). This also includes the energy demand for CO_2 compression, to the mentioned pressures as in Table 1, prior to transport or storage.

As can be seen in Table 1, in earlier literature, natural gas has been mainly suggested for the supply of high-grade heat demand. However, this would not be a sustainable solution. Providing 2000 kWh_{th} high-grade heat by oxy-fuel combustion of natural gas with 90% efficiency for capturing 1 ton of atmospheric CO_2, would release 0.44 ton of direct natural gas based CO_2 emissions, without taking into account its life cycle emissions. One of Carbon Engineering (2018c) DAC technologies fully powered by natural gas would release 0.5 ton of CO_2 per ton of atmospheric CO_2 captured. Even though this CO_2 can be captured and utilised as feedstock for other purposes, it will finally end up in the atmosphere after some cycles of utilisation. In addition, this impact would dramatically increase the cost of the net-captured CO_2, as the reported costs in literature are mainly based on atmospheric or total captured CO_2. The use of carbon-neutral renewable synthetic natural gas (RE-SNG) might be a solution to this problem. However, even with a 100% closed cycle of SNG-based CO_2 and no extra energy demand for CO_2 recycling, converting that 0.5 ton of fuel-based CO_2 to synthetic natural gas (SNG) would need about 4400 kWh_{el} for generation of the required hydrogen, utilising 2030 electrolyser technology (Fasihi et al., 2017a). This is a huge increase in primary energy demand and production costs due to the high costs of SNG production. Thus, a sustainable and affordable system should be fully electrified, which has been discussed in relatively newer studies. Content of the Carbon Engineering website (2018c) in March 2018 included a fully electrified system with a total of 1500 kWh_{el} demand for both power and heating, in order to deliver 1 ton of atmospheric CO_2 at 150 bar. Thus, a fully electrified HT DAC is practically possible and has been chosen as the final model for aqueous solution technology in our study. In our study, to have a common ground for comparison between different technologies, the CO_2 compression step is avoided. The latest publication from the Carbon Engineering group (Keith et al., 2018) shows some improvement in total energy demand and presents 3 different scenarios. In the first scenario, all the heat and power demand is provided by natural gas oxy-fuel combustion, gas turbine and steam turbine. In the second scenario, gas turbine has been removed and the respective power is supplied from the grid. This also decreases the ratio of fuel-based/atmospheric captured CO_2 from 0.48 to 0.3, which results in downsizing of several process

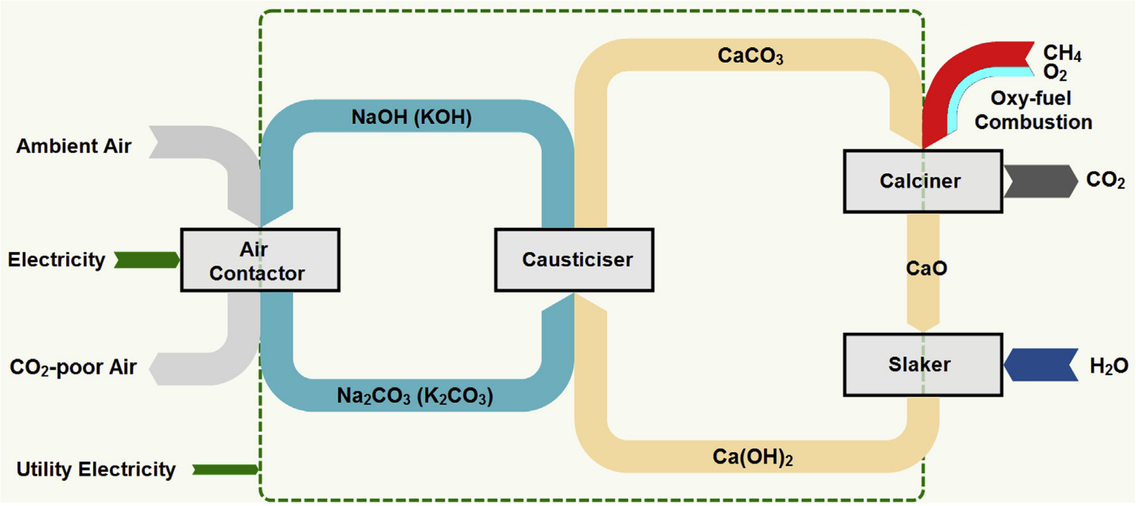

Fig. 2. Example of CO_2 direct air capture based on aqueous solution of sodium hydroxide (NaOH) and potassium hydroxide (KOH) as an alternative. Reproduced and modified based on a process diagram by Keith et al. (2018).

Table 1
HT aqueous solution DAC specifications.

type	1^{st} cycle sorbent	2^{nd} cycle sorbent	CO_2 con.	absorption	desorption	energy demand			outlet pressure	CO_2 purity	reference
			ppm	T (°C)	T (°C)	kWh_{el}/t	kWh_{th}/t	by	bar	%	
2-cycle	NaOH	$Ca(OH)_2$	-	ambient	900	-	-	NG	100	-	Keith et al. (2006)
	NaOH	$Ca(OH)_2$	500	ambient	900	440	1678	NG	58	-	Baciocchi et al. (2006)
	NaOH	$Ca(OH)_2$	380	ambient	900	764	1420	NG/coal	-	-	Zeman (2007)
	NaOH	$Ca(OH)_2$	-	-	900	$1199\text{-}2461_{el,th}$ [a]		-	-	-	Stolaroff et al. (2008)
	NaOH	$Ca(OH)_2$	500	-	900	494	2250	NG	100	-	Socolow et al. (2011)
	NaOH	$Ca(OH)_2$	-	ambient	900	2790	-	wind + battery [b]	-	-	Li et al. (2015) [c]
	KOH	$Ca(OH)_2$	-	-	900	-	2780	NG [d]	150	-	Carbon Engineering (2018c)
	KOH	$Ca(OH)_2$	-	-	900	1500	-	el.	150	-	
	KOH	$Ca(OH)_2$	400	ambient	900	-	2450	NG	150	97.1	Keith et al. (2018)
	KOH	$Ca(OH)_2$	400	ambient	900	366	1458	NG + el.	150	97.1	(Carbon Engineering)
	KOH	$Ca(OH)_2$	400	ambient	900	77 [e]	1458	NG + el.	1	97.1	
	NaOH	$Na_2O.3TiO_2$	-	ambient	850	-	[f]	-	15 [g]	pure	Mahmoudkhani and Keith (2009)
1-cycle	-	CaO	500	365-400	800-875	-	-	CSP	-	99.9	Nikulshina et al. (2009)
2-cycle	**KOH**	**$Ca(OH)_2$**	**400**	**ambient**	**900**	**1535**	-	**el.**	**1**	**>97**	**final model (this study)**

[a] Based on different contactors
[b] Based on Zeman (2007), without heat recycling.
[c] The heat generation method not available.
[d] Heat and electricity generation ratio not available.
[e] Air separation unit and CO_2 compressor excluded.
[f] 50% less high-grade heat than conventional causticisation.
[g] CO_2 separation at 15 bar and then compression to 100 bar.

units as well. For both scenarios, all the captured CO_2 is compressed to 150 bar. In a third scenario, heating is still done by natural gas combustion, while CO_2 is not compressed and it is assumed that O_2 is available for free, thus power demand and costs of CO_2 compressor and air separation unit have been avoided. The fuel and electricity demand in all the 3 scenarios are presented in Table 1. In a fully electrified system, the total captured CO_2 would be lowered to the level of atmospheric CO_2 captured. This would decrease the size and energy demand of several parts. The exact electricity demand of a fully electrified model could be calculated via the same simulation software. In a conservative approach, assuming the same energy demand as the third scenario would result in 1535 kWh_{el}/t_{CO2} for a fully electrified system based on the Carbon Engineering technology. In this technology, NaOH has been also substituted by potassium hydroxide (KOH) (Carbon Engineering, 2018c; Keith et al., 2018).

4.1.2. *Low temperature (LT) solid sorbent*

Mainly, technologies in this group have a single unit with solid sorbent, where adsorption and desorption (regeneration) happen one after another. As illustrated in Fig. 3, in the first step the system is open, ambient air goes through naturally or with the help of fans. At ambient temperature, CO_2 chemically binds to the filter and CO_2 depleted air leaves the system. This step is completed when the sorbent is fully saturated with CO_2. In the next step, the fans are switched off, the inlet valve is closed and the remaining air is optionally swept out through a pressure drop by vacuuming or inserting steam into the system. Then, regeneration happens by heating the system to a certain temperature, depending on the sorbent. Released CO_2 is collected and transported out of the system for purification, compression or utilisation. In order to start another cycle, the system should be cooled down to ambient conditions. The sorbent determines the specific conditions of the cycles. Several different sorbents were proposed in literature, which have been described subsequently.

Amines are known for their selective ability to absorb CO_2 molecules from diluted concentrations. Climeworks uses a filter made of special cellulose fiber that is supported by amines in a solid form, which binds CO_2 molecules along with air moisture, thus the plant provides enough water for its own use (Climeworks, 2018b; Vogel, 2017). In order to release CO_2, pressure is reduced and the system is heated to 100 °C. The system requires 200–300 kWh_{el}/t_{CO2} mainly for the fans and control systems. It also needs 1500–2000 kWh_{th}/t_{CO2} for regeneration, which can be supplied by low-grade or waste heat, as demonstrated in the recent respective pilot plant (Climeworks, 2018b). A full cycle of the system takes 4–6 h with an output of 99.9% pure stream of CO_2.

Global Thermostat's proprietary amino-polymer adsorbent decreases the system's full cycle time to well below 30 min, where the regeneration occurs in less than 100 s at temperatures of 85–95 °C. To achieve such a fast process, saturated steam at sub-atmospheric pressure is used as a direct heat transfer fluid and as a sweep gas. 50% of the regeneration heat is recovered and depending on the plant's size, location and desired CO_2 purity (>98.5%), the overall

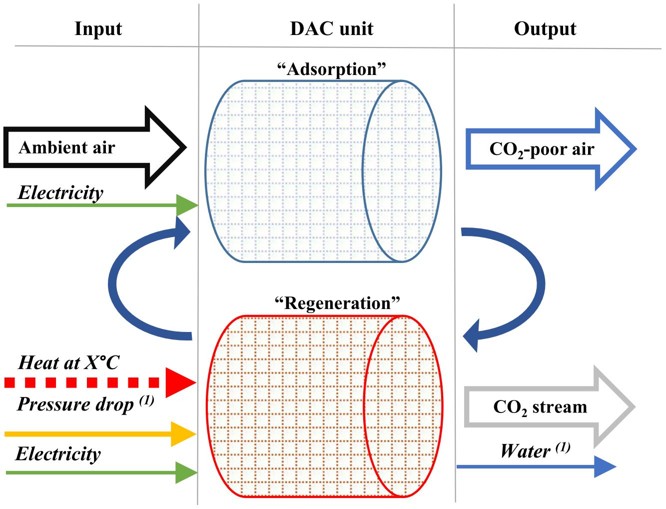

Fig. 3. Example of a low temperature solution DAC system.
(1) Conditional (depends on the system).

electricity and heat demand are 150–260 kWh_{el}/t_{CO2} and 1170–1410 kWh_{th}/t_{CO2}, respectively (Ping et al., 2018a).

The system proposed by Kulkarni and Sholl (2012) is different in the way that desorption of the sorbent silica (TRI-PE-MCM-41) occurs, by the introduction of steam at 110 °C. The output of this system is 88% CO_2 and 12% N_2 and water together. Sinha et al. (2017) has studied the same temperature swing system and analysed two amino-modified metal organic frameworks (MOF), MIL-101(Cr)-PEI-800 and mmen-Mg_2 (dobpdc). This system has the same cycles, but due to high possibilities of MOFs oxidisation at higher temperatures, vacuum is necessary before heating. Cooling is achieved by water evaporation from the surface. He concludes that among two MOF options, the one based on magnesium (Mg) is more favourable due to lower electricity and heat demand, which is 997 kWh/t_{CO2} (Sinha et al., 2017).

In Antecy's system, CO_2 is adsorbed by composite sorbent based on potassium carbonate (K_2CO_3) at ambient conditions. Before regeneration, air needs to be evacuated by water, then pressure is reduced and the sorbent is heated up to 80–100 °C by low-grade heat (Roestenberg, 2015). This slightly lower regeneration temperature in comparison to Climworks is achieved by due to the moisture-aided process. Derevschikov et al. (2014) introduced a DAC system based on K_2CO_3/Y_2O_3 sorbent powered by wind energy that regenerates at temperatures of 150–250 °C. The sorbent is rather sensitive to high temperatures and can be easily destroyed.

Table 2 summarises the main technical characteristics gathered from literature. Although Antecy claims to benefit from both cheaper material and lower energy demand than other DAC technologies (Antecy, 2018), the reported energy demand of Climeworks appears to be lower, followed by an even lower energy demand by Global Thermostat (Ping et al., 2018a). Thus, as a mean value, Climeworks' average energy demand has been selected as the energy demand for the LT DAC technology in this study. Aiming for a generic LT DAC system from an energy system perspective, no final sorbent has been selected. In a conservative approach, a desorption temperature of 100 °C has been chosen, as the highest required temperature by reviewed LT DAC companies. The comparisons of chosen electricity, heat and desorption temperature values to the available range of data have been visualised in Fig. 4. Antecy's CO_2 purity is unknown to the authors, however Antecy's plan for synthetic fuels production could only be achieved with a CO_2 purity of about 99%. Thus, a CO_2 purity of more than 99% has been assumed for the final model as an average of CO_2 purity from Climeworks, Global Thermostat and Antecy.

4.1.3. Other technologies

In addition to the described major models, new approaches have

Table 2
LT solid sorbent DAC specifications.

sorbent	CO_2 con.	adsorption	desorption		energy demand			cooling		CO_2 purity	reference
	ppm	T (°C)	T (°C)	P (bar)	kWh_{el}/t	kWh_{th}/t	by	T (°C)	by	%	
amine-based	400	ambient	100	0.2	200–300	1500–2000	waste heat	15	air/water	99.9	Climeworks (2018b); Vogel (2017)
amino-polymer	400	ambient	85–95	0.5–0.9	150–260	1170–1410	steam	ambient	water evaporation	>98.5	Ping et al. (2018b) (Global Thermostat)
TRI-PE-MCM-41	400	ambient	110	1.4	218	1656	steam	–	–	88	Kulkarni and Sholl (2012)
MOF (Cr)	400	ambient	135–480	1	1420		HT steam	–	–	–	Sinha et al. (2017)
MOF (MG)	400	ambient	135–480	1	997		HT steam	–	–	–	
K_2CO_3/Y_2O_3	400	ambient	150–250	–	–	–	el. heater	–	–	–	Derevschikov et al. (2014)
K_2CO_3	–	ambient	80–100	–	694	2083	waste heat	ambient	airflow	–	Roestenberg (2015); Antecy (2018)
-	**400**	**ambient**	**100**	–	**250**	**1750**	**heat pump/waste heat**	–	–	**>99**	**final model (this study)**

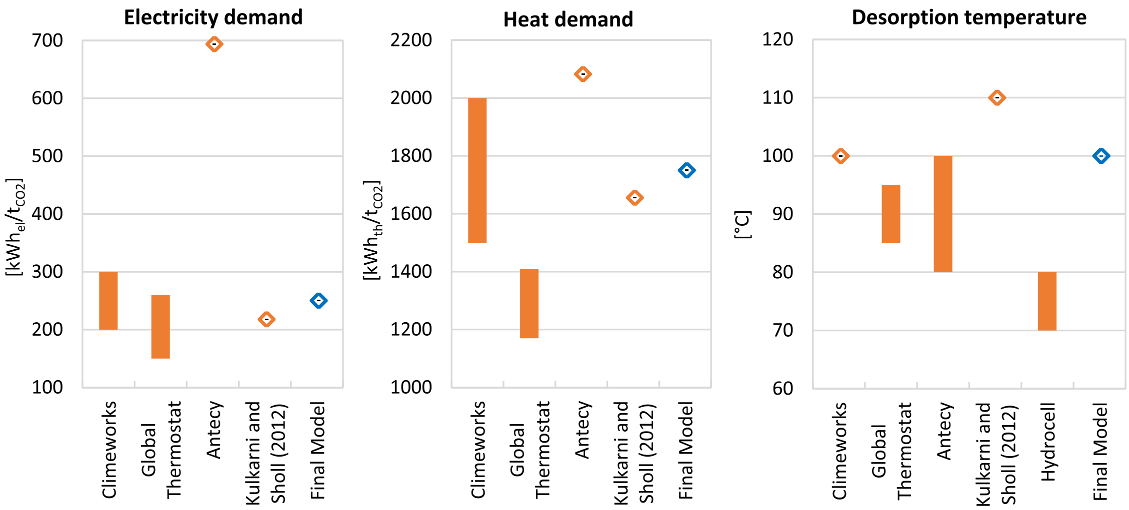

Fig. 4. The comparisons of electricity, heat and desorption temperature values of the final LT DAC model in 2020 to the available data.

been suggested in literature. Due to lack of publicly available technical and financial information or pilot-scale implementation of these technologies, they have not been further discussed in this paper.

Electrochemical CO_2 capture and modified fuel cell approaches at ambient temperature were suggested by Eisaman et al. (2009). However, no cost assumptions have been presented.

Ion-exchange resin can capture CO_2 by MSA approach. Thin resin sheets are exposed to ambient air to facilitate free flow of the air through the material. When loading is finished, the sheets are moved to a closed system. Inside the system, air is removed and moisture is added. The resin releases CO_2 by contacting with water. CO_2 is collected, dried and can be compressed if needed. After gas is removed, the system is heated up to 45 °C to speed up the drying process (Lackner, 2009; Goldberg et al., 2013). Lackner (2009) claims that the system with natural airflow would only require electrical energy in the amount of 316 kWh_{el}/t_{CO2}, including compression for liquefaction, but using fan will add 10 kWh_{el}/t_{CO2}. The system utilises heat released from compression as well. Goldberg et al. (2013) has proposed a complex DAC system where CO_2, after being captured, is cooled until it precipitates as dry ice and after warming, it turns into a pressurised liquid for sequestration. This system is powered by wind energy and requires 423 kWh_{el}/t_{CO2}, excluding freezing and 631 kWh_{el}/t_{CO2} including it. As mentioned in section 3, MSA technology is also used by the companies Infinitree and Skytree.

Freitas (2015) has proposed a conceptual design of nanofactory based molecular filters that are able to capture CO_2 from the air powered by solar energy. The system requires only 333 kWh_{el}/t_{CO2} of electricity and delivers pure CO_2 stream at a pressure of 100 bar with the final production cost of about 14 €/t_{CO2}. If this approach makes it at a commercial-scale, it could be a revolution for DAC technologies.

Seipp et al. (2017) has suggested a new two-cycle approach based on Na_2CO_3 and PyBIG (2.6-Pyridine-bis(iminoguanidine)). In this method, regeneration can happen at temperatures of 80–120 °C, avoiding high-grade heat demand by conventional aqueous solution-based DAC plants. It is claimed that this crystallisation approach could offer the prospects for low-cost DAC technologies, however, no financial data has been provided.

Available technical parameters from literature for the technologies in this group are presented in Table 3.

4.2. Economics of CO_2 DAC

Most articles regarding DAC are focused on technical parameters and only a few have conducted economic estimations. All reviewed economic specifications and the recalculated costs are summarised in Table 4.

The first originally reported costs associated with HT aqueous solution DAC reviewed in this study was 376 €/t_{CO2} by Keith et al. (2006). Later Holmes and Keith (2012) changed the contact design of the previous model fundamentally, which reduced the cost to 258 €/t_{CO2}. Socolow et al. (2011) present a benchmark DAC system with relatively more details for both energy balance and economic aspects. Considering the equipment investment costs, the study introduces an optimistic and realistic scenario. For the optimistic scenario, an installation multiplying factor of 4.5 (same as PSCC) is used to convert equipment's purchase price to the total plant's installation cost. Considering the novelty of DAC technology, an installation multiplying factor of 6 has been used for the installation cost of the system in the realistic scenario. This has increased the total reported costs of captured CO_2 from 309 to 395 €/tCO_2. The benchmark system described by Socolow et al. (2011) was further investigated by Mazzotti et al. (2013), where new packing materials were suggested for the optimisation of air contacting unit and the final estimated costs were reduced to 283–300 €/$t_{CO2,}$ depending on the costs and the energy consumption of the three different proposed packing materials. Zeman (2014) also modified and recalculated the costs and energy demand of the Socolow et al. (2011) model and concluded that the equipment investment costs could be lowered by 2.4% and the annual opex could be reduced from 4% to 3%. Keith et al. (2018) from Carbon Engineering provided the techno-economic assessments of their HT DAC systems, where both capex and final costs of the HT DAC systems have been significantly lowered in comparison to American Physical Society model (Socolow et al., 2011), through a new design and choice of material. Carbon Engineering has also practically achieved a CO_2 capture rate of 74.5%, in comparison to 50% capture rate in the APS model. For the base configuration (powered by natural gas and outlet CO_2 at 150 bar), it provides the capex of the first plant at 1132 €/t_{CO2} (1146 USD/t_{CO2}) and the Nth plant is expected to be 31% cheaper at 714 €/$t_{CO2}\cdot$a, due to improvement of constructability and built supply chain relationships. In addition, the capex of the Nth plant based on the second configuration (using grid electricity instead of gas turbine) and the third configuration (avoiding CO_2 compression and assuming availability of free O_2) are reported at 625 €/$t_{CO2}\cdot$a and 549 €/$t_{CO2}\cdot$a, respectively. The CO_2 capture costs of all configurations, based on 5.6% and 11.7% WACC (7.5% and 12.5% annuity factor) and 27–54 €/MWh for grid electricity, are provided in Table 4.

The third configuration by Keith et al. (2018) is the closest to the desired fully electrified system explained in section 4.1.1., with CO_2 at ambient pressure in order to have a common ground for comparison with LT solid sorbent DAC technology. In addition, such a system would not need O_2 due to substitution of natural gas with direct electrification. Moreover, any direct fuel-based CO_2 is avoided in such a system, which could downscale some subunits and the costs of fuel combustion and heating system could be possibly lowered as well. With a conservative approach, in our model, such cost reductions have not been included and the project costs have been recalculated for the first plant rather than the Nth one, which increases the capex from 549 to 815 €/$t_{CO2}\cdot$a. The annual opex has

Table 3
Technical specifications of other DAC technologies.

sorbent	CO_2 con.	adsorption	desorption		energy demand			cooling		CO_2 purity	reference
	ppm	T (°C)	T (°C)	P (bar)	kWh_{el}/t	kWh_{th}/t	by	T (°C)	by	%	
ion-exchange resin	400	ambient, dried resin	by moisturising	-	316	-	self-heating	45	drying	-	Lackner (2009)
ion-exchange resin	400	ambient, dried resin	by moisturising	-	423-631	-	wind power	45	drying	-	Goldberg et al. (2013)
K_2CO_3 [a]	400	-	25	10-100	2209	-	-	-	-	-	Eisaman et al. (2009)
Na_2CO3 & PyBIG	400	-	80-120	-	-	-	-	-	-	-	Seipp et al. (2017)
Nanofactory-based [b]	400	-	-	-	333	-	solar power	-	-	100	Freitas (2015)

[a] Electrodialysis-based CO_2 capture system.
[b] Molecular filters.

Table 4
Economics of DAC as reported and recalculated.

technology	capacity	capex	opex	lifetime	el. demand	el. price	heat/fuel demand	indicated time of cost	cost reported	cost recalculated	type of source[a]	reference
	t_{CO2}/a	€/t_{CO2}·a	%	years	kWh_{el}/t	€/MWh_{el}	kWh_{th}/t	year	€/t_{CO2}	€/t_{CO2}		
HT aqueous solution	280 000	-	-	20	-	-	-	2005	376	-	O	Keith et al. (2006)
	1 000 000	-	-	-	-	60	-	-	258	-	O	Holmes and Keith (2012)
	1 000 000	1583[b]	4[d]	20	494	53	2250	2011	309[b]	314	O	Socolow et al. (2011)
	1 000 000	2086[c]	4[d]	20	494	53	2250	2011	395[c]	388		
	1 000 000	-	-	-	-	53	1840	2013	283-300[e]	-	O	Mazzotti et al. (2013)
	-	-	-	-	1500	-	0	large-scale	75-113[f]	-	O	Carbon Engineering (2018c)
	1 000 000	1032[k]	3.7	25	0	-	2450	2018	151, 209[j]	200	O	Keith et al. (2018) (Carbon Engineering)
	1 000 000	714[k, l]	3.8	25	0	-	2450	2018	114, 153[j]	158		
	1 000 000	625[k, l]	3.7	25	366	27-54	1460	2018	110-112, 137-147[j]	139		
	1 000 000	549[k, l]	3.8	25	77	27-54	1460	2018	85-87, 115-117[j]	115		
	1 000 000	**815**[k]	**3.7**	**25**	**1535**	50	**0**	**2020**	**-**	186		**final model (this study)**
LT solid sorbent	3600	1220	-	25	694	-	2083	2015	-	244, 203[g]	O	Roestenberg (2015) (Antecy)
	360 000	730	-	25	694	-	2083	2015	-	177, 135[g]		
	-	-	-	-	150-260	-	1170-1410	first plant	<113	-	O	Kintisch (2014); Ping et al. (2018a; 2018b) (Global Thermostat)
	-	-	-	-	150-260	-	1170-1410	n/a	11-38	-		
	300	-	-	20	200-300	-	1500-2000	2014	-	-	O	Climeworks (2018b)
	-	-	-	-	-	-	-	large-scale	75	-		
	360 000	**730**	**4**	**20**	**250**	-	**1750**	**2020**	-	155, 120[g]	-	**final model (this study)**
moisture swing solid sorbent	365	421	-	10	306	38	-	2009	144	99	O	Lackner (2009)
	-	41	-	-	-	-	-	long-term	23	-		
generic	400	470	1.5	30	-	low	-	2011	900[h]	-	O	Simon et al. (2011)
	400	940	2.5	30	-	medium	-	mid-term	220[h]	-		
	400	2350	3.5	30	-	high	-	long-term	75[h]	-		
	-	-	-	-	3156	75-150	-	2011	750	-	R	House et al. (2011)
	-	-	-	-	3156	75-150	-	2050	225	-		
	500 000	330	4	50	-	-	-	2029	45	-	O	Nemet and Brandt (2012)
	500 000	330	4	50	-	-	-	2050	23	-		
	500 000	330	4	50	-	-	-	2100	14	-		
	-	-	-	-	-	-	-	long-term	30, 71, 105[i]	-	R	Broehm et al. (2015)

[a] (O) original source and (R) review article.
[b] Optimistic.
[c] Pessimistic.
[d] Additional 2.88 €/t_{CO2} as opex variable.
[e] Based on different packing material.
[f] Compressed to 150 bar.
[g] Based on free waste heat.
[h] Wind power, water consumption and carbon sequestration cost included.
[i] Optimistic, realistic and pessimistic assumptions.
[j] WACC: 5.6%, 11.7%.
[k] Based on €/USD exchange rate in 2016: 1.11.
[l] N^{th} plant.

been set to 3.7%, accordingly. The lifetime in 2020 is set to 25 years according to Keith et al. (2018).

The economic data of LT systems based on solid sorbents are more limited. Climeworks has claimed a target cost of less than 75 €/t_{CO2} for large-scale plants (Climeworks, 2018b); however, no electricity price or financial assumption have been provided. Global Thermostat expects CO_2 capturing costs below 113 €/t_{CO2} (150 USD/t_{CO2}) for their first commercial-scale plant (Ping et al., 2018b), while Kintisch (2014) has reported a target cost of 11–38 €/t_{CO2}, depending on the lifetime of amine surfaces. The time or scale for reaching this cost level is unknown to the authors. Although Climeworks is the forerunner in commercialising of solid sorbent DAC technologies, Antecy's capex estimation of 730 €/t_{CO2}·a is the only valid public data found, as explained in section 4.1.2. In a conservative approach, the lower reported lifetime of Climeworks (20 years) and 4% annual opex have been assumed for the final LT DAC model in this study, for 2020.

Lackner (2009) has proposed a very promising LCOD of 144 €/t_{CO2} for moisture swing technology as of today, which is due to relatively lower capex of 421 €/t_{CO2}·a, amount of resin required and assumed cost of electricity. However, in the absence of a pilot plant, it has not been considered for further analysis in this study.

With a skeptical approach, House et al. (2011) investigated the energetic and capital costs of existing DAC systems in an empirical analysis, and concluded that the final costs of the system are underestimated and could be at the level of 750 €/t_{CO2}. The main argument is that at 500 ppm CO_2 concentration in ambient air, the work requirement and, to a larger scale, the capital costs of CO_2 DAC would be more than those proposed in literature. In addition, carbon-free electricity with costs of 75–150 €/MWh in a foreseeable future have been considered as the only source of energy. It has been stated that the air capture of CO_2 would likely, require more thermodynamic work than NO_x removal from flue gas at 500 kJ/mol_{NOx}, equal to 3156 kWh_{el}/t_{CO2}. However, with an operational plant, Carbon Engineering has already proven these energy demand and capex assumptions to be too high. In addition, with the ongoing sharp decline in the costs of renewable electricity (Lazard, 2017; Liebreich, 2017), the assumed LCOE is too high as well.

The costs from literature are not comparable, due to lack of transparency with technology descriptions, different output conditions (e.g. pressure and CO_2 purity) and cost assumptions for input energy (heat and electricity) or WACC. Thus, a generic standardised cost evaluation has been performed for the final models, based on the following assumptions: WACC 7%, electricity cost of 50 €/MWh_{el}, low-temperature heat cost of 20 €/MWh_{th} (<100 °C), high-temperature heat cost of 25 €/MWh_{th} (900 °C) and FLh of 8000 h. It is important to emphasise that such costs are comparable with today's NG-based electricity and heat generation systems, which induce CO_2 emissions. For a truly sustainable system, renewable energy should be applied, which has been later studied in section 4.3.2., for the years 2020–2050. In case of lack of data, a lifetime of 30 years and an opex of 4% of the capex have been assumed. These recalculated costs are presented in Table 4. The cost recalculation was only possible for the systems of Socolow et al. (2011), Keith et al. (2018), Roestenberg (2015) and Lackner (2009), as the crucial data, such as input energy or capex is missing from the other models' specifications. According to the results, it can be seen that the final costs reported by Socolow et al. (2011) are recalculated to 314–388 €/t_{CO2}, which matches the reported costs. At 200 €/t_{CO2}, the recalculated cost of the base scenario of Keith et al. (2018) is 36% cheaper than APS's optimistic model at 314 €/t_{CO2}. Despite of higher cost assumptions for electricity than high temperature heat, at 186 €/t_{CO2}, the recalculated LCOD of the final HT DAC model (fully electrified, 1st plant, 1 bar outlet pressure) is lower than the base scenario of Keith et al. (2018), due to lower capex and energy demand of the system, considering the relief of avoided air separation unit, CO_2 compression to 150 bar and downscaling of fuel-based CO_2 handling subunits. The LCOD of the final LT DAC model is slightly lower than the recalculated costs of Antecy's commercial-size model, which is due to lower energy demand of Climeworks technology; however, Antecy's originally reported costs are unknown to the authors. The cost of Lackner's system is lowered from 144 €/t_{CO2} to 99 €/t_{CO2}. Such a difference could be possibly related to a higher rate of opex for MSA systems. In total, the recalculated LT DAC system costs are lower than HT DAC system.

Currently, DAC is in an early stage of development. However, it is assumed that the maintenance costs will be reduced along with equipment capex due to mass production, along with lower energy consumption due to technical advances in the long term (Lackner, 2009; Simon et al., 2011). Keith et al. (2006) considered a factor of three, as the accuracy range for any estimation of DAC plants. While suggesting 376 €/t_{CO2} as an achievable cost with today's technology, this study expects a cost decline to the same range as conventional mitigation technologies, due to independency and stronger economies of scale. Socolow et al. (2011) emphasised the significant amount of uncertainty, which makes it hard to predict the performance of a plant commissioned in the future.

While the current CO_2 DAC costs for LT solid sorbent technologies are rather unrevealed, Climeworks has set a goal of 75 €/t_{CO2} for large-scale plants (Climeworks, 2018b). In addition, moisture swing solid sorbents are also predicted to develop significantly. Lackner (2009) expects that the sorbent material (as the most expensive part of this technology) will be improved significantly with 10 times higher surface area and uptake capacity per kg of sorbent. This would also decrease the volume of the filter box by 10 times, increasing CO_2 capture capacity per volume of the device as well. It is projected that this, together with the economies of scale and decrease in the costs of other materials, would decrease the capex from 421 to 41 €/$t_{CO2}\cdot a$ and the final cost could be lowered to 23 €/t_{CO2}, taking into account low-cost electricity along with reduction of operational expenditures.

In order to estimate potential costs of DAC, Simon et al. (2011) conducted research where a generic DAC technology was examined based on assumptions such as electricity, heat, land and water use. The study claims that it is possible to capture CO_2 for 220 €/t_{CO2}, however, it points out that substantial research into kinetics and thermodynamics of capture chemistry is needed to prove it. In addition to the reference scenario, based on pessimistic (achievable today) and optimistic scenarios, a cost range of 75 €/t_{CO2} to more than 800 €/t_{CO2} have been provided.

As mentioned in the previous section, House et al. (2011) skeptically pointed out that the current costs of CO_2 capture from ambient air have been underestimated and could be around 750 €/t_{CO2}. However, the study suggests that technological breakthrough can dramatically improve DAC technology, which could make it possible to reduce production costs to a moderate level of 225 €/t_{CO2}.

Nevertheless, most of the papers agree on the long term improvement of DAC technologies. It was concluded by Broehm et al. (2015) that, among all different approaches, aqueous solution is the most developed DAC system and has shown significant technological improvement over the past years and will continue to follow the pattern which in the long term will bring capital and operational expenditures down. For a generic DAC system in the long term, Broehm et al. (2015) expect the costs for captured CO_2 to go down to 30, 71 and 105 €/t_{CO2} for optimistic, realistic, and pessimistic assumptions, respectively. The same opinion is shared by Nemet and Brandt (2012). They performed a sensitivity analysis of the appropriate techno-economic environment for DAC implementation on a large scale, estimated competitive costs of DAC and the effects it will have on conventional type of liquid fuels. They pointed out that after commercialisation of DAC, which is likely in the near term, the costs will go down rapidly due to economies of scale and learning by doing. They consider learning rates of 0.101 for capital costs, 0.135 for energy costs and 0.135 for operational and maintenance costs from previous researches performed by Rubin et al. (2007) and van den Broek et al. (2009), dedicated to PSCC (the closest technology to DAC). Nemet and Brandt (2012) conclude that under these assumptions, by 2029, DAC will reach the floor cost of 45 €/t_{CO2}, with possible further reduction to 23 €/t_{CO2} and 14 €/t_{CO2} in 2050 and 2100 respectively. In addition, Nemet and Brandt (2012) suggest a lifetime of 50 years for a generic DAC system, which exceeds any other lifetime assumptions in literature by 20 years.

4.3. Estimates for DAC development in the period 2020 to 2050

4.3.1. Potential cumulative DAC capacity demand and the learning curve impact on capex

The standard learning curve approach is applied for estimating the DAC capex development, according to Caldera and Breyer (2017), as summarised in Equations (9-11) for the log-linear learning curve concept. Abbreviations are capital expenditures, *capex*, progress ratio, *PR*, binary exponential expression of the progress ration, *b*, learning rate, *LR*, applied for the historic cumulative production for specific years, *prod*:

$$capex_{new} = capex_{initial} \cdot \left(\frac{prod_{new}}{prod_{initial}}\right)^{-b} \qquad (9)$$

$$PR = (2)^{-b} \tag{10}$$

$$LR = 1 - PR \tag{11}$$

Three fundamental input data are required for estimating future DAC system capex: (1) The initial capex are taken from Table 4; (2) The historic cumulative DAC capacity demand is derived in the following manner; (3) The learning rates for DAC systems are discussed based on respective DAC literature and experience from comparable technologies.

Article 2 of the Paris Agreement sets the target of limiting global temperature increase to well below 2 °C and preferably 1.5 °C above pre-industrial levels. In Article 4, reaching a net zero GHG emission system in the second half of the century is suggested as a means of achieving the targets of Article 2. However, scientists report that we are already on the edge of exploiting the carbon budget for 1.5 °C scenario and net negative GHG emission systems are necessary to achieve the targets of the Paris Agreement (Kriegler et al., 2017; Rogelj et al., 2018).

In the following it is assumed that the targets of the Paris Agreement shall be achieved by the mid of this century. We consider a 2050 scenario with high rates of direct RE-based electrification, substitution of remaining fossil fuels demand by RE-based synthetic fuels and chemicals, as well as direct carbon removal in the energy system. As such, the remaining CO_2 sources, demands and sinks are presented according to the listed bullet points and the equivalent DAC capacities, as the main potential CO_2 suppliers, are estimated. Seawater CO_2 extraction is not considered due to its early stage of development. The annual DAC capacity demands, as summarised in Table 5, are estimated for the period 2020 to 2050, in the sectors power (power-to-gas, waste-to-energy, sewage plants), transport (road, rail, marine, aviation), industry (chemical industry, pulp and paper, cement mills, others) and in future sector of CO_2 removal. In the power sector, carbon capture and utilisation (CCU) is not applied to SNG-based gas turbines due to their balancing role with low FLh in a RE-based power system. The fossil energy based CCU is limited to almost unavoidable limestone related CO_2 emissions from cement mills. A fossil-based transport and chemical industry could reduce their respective synthetic fuels and, consequently, CO_2 demand. However, approximately the same amount of CO_2 would add up to the direct CO_2 removal section to keep the system's CO_2 at the same level. Since, PSCC cannot be applied to transport and most remaining non-energetic uses of fossil fuels in chemical industry. Moreover, this would cause additional CO_2 emissions from fossil-based hydrogen production (mainly steam methane reforming) instead of water electrolysis. The iron and steel sector is not listed due to the assumption that the least cost pathway for this industry would lead to hydrogen-based direct reduction of iron (H_2-DRI) and later to electricity reduced iron, as discussed by Otto et al. (2017) and Fischedick et al. (2014). The DAC capacity demand is for:

- power-to-gas taken from Breyer et al. (2018) and Ram et al. (2017);
- waste-to-energy negative due to its CCU potential and based on waste resource potential taken from Breyer et al. (2018) and Ram et al. (2017), a CCU implementation rate assumed to grow from 2% (2025) to 50% (2050), a carbon capture efficiency of 87% (EC, 2014) and a CO_2 content in waste to be 0.37 $Mt_{CO2}/TWh_{th, waste}$ (IPCC, 2003);
- transport modes' demand is taken from Breyer et al. (2019a) for the synthetic Fischer-Tropsch-fuel demand, whereas, the relative mix of diesel and kerosene may change throughout the transition period, and a specific CO_2 DAC capacity demand of 0.36 Mt_{CO2}/a per $TWh_{th, fuel}$ for 8000 FLh based on Fasihi et al. (2017a; 2017b);
- chemical industry based on the chemical industry's energy feedstock and final process energy demand growth, excluding electricity, from 10 280 TWh_{th} (2015) to 19 200 TWh_{th} (IEA, 2009; Rembrandt and Matt, 2016), a demand coverage growth by naphtha as the by-product of Fischer-Tropsch fuels production from 2% (2030) to 16% (2050) according to Breyer et al. (2019a), an estimated 80% energy share of carbon-based chemicals and a specific CO_2 DAC capacity demand of 0.25 Mt_{CO2}/a per $TWh_{th, feedstock}$ for 8000 FLh based on Fasihi et al. (2017a) for an average of carbon-based feedstock chemicals;
- pulp and paper negative due to its CCU potential and based on the 2015 pulp production and extrapolated till 2050 with the

Table 5
Global annual CO_2 DAC (or equivalent) capacity demand by sector.

sector		unit	2020	2030	2040	2050
power	power-to-gas	Mt_{CO2}/a	3	7	142	363
	waste-to-energy	Mt_{CO2}/a	0	−17	−99	−165
	sewage plant	Mt_{CO2}/a	0	n/a	n/a	n/a
transport	road (cars/bus/trucks)	Mt_{CO2}/a	0	218	1309	1101
	rail	Mt_{CO2}/a	0	7	66	82
	marine	Mt_{CO2}/a	0	56	962	1667
	aviation	Mt_{CO2}/a	0	54	964	1543
industry	chemical industry	Mt_{CO2}/a	0	224	1157	3255
	pulp and paper	Mt_{CO2}/a	0	−8	−52	−95
	cement mills (limestone)	Mt_{CO2}/a	0	−69	−425	−607
	others	Mt_{CO2}/a	0	n/a	n/a	n/a
CO_2 DAC, energy system		Mt_{CO2}/a	**3.0**	**473**	**4025**	**7144**
CO_2 removal		$Mt_{CO2,captured}/a$	0	0	1000	10 000
thereof other Negative Emission Technologies		$Mt_{CO2,captured}/a$	0	0	300	2500
thereof **CO_2 DAC, CO_2 removal**		Mt_{CO2}/a	**0**	**0**	**767**	**8213**
CO_2 DAC, total		Mt_{CO2}/a	**3**	**473**	**4791**	**15 356**

compound annual growth rate between 2000 and 2015 taken from Kuparinen et al. (2018), a CCU implementation rate assumed to grow from 2% (2025) to 50% (2050), a carbon capture efficiency of 87% (EC, 2014);

- cement mills negative due to its CCU potential and based on cement production estimates taken from Farfan et al. (2019), a CCU implementation rate assumed to grow from 5% (2030) to 50% (2050), an efficiency increase of overall captured CO_2 from 60% (2030) to 80% (2050);
- CO_2 removal demand based on Kriegler et al. (2017), but with a demand for 10 Gt_{CO2}/a removal for 2050 instead of 2055 for a higher level of sustainability and thereof a 300 and 2500 Mt_{CO2}/a removal share by afforestation in 2040 and 2050, respectively, and the remaining for CO_2 DAC systems with 8000 FLh.

The estimated annual CO_2 DAC capacity demand grows from 3 Mt_{CO2}/a (2020) to about 15 360 Mt_{CO2}/a (2050), thereof about 8200 Mt_{CO2}/a from CO_2 removal (2050).

The estimates of annual CO_2 DAC capacity demands in Table 5 and respective DAC lifetimes define the historic cumulative CO_2 DAC capacity demands in Table 6, which are taken as input for the DAC capex estimates, according to the learning curve approach for a conservative and a base case scenario. The two scenarios for DAC capex development are defined as follows:

- The conservative scenario assumes only 50% realisation of the cumulative DAC capacity demand due to delayed execution of the Paris Agreement and a DAC learning rate of 10%, as assumed by Nemet and Brandt (2012) and based on Rubin et al. (2007), van den Broek et al. (2009) and Rubin et al. (2004).
- The base case scenario assumes an effective execution of the Paris Agreement without delay, leading to net zero GHG emissions from the energy system and already started CO_2 removal. The DAC learning rate is assumed to be 15%, which matches better the technology specific characteristics of CO_2 DAC systems than the effectively assumed sulphur removal systems of large-scale centralised coal-fired power plants that are the basis for the assumed 10% learning rate (Nemet and Brandt, 2012; Rubin et al., 2007, 2004). Highly modular energy technologies exhibit learning rates around 15%, as documented for water electrolysers with 18% (Schmidt et al., 2017), seawater reverse osmosis desalination with 15% (Caldera and Breyer, 2017), lithium-ion battery systems with 12%–17% (Kittner et al., 2017; Schmidt et al., 2017), which are finally a consequence of more comprehensive international product standardisation and substantial economies of scale.

Results of the learning curve approach for estimating the DAC system capex are summarised in Table 6 and visualised in Fig. 5. The DAC system capex are assumed to be 730 €/t_{CO2}·a (LT) and 815 €/t_{CO2}·a (HT) in 2020 (Table 4). The capex can decline for LT DAC systems to 199 €/t_{CO2}·a (conservative) and 84 €/t_{CO2}·a (base case) and for HT DAC systems to 222 €/t_{CO2}·a (conservative) and 93 €/t_{CO2}·a (base case) in 2050, respectively. The considered initial DAC capacity in 2020 (1.5 Mt_{CO2}/a) used in capex development calculations are well above the reported capacities of reference units of LT DAC (0.36 Mt_{CO2}/a) and HT DAC (1 Mt_{CO2}/a), which emphasises the room for further capex reduction.

The estimated DAC capex projections are used in the following as input for the cost scenarios in levelised cost of CO_2 DAC for specific sites.

4.3.2. Levelised cost of CO_2 DAC (LCOD) in the period 2020 to 2050

HT aqueous solution and LT solid sorbent are the two main technologies, which are ready for commercial scale implementation. The final models of HT aqueous solution and LT solid sorbent DAC technologies in 2020, presented in sections 4.1. and 4.2., have been further studied based on assumptions for long term development of the main specifications based on the ***conservative scenario*** described in section 4.3.1., and as shown in Table 7.

The capex assumptions for both technologies are based on the cumulative installed capacities and learning rates, applying the conservative scenario, described in section 4.3.1. The lifetime of LT DAC technology in 2020 is 20 years (Climeworks, 2018b), which has been expanded to 25 and 30 years in 2030 and beyond, respectively, according to the long-term estimations for generic DAC plants in literature. The lifetime of HT DAC is set to 25 years in 2020 according to Keith et al. (2018), and later has been extended to 30

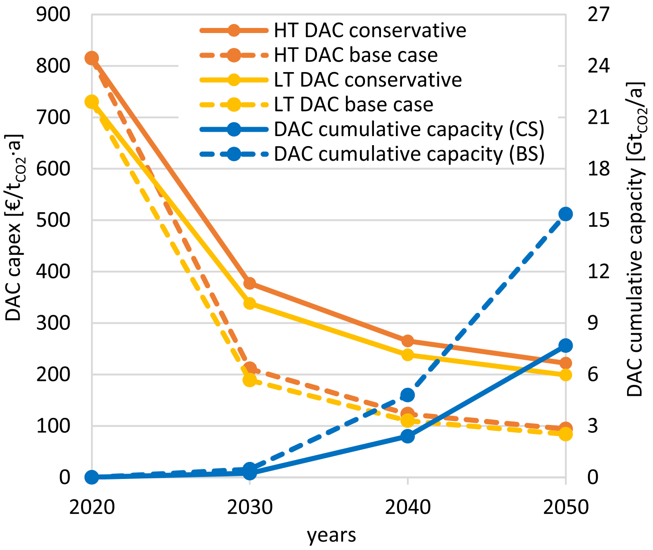

Fig. 5. CO_2 DAC capex development for LT and HT systems based on the learning curve approach and the applied conservative (CS) and base case scenarios (BS). The DAC cumulative capacity is based on the findings in Tables 5 and 6 and the respective DAC capex are based on Eqs. (9)-(11).

Table 6
Conservative and base case scenarios for LT and HT DAC capex reduction.

parameter	unit	2020	2030	2040	2050
CO_2 DAC, total	Mt_{CO2}/a	3.0	473	4791	15 356
thereof 50%, conservative scenario	Mt_{CO2}/a	1.5	237	2396	7678
thereof 100%, base case scenario	Mt_{CO2}/a	1.5	473	4791	15 356
historic cumulative capacity (conservative/base case)	Mt_{CO2}/a	1.5/1.5	237/473	2397/4793	7679/15 357
doublings between periods (conservative/base case)	-	0	7.3/8.3	3.4/3.4	1.7/1.7
capex CO_2 DAC LT (conservative/base case)	€/t_{CO2}·a	730	338/189	237/110	199/84
capex CO_2 DAC HT (conservative/base case)	€/t_{CO2}·a	815	378/211	265/122	222/93

years for the years 2030 and beyond, as Simon et al. (2011) and Nemet and Brandt (2012) consider a lifetime of 30 and 50 years, respectively. In addition, although Nemet and Brandt (2012) suggest a higher learning rate for opex of DAC systems, it has been kept constant at 3.7% and 3% of capex from 2020 to 2050 for LT and HT DAC technologies, respectively.

In a personal communication with Climeworks (Kronenberg, 2015), the average electricity and LT heat demand for 2030 were estimated to be 10% and 14.3% less than the current numbers. Considering the minimum achieved electricity and heat demand by other LT companies (Fig. 4), the same demand reduction rates have been assumed for each 10-year step until 2050. An electricity demand reduction rate of 5% has been applied to a fully electrified HT DAC system from 2020 onwards, considering the limits by the theoretical heat demand of the calciner unit in the currently known setup.

Morocco was chosen as a potential site for a large scale DAC plant implementation with 2400 FLh for single-axis tracking solar photovoltaic (PV) system and 3500 FLh for wind power technology (Fasihi et al., 2017a). DAC plants and heat pumps are capex intensive, thus it is important to run them on high FLh, which would demand high availability of electricity. Batteries are needed to increase the availability of renewable electricity, especially for a PV-based system. Fig. 6 illustrates the impact of DAC FLh on the net LCOE and LCOD. As can be seen, increasing FLh from 3000 to 8000 h would increase the net LCOE. However, the negative impact of higher LCOE on LCOD has been offset by higher DAC FLh which provides the chance for further reduction of LCOD. The highest impact is observed for increasing FLh of LT DAC from 3000 to 6000 h and from there to 8000 FLh, the decrease in LCOD is very low. For the case of HT DAC, LCOD stays more or less stable at 5000 to 7000 FLh, with a slight increase at 8000 FLh, which is due to bigger impact of energy cost on HT DAC.

The LCOE net for 4000 and 8000 FLh have been calculated based on the specifications of power sector components as in Table 8. The ratio of installed capacity of PV to wind gradually increases from 7 in 2030 to 10 in 2050, due to faster decline in PV LCOE and cost decline of supportive battery systems. Battery share is 11% and 56% for 4000 FLh and 8000 FLh, respectively. Electrical compression heat pumps have been used for LT heat generation, where the Coefficient of Performance (COP) gradually increases from 3.0 in 2020 to 3.5 in 2050 (DEA, 2016). LCOE, LCOD and LCOH were calculated for 4000 and 8000 FLh conditions and based on the conservative scenario with the above described assumptions. The results are presented in Table 7.

Fig. 7 illustrates the final contributions for LCOD of the LT and HT DAC systems at 8000 FLh in 2040 for the conservative scenario. The LCOD of the LT DAC system reaches 69 €/t_{CO2}, where the highest shares belong to heat demand at 43% and to DAC capital expenditures at 30%. In case of access to free waste heat, the LCOD could be lowered to about 40 €/t_{CO2}. On the other hand, at 91 €/t_{CO2}, the LCOD of the HT DAC system in 2040 is higher than LT DAC, where the electricity cost dominates the total costs at 62% and the share of capital expenditures is about 26%. Thus, it is rather crucial for both DAC systems to have the DAC plants located at sites of abundant and very low-cost renewable electricity in order to bring the final CO_2 production costs down. In the case of access to very low-cost or free waste heat for LT system, its dependency on very low-cost electricity is relatively lower.

4.3.3. Sensitivity analysis

Due to uncertainties about literature-based DAC system models' specifications and their developments in the long term, a sensitivity analysis is crucial in this study. In addition, input values can vary based on the selected location of the DAC plant and overall economic environment. Thus, a sensitivity analysis was conducted for ±10% changes in economic, energetic and geographical factors for LT and HT DAC systems with 8000 FLh in 2040, for which the results are presented in Fig. 8. As illustrated in Fig. 8a, a 10% change in WACC or DAC capex has a 4–5% impact on LCOD, followed by 2–3% and 1% impact from battery and PV capex, respectively. Although wind has a higher capex, its impact on the results are negligible, as the installed capacity of wind is set to one ninth of PV capacity in 2040. As shown in Fig. 8b, the impact of a 10% change in opex of PV, wind or battery on LCOD is negligible, while the DAC opex impact is about 1.5–2%. However, the biggest operational cost impacts are

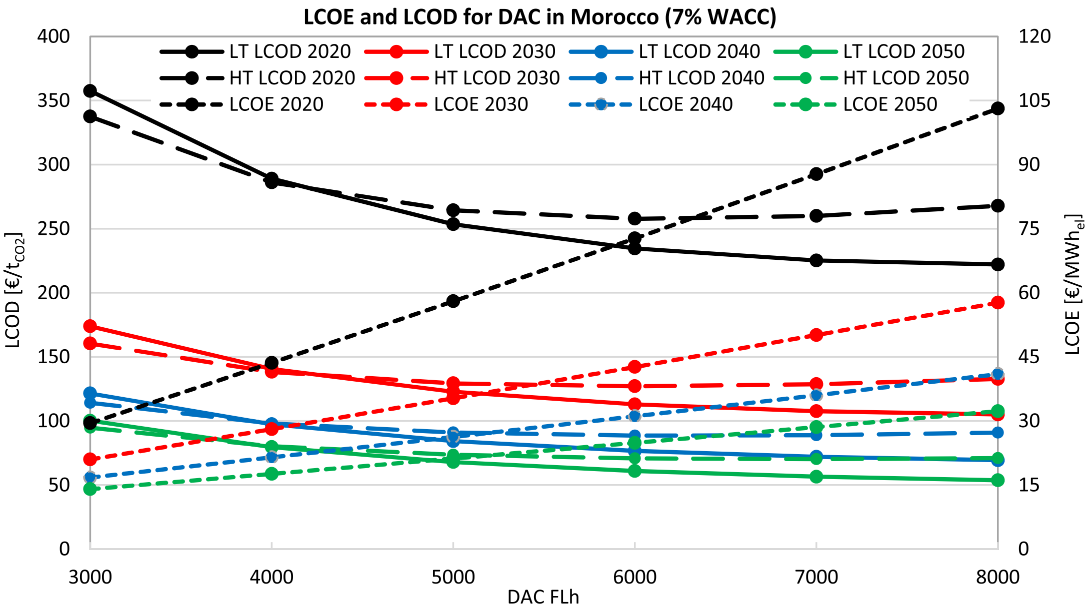

Fig. 6. The impact of DAC FLh on net LCOE, LT LCOD and HT LCOD (conservative scenario).

Table 7
Long-term specifications of DAC and generic costs (conservative scenario).

		unit	2020	2030	2040	2050
LT DAC	capex	€/$t_{CO2}\cdot a$	730	338	237	199
	opex	% of capex p.a.	4%	4%	4%	4%
	lifetime	a	20	25	30	30
	el. demand	kWh_{el}/t_{CO2}	250	225	203	182
	LT heat demand	kWh_{th}/t_{CO2}	1750	1500	1286	1102
HT DAC (electrified)	capex	€/$t_{CO2}\cdot a$	815	378	265	222
	opex	% of capex p.a.	3.7%	3.7%	3.7%	3.7%
	lifetime	a	25	30	30	30
	el. demand	kWh_{el}/t_{CO2}	1535	1458	1385	1316
4000 FLh	LCOE net	€/MWh_{el}	44	28	21	18
	LCOH - LT (by heat pump)	€/MWh_{th}	36	27	24	22
	LCOD - LT	€/t_{CO2}	289	141	97	80
	LCOD - LT (free waste heat)	€/t_{CO2}	226	99	67	56
	LCOD - HT	€/t_{CO2}	286	138	98	80
8000 FLh	LCOE net	€/MWh_{el}	103	58	41	32
	LCOH - LT (by heat pump)	€/MWh_{th}	51	30	23	20
	LCOD - LT	€/t_{CO2}	222	105	69	54
	LCOD - LT (free waste heat)	€/t_{CO2}	133	60	40	32
	LCOD - HT	€/t_{CO2}	268	133	91	71

associated with energy consumption of the plant. For the LT DAC system, with a 5% change in LCOD, heat demand has the biggest impact as the majority of energy demand is supplied by heat, while at 7%, electricity demand of a fully electrified HT DAC would have the same impact on LCOD. Fig. 8c emphasises the big role of DAC FLh on LCOD, however, unlike Fig. 6, here it is assumed that increasing DAC FLh has no impact on LCOE. It also shows that a region with 10% more PV FLh could decrease the LCOD by about 2%. Fig. 8d illustrates that a 10% lower battery or LT DAC lifetime could increase the cost by about 1%.

4.4. Area demand and risk of local CO_2 depletion

One of the most common concerns about wide scale DAC plants implementation is local CO_2 depletion, as it may affect the environment and vegetation. In addition, a CO_2-poor environment would decrease the efficiency of DAC systems and increase final CO_2 capture costs. Thus, it is important to evaluate the recovery time and the minimum distance between DAC units to avoid such problems. In addition, footprint and respective land usage may be a key issue, as substantial land requirement might be a barrier for the

Table 8
Power and heat sector key specifications.

	unit	2020	2030	2040	2050	reference
PV single-axis tracking plant						ETIP-PV (2017); Bolinger et al. (2017)
capex	€/kW_p	638	429	330	271	
opex fix	€/($kW_p\cdot a$)	15.0	12.0	10.0	8.0	
opex var	€/kWh_{el}	0	0	0	0	
lifetime	Year	30	35	40	40	
Wind power plant						Neij (2008); Breyer et al. (2018)
capex	€/kW_p	1150	1000	940	900	
opex fix	% of capex p.a.	2.0%	2.0%	2.0%	2.0%	
opex var	€/kWh_{el}	0	0	0	0	
lifetime	Year	25	25	25	25	
PV/Wind capacity ratio	–	7	8	9	10	this study
Battery						Breyer et al. (2018)
capex	€/kWh_{el} (energy)	300	150	100	75	
opex $_{fix}$	% of capex p.a.	2.5%	2.5%	2.5%	2.5%	
opex $_{var}$	€/kWh_{el}	0.0002	0.0002	0.0002	0.0002	
lifetime	Year	20	20	20	20	
cycle eff.	%	91	93	95	95	
energy to power ratio	–	6	6	6	6	
Electrical Compression Heat Pump						DEA (2016)
capex	€/kW_{th}	660	590	554	530	
opex $_{fix}$	€/($kW_{th}\cdot a$)	2	2	2	2	
opex $_{var}$	€/kWh_{th}	0.00180	0.00170	0.00163	0.00160	
lifetime	year	25	25	25	25	
COP	–	3	3.26	3.41	3.51	

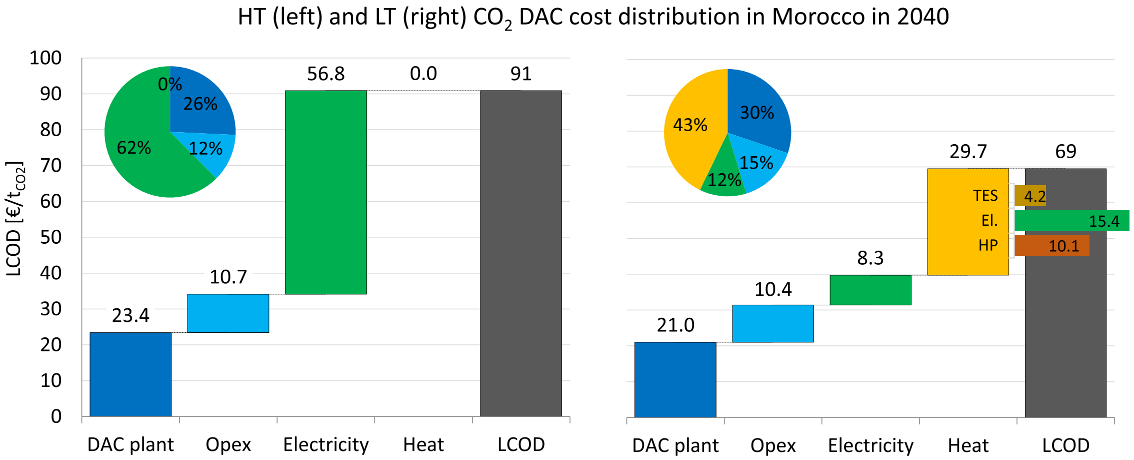

Fig. 7. LCOD cost breakdown for the fully electrified HT DAC system (left) and LT DAC system (right) for 8000 FLh and conditions in Morocco in 2040.

large scale implementation of the technology. The study by Johnston et al. (2003) has analysed the carbon capture potential of an engineered flat sink with 4° × 5° latitude/longitude resolution and its long term local CO_2 depletion impact in 5 different regions of the world, with a three dimensional chemical transport model. It concludes that the local depletion could be in the range of natural daily, seasonal CO_2 flections, thus not an issue for the implementation of DAC systems. In addition, it notes that the CO_2 uptake depends on the CO_2 velocity and, at a typical velocity of 1 m/s, an area of 75 000 km^2 would be enough to capture 3 Gt_{CO2}/a, representing a footprint of 25 km^2/Mt_{CO2}. It has been emphasised that the same uptake capacities can be expected from vertically aligned systems, while decreasing the direct land use at the same active area. On the other hand, by spreading this very large-scale system in smaller units across different regions to avoid meeting each other's CO_2 shadow, the active area demand could be reduced by more than an order of magnitude.

Socolow et al. (2011) claims that for a HT aqueous based DAC system with 1 Mt_{CO2}/a capacity, the total area demand would be 1.5 km^2 that leads to a footprint of 1.5 km^2/Mt_{CO2}, which is based on the following assumptions: Five contacting facilities with a length of 1 km and width of 1 m are located 250 m apart from each other, which is the minimum allowed distance to prevent dual depleted air intake. This indicates that, like wind farms, the major are demand of DAC systems is reserved for the free space between DAC units. In addition, a warehouse for chemical storage and a regeneration unit is included in the footprint. Climeworks (2018b) capture plant has 18 units located in 3 rows on top of each other and is currently the maximum vertical expansion for Climeworks. However, the overall footprint of their system for capturing 8 Gt_{CO2} per year is 3300 km^2, which is equal to 0.4 km^2/Mt_{CO2} annually. Although, none of these two sources have specified how the total land demand or the minimum allowed distance between units were estimated, their overall footprint is in line with Johnston et al. (2003), which conducted land use estimation for relatively small-scale DAC systems. Keith et al. (2006) also discussed DAC systems land requirements in lesser detail, where it has been concluded that the direct area demand of potential DAC plants can be rather small, as the land between the units can be freely used for other purposes.

4.5. Water demand

The water demand of DAC units is the other factor which should be considered for the large scale implementation of the technology. The water loss in HT aqueous solution DAC systems could be between 0 and 50 tons per ton CO_2 captured, depending on the temperature and humidity of the ambient air and concentration of the solution (Keith et al., 2006; Stolaroff et al., 2008; Smith et al., 2016; Zeman, 2007). The new Carbon Engineering design needs 4.7 tons of water per ton CO_2 captured, at ambient conditions of 64% relative humidity and 20 °C (Keith et al., 2018). In case of water stress in the region, water desalination and transportation could cost 0.6 to 1.6 €/m^3 in 2030 (Caldera et al., 2016), which would add about 3–8 €/t_{CO2}, according to water cost impact in Keith et al. (2018). This could limit the locational flexibility of DAC plants, particularly in dry and remote desert regions where both water demand and its transportation cost could be significantly higher. On the other hand, some LT DAC systems can capture water as a by-product. For example, Climeworks technology can capture 2–5 mol of water per mole CO_2 captured, equal to 0.8–2 ton water per t_{CO2}. Generally, from an energy point of view, it is their goal to capture as little water as possible. However, at 2 mol water per mole CO_2 the energy demand would be in the lower end of energy consumption range of Climeworks technology (Kronenberg, 2015). According to Bajamundi et al. (2018), Hydrocell's DAC system operated in the Finnish climate has also produced 4.6 mol of water per mole of captured CO_2, equal to 1.9 ton water per t_{CO2}. Thus, water demand would not be a constraint for LT DAC systems, quite to the contrary DAC systems could provide water needed for subsequent water electrolysis processes, as required for power-to-fuel and power-to-chemical conversion (Fasihi et al., 2017a, 2017b).

4.6. CO_2 compression, transport and storage

The captured CO_2 could be stored or utilised as feedstock for other applications. For these matters, additional steps such as purification, compression and transportation (in gaseous or liquid phase) may be needed, which could be energy and cost intensive (Aspelund and Jordal, 2007; Johnsen et al., 2011; Knoope et al., 2014).

CO_2 could be liquefied by compression to a critical pressure of 73.8 bar and then can be pressurised further by pumps (McCollum and Ogden, 2006). When compressing CO_2, recoverable heat is generated and can be utilised in other parts of the system (Lackner, 2009). In PSCC, prior to compression, CO_2 needs to be cleaned from a wide range of impurities associated with flue gases. Thus, the

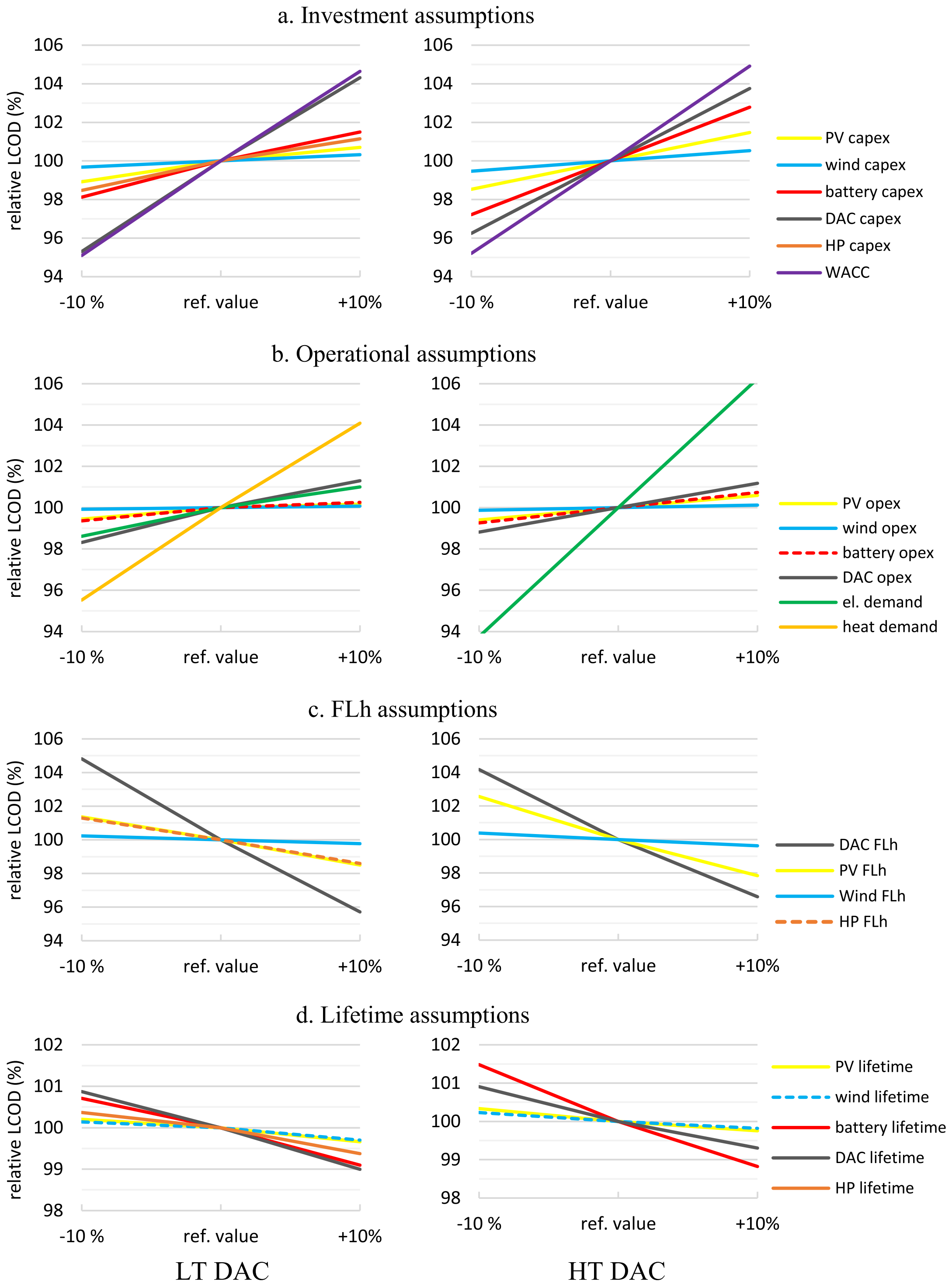

Fig. 8. Sensitivity analysis of LCOD for the LT DAC (left) and HT DAC (right) systems based on input data for (a) investment, (b) operational, (c) FLh and (d) lifetime assumptions for 8000 FLh in 2040.

compression station is combined with the purification unit (Skaugen et al., 2016). Simon et al. (2011) reported 62.5 kWh_{el}/t_{CO2} as the minimum energy requirement for CO_2 compression to 138 bar after DAC, equal to 104 kWh_{el}/t_{CO2} of practical energy demand based on a compression efficiency of 60%. Kolster et al. (2017) reported an energy requirement of 96–103 kWh_{el}/t_{CO2} for CO_2 dehydration and compression to 120 bar, for PSCC. Keith et al. (2018) reported an energy requirement of 132 kWh_{el}/t_{CO2} for CO_2 compression to 150 bar from DAC, where the compressor stands for about 3% of the total direct field cost.

CO_2 transportation can be done by pipelines, ships, railways, trucks, tank containers or a combination of them. Transportation type strongly depends on the terrain, distance and capacity. Pipeline is a well-regulated, safe and mature option (IEA, 2016) that is favourable for big volumes of CO_2 with annual transportation capacity of 1–5 million ton and distances in the range of 100–500 km (IEA, 2010). Over long distances (>2400 km), ship transport is more cost-effective (IEA, 2016). It also has advantages over pipeline network in terms of flexibility and scalability. On the other side, ships require well-developed hubs and terminals. CO_2 is transported only in the liquefied form by ships, thus an additional pressurisation station is needed at the harbour. Karjunen et al. (2017) has analysed different sites at the terrain where ships and sufficient infrastructure of pipelines do not exist and concluded that the price of CO_2 transportation by trucks, trains and pipelines for short distances (100–400 km) will be in the range of 4.4–14 €/t_{CO2}. Cost parameters associated with all mentioned means of transportation are summarised and presented in Table 9.

Traditional options for CO_2 sequestration (permanent storage) are limited to deep saline formations (1000–~10 000 Gt_{CO2}), depleted oil and gas fields (675–900 Gt_{CO2}), coal seams (3–200 Gt_{CO2}), basalts, shales, salt caverns and abandoned mines (IEA, 2016; Svensson et al., 2004). Chen and Tavoni (2013) have reported a CO_2 storage cost of about 10 €/t_{CO2} for the best sites in the world, with a cumulative capacity of about 700 Gt_{CO2}. Transportation distance and associated costs could increase for future projects. A more sustainable long-term CO_2 storage solution would convert CO_2 into a chemically inert compound with a high combustion point so that later emission risks can be reduced to an absolute minimum. Also, CO_2 from DAC technologies could be used for synthetic fuel production in a closed carbon loop (Vázquez et al., 2018). For coupling these sectors, depending on the operation timing and capacities of DAC systems and synthetic units, intermediate and seasonal storage with high capacities might be needed. However, most plants would be operated close to base load, which reduces the need for seasonal storage. Gas tanks can be used for intermediate storage of CO_2. Karjunen et al. (2017) has stated that costs of intermediate storage in cylindrical tanks can be about 10 €/t_{CO2}.

5. Discussion

5.1. Relevance of DAC with respect to the Paris Agreement

The Paris Agreement symbolises a common understanding of the extreme situation and actions needed to be taken. To reverse this trend, a deep and fast defossilisation of the power, heat, transportation and industry sectors through higher utilisation of RE by 2050 is needed (Breyer et al., 2018; Jacobson et al., 2017; Mathiesen et al., 2015; Ram et al., 2017; Sgouridis et al., 2016). However, a 100% direct electrification of these sectors is not possible, especially for high temperature industrial heating, long-range aviation and marine transportation, where fossil fuels and later synthetic fuels are expected to be play a role by 2050. Some balancing gas power plants would be needed for the power sector during the transition period, which could switch during the transition period to synthetic natural gas or other synthetic fuels (Ram et al., 2017). In addition, a part of non-energetic use of fossil fuels in the chemical industry could finally turn to CO_2 emissions in the atmosphere, such as burning of plastic wastes in incinerators. The unavoidable fossil CO_2 emissions from cement industry would also still contribute to climate change (Farfan et al., 2019). Point source

Table 9
CO_2 transportation cost.

transp. type	capacity	distance	cost	reference
	Mt_{CO2}/a	km	€/t_{CO2}	
truck	$15–20 \times 10^{-6}$	>100	13	Freitas (2015)
train	1.46	598	7.3	Gao et al. (2011)
onshore pipeline	0.73	100	6.8	McCollum and Ogden (2006)
	0.73	500	43.6	McCollum and Ogden (2006)
	2.5	180	5.4	ZEP (2011)
	7.3	100	1.5	McCollum and Ogden (2006)
	7.3	500	9.8	McCollum and Ogden (2006)
	20	180	1.5	ZEP (2011)
	20	750	5.3	ZEP (2011)
offshore pipeline	2.5	180	9.3	ZEP (2011)
	2.5	1500	51.7	ZEP (2011)
	20	180	3.4	ZEP (2011)
	20	1500	16.3	ZEP (2011)
shipping	2	750	11.1 [a]	Aspelund et al. (2006)
	2.5	180	13.5 [a]	ZEP (2011)
	2.5	1500	19.8 [a]	ZEP (2011)
	3	1950	11.8 [b]	Kujanpää et al. (2011)
	20	180	11.1 [a]	ZEP (2011)
	20	1500	16.1 [a]	ZEP (2011)

[a] Liquefaction cost included.

[b] Liquefaction cost not included.

carbon capture and storage (CCS) could only decrease the GHG emissions from these sectors, and not fully remove them (Leeson et al., 2017). In addition, point source CCS could not be applied to ships, planes and smaller polluters Thus, a fossil-based system, even with CCS or CCU, would still be a net-polluter (SAPEA, 2018). DAC will finally allow to close the carbon cycle in a world where it is not possible to eliminate GHG emissions produced by aviation and marine sectors, along with untapped CO_2 from unavoidable point sources (cement and waste-to-energy incinerators) and from land use and agriculture. Targets of the Paris Agreement are most likely not achievable by point source CCS, as not a single proposed technology can capture all emitted CO_2, whereas it can be collected by DAC plants. In addition, as mentioned in section 4.3.1., DAC capacities coupled with CO_2 storage are needed as a negative emission technology to reverse climate change impacts. Integrated Assessment Models (IAMs) have preferred BECCS as NET in the past, as criticised by Creutzig et al. (2019), whereas DAC systems are superior in most criteria. But the reported costs of DAC are still regarded as the main obstacle for a broader consideration of DAC systems as an impactful NET. Breyer et al. (2018) found for the case of the Maghreb region that DAC systems can be a very cost-effective NET in 2050. Creutzig et al. (2019) also point out that the energy system integration of DACCS can be expected to be superior to BECCS for renewables based energy systems, which is confirmed by Breyer et al. (2019b) for DACCS coupled to a 100% renewable energy system in the Maghreb region. According to Wilcox et al. (2017), CO_2 purities of about 50% are suitable for mineral carbonation as a permanent CO_2 storage solution. At such purity levels, the energy demand and consequently the cost of DAC systems are relatively lower than DAC systems with more than 99% purity discussed in this work. This could potentially lead to a cheaper DACCS process, assuming no significant negative impact by impurities during post-capture processes.

5.2. Benefits and challenges of the main DAC technologies

LT solid sorbet-based and HT aqueous solution-based DAC systems have been reviewed in this study. The HT technology is adopted from PSCC with proven absorbent materials. Nevertheless, in most HT DAC models fossil fuels are used to provide the required high-grade heat. This would be an unsustainable system for CCU, as the fossil CO_2 part would finally end up in the atmosphere. A CCS chain based on this system could enable only partially negative emissions, which would increase the net LCOD of avoided CO_2. The use of synthetic fuels would also dramatically increase the primary energy demand and the cost of the system. However, a fully electrified HT DAC technology provides the chance to fully run the system on RE. On the other hand, LT DAC systems have more options for providing heat, such as heat pumps, which are more energy efficient and can be directly powered by RE. The waste heat from industry could be seen as a source of free or cheap energy, which could reduce the LCOD significantly (Fig. 6). For some CCU processes, and in particular synthetic fuels production integrated with LT DAC units, the waste heat from fuel production processes could be recycled and used in the LT DAC units, reducing the overall costs of final output (Fasihi et al., 2017b; Ram et al., 2018). This is a clear advantage of LT DAC systems. Moreover, while the water demand of HT DAC systems is typically seen as a negative factor, some LT DAC technologies are capable of capturing moisture from the atmosphere as a by-product, which could be used for hydrogen production as the first step in synthetic fuels and chemicals production. This could partially or fully avoid the dependency of such systems on external water (Fasihi et al., 2017b). The moisture aided LT DAC technologies, such as the one applied by Antecy (Roestenberg, 2015), could further decrease the temperature and the amount of heat demand, opening the room for more variety of waste heat sources and higher energy efficiency of such DAC systems. On the other hand, to the knowledge of the authors, so far LT DAC systems have been operated in moderate climates. Operating these systems in sunny and hot regions such as Morocco may decrease the heating demand, however this would increase the cooling demand of the system, as the natural air cooling would not be enough anymore. The impact of such a change on the overall energy demand of the system is unknown to the authors, same as the change in moisture in the atmosphere of dry regions.

HT DAC systems consist of separate carbon capture and regeneration units, which make the constant carbon absorption and regeneration possible. On the other hand, for the available LT DAC technologies, both adsorption and desorption happen stepwise in one unit, which limits the operating hours of each step. This may cause additional costs to the system for time management and storage of RE and RE-based heat. Antecy (2018) and Global Thermostat (Ping et al., 2018b) have introduced LT DAC systems with separate units exclusively designed for adsorption or desorption, which have a higher efficiency and operating time that could decrease the final system costs. From an economic perspective, judging by publicly available information and promises for further cost reductions, LT DAC seems to be the cheaper option when free waste heat is available. It is important to emphasise that even lower costs are foreseen for LT DAC by Global Thermostat (Table 4). However, as no financial details are publicly available, it has been excluded from this comparison.

5.3. Final cost of large-scale DAC

As discussed in section 4.3.2, LCOD of HT/LT DAC systems with 8000 FLh, under the conservative scenario with 50% implementation of needed DAC systems and 10% learning rate of DAC capex, is projected to be about 268/222, 133/105, 91/69 and 71/54 €/t_{CO2} in 2020, 2030, 2040 and 2050, respectively. However, as illustrated in Fig. 9, under base case scenario assumptions with 100% implementation of needed DAC systems and 15% learning rate, the costs for HT/LT DAC systems could go down to 268/222, 111/84, 72/53 and 54/38 €/t_{CO2} in 2020, 2030, 2040 and 2050, respectively. At 111–133 €/t_{CO2}, the results for HT DAC in 2030 are higher than the projected costs of Carbon Engineering (third scenario), at 85–87 €/t_{CO2}, for the Nth gas-based plant with a well regulated

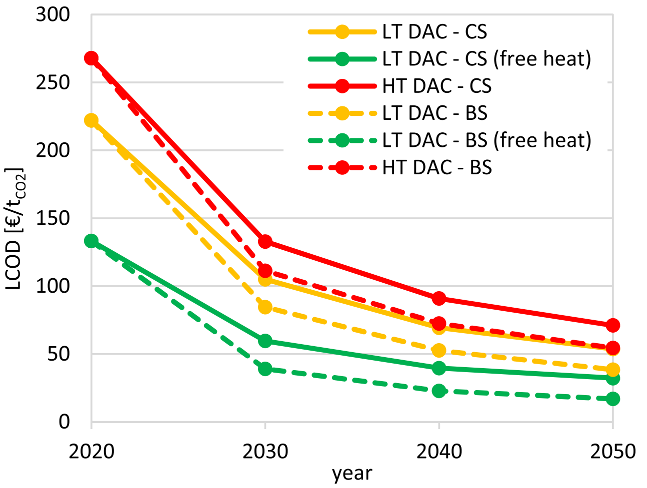

Fig. 9. LCOD for LT and HT DAC systems with 8000 FLh and 7% WACC for the conservative scenario (CS) and base case scenario (BS) assumptions.

construction and supply chain relationship. In this year, the historic cumulative DAC in the set scenarios have well passed the maturity level and the capex is below the Nth plant's capex. However, the impact of close-to-baseload renewable electricity (58 €/MWh$_{el}$) on the final costs is significantly bigger than the assumed cheap gas price of 11 €/MWh$_{th}$ by Keith et al. (2018), wherein the costs of fossil-CO$_2$ emissions have not been taken into account. Based on this, the long-term costs recalculated in this research of 54–71 €/t$_{CO2}$ for HT DAC in 2050 appears achievable. No final number is provided in literature for the current costs of LT DAC, however, as the defined generic LT DAC in this research is fully based on specifications of available plants or commercial designs. The calculated cost of 222 €/t$_{CO2}$ in 2020 is expected to be reliable. For the 2040–2050 period, LT DAC costs have been calculated to be 38–69 €/t$_{CO2}$, which is in line with projected costs of Climeworks (75 €/t$_{CO2}$) and Global Thermostat (11–38 €/t$_{CO2}$) for long-term or large-scale deployment of DAC technologies.

Besides the impact of more energy efficient systems and accessibility to cheaper energy in the future, the capex development and relative cost reduction from 2020 to 2050 emphasises the big role of the implementation rate and learning curve. Nevertheless, the relatively high cost of DAC in 2020 could remain as a challenge for attracting investments needed for introducing the system to the market and scaling up.

In this study, a COP of 3 has been used as a global average for heat pumps in 2020, which gradually increases to 3.51 in 2050 (DEA, 2016). However, this could be a rather conservative assumption for the warm climate of Morocco. On the other hand, the nature of the market in 2020–2030 could be relatively different from those in 2040–2050, as DAC coupled with permanent storage as a negative emission technology is projected to be implemented from 2040 onwards. All the projected DAC capacity in 2020–2030 is associated with synthetic fuels and chemicals production with possibly available excess heat as a byproduct, from which the LT DAC system could benefit to further decrease the production cost to 133, 60, 40 and 32 €/t$_{CO2}$ in 2020, 2030, 2040 and 2050, respectively, which could make market entry easier. On the other hand, for the 2020–2030 period, the global energy system would still include high shares of fossil-based point source CO$_2$ from power and industrial sectors, which could be a cheaper source of CO$_2$ through point source CCU and could be a competitor to DAC. Whether regulators allow it remains unclear. However, looking at the big picture, there would not be enough point source CO$_2$ to meet all the CO$_2$ demand in a fully sustainable energy system in 2050 (Table 5). Thus, DAC would finally have the larger market share and, to make it cheap by then, the implementation needs to start today.

All cost analyses in this research are based on 7% WACC, however, a business case with 5% WACC may be possible in some regions of the world. Access to cheap RE in such regions could further reduce the LCOD by about 12%. Niche markets could also help to increase the market share of DAC. As an example, the awareness and demand for sustainable CO$_2$ or CO$_2$-based products such as synthetic fuels or chemicals is growing, which makes DAC one of the very few available options. Finally, CO$_2$ emissions costs are the last means of regulating the market, which could have a small or big impact on cost competitiveness of DAC systems, depending on the regulations developed by policy-makers.

5.4. CO$_2$ DAC vs. point source carbon capture, today and in the future

DAC is usually compared to PSCC based on costs, which is not fully correct. As explained in section 5.1., point source CCU and CCS can only reduce the pace of CO$_2$ emissions increase due to implementation rate and carbon capture efficiency losses, while DAC coupled with CO$_2$ storage (DACCS) can truly act as a net NET (Choi et al., 2011b). In addition, as shown in section 4.3.1, in a sustainable energy system by 2050, there would not be enough point source CO$_2$ as feedstock for other applications. Thus, the two technologies could complement each other for different applications. However, there could be some market segments where both technologies could be applied, but the final choice could be derived by financial factors. Under equal preconditions such as energy demand and costs, it seems logical to expect lower carbon capture costs from point sources due to the higher concentration of CO$_2$.

Fig. 10 illustrates the cost range of PSCC in 2020 and projected costs in 2050, based on the scenario explained by Leeson et al. (2017) and DAC costs in 2040 and 2050, based on the conservative (upper limit) and base scenarios (lower limit) presented in this study. Literature-based industrial PSCC cost range for each

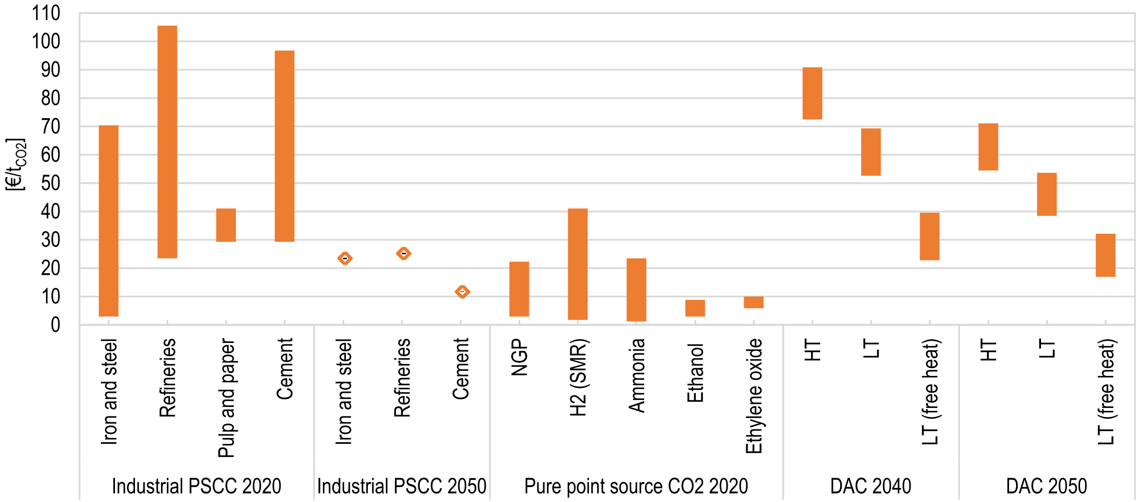

Fig. 10. Cost distribution range of PSCC for different industries (reproduced after Leeson et al. (2017)) and DAC. Abbreviations: natural gas production, *NGP*, steam methane reforming, *SMR*.

sector in 2020 represent different studies under different technologies, carbon capture efficiencies and cost assumptions. The costs in Leeson et al. (2017) have been converted from USD/$t_{CO2,avoided}$ to €/$t_{CO2,captured}$ by the fixed USD/€ conversion rate of 1.33 and the avoided CO_2 is set to 78% of captured CO_2 based on coal-powered PCSS described in Socolow et al. (2011). The minimum PSCC cost from iron and steel industry is related to usage of steel slag for carbonation with only 8% efficiency, which cannot fulfill the initial goal of PSCC. In addition, the sustainable pathway for iron and steel industry could be CO_2-free (Fischedick et al., 2014; Otto et al., 2017). PSCC cost range from refineries and cement in 2020 is about 30–100 €/t_{CO2}, while the cost range from pulp and paper is between 29 and 41 €/t_{CO2}, originated from reviewing two publications. The projected costs of industrial PSCC in 2050 have been calculated by Leeson et al. (2017) based on the mean values for the costs of best candidate PSCC technologies for each sector in 2020 and applied installed capacities by 2050. Under this scenario, PSCC costs from cement reach 12 €/t_{CO2}, however, still using fossil fuel, which may be priced very high for avoidable fossil fuel sources in 2050. In addition, high purity (>95%) sources of industrial CO_2 already have the PSCC potential with costs well below 20 €/t_{CO2}, as such CO_2 streams only require compression, and do not need expensive carbon capture devices. In case fossil fuels had been the input feedstock, one may have to pay in addition a CO_2 price for the final emissions, which could drastically increase the costs, compared to the sustainable DAC route. Natural gas processing (NGP), ammonia production, ethylene oxide production and steam-methane reforming for hydrogen production are some of the processes with fossil-based feedstock, which account for about 7% of industrial emissions Leeson et al. (2017). These are the so called low hanging fruits for PSCC, however, some of these processes could be substituted with a decarbonised technology in the future energy system, decreasing their CO_2 production potential. For instance, with further cost decline of RE and electrolysers, hydrogen could be produced by water electrolysis with oxygen as the only by-product, and further upgraded to higher valued products with additional RE-based power-to-chemicals processes.

As shown in Fig. 10, HT DAC, LT and free-heat LT DAC in 2040 start to be cost competitive with upper range, middle range and lower range PSCC costs in 2020, respectively. The further cost reduction of DAC systems in 2050 could make them even more cost competitive, depending on whether the projected PSCC costs in 2050 are achieved or not. However, the PSCC costs are not the full costs for captured CO_2, if the source had been fossil fuels. Because, not all the released CO_2 could be captured and also later emissions to the atmosphere have to be considered for almost all routes (e.g. synthetic fuels used in aviation or marine sectors) and the respective CO_2 price has to be taken into account as an additional cost. This is not the case for RE-based DAC. Therefore, DAC may be cost competitive earlier as indicated by Fig. 10.

Higher modularity and locational flexibility of DAC systems could make them even more cost competitive in the whole CCU or CCS chain. PSCC is limited to locations with high capacities of CO_2 stream, which could also limit the access to cheap energy for PSCC. A probable long distance to utilisation or storage sites could increase the transportation costs as well. On the other hand, DAC systems could be located in cost-optimal sites, taking into account access to low cost energy and utilisation or storage sites.

5.5. The cost share of CO_2 in power-to-gas

As mentioned in section 5.3., CO_2 from DAC is not only a product for storage, but also a feedstock for production of synthetic fuels and chemicals. In that case, costs of the final product is of higher importance than the LCOD, as long as the cost share of CO_2 is not significant or if the final product costs are in an attractive range regardless of LCOD.

As an example, the production costs of synthetic natural gas (SNG), integrated with CO_2 DAC in Morocco have been investigated. The electrolyser and methanation plants' specifications are taken from Ram et al. (2017). According to Fasihi et al. (2017a), the waste heat from water electrolyser and methanation units can supply all the LT heat demand of LT DAC systems in 2030, which would be the case for years afterwards, as the energy demand of the DAC system decreases. However, in 2020, the energy demand of LT DAC systems could exceed the available waste heat by 10%. For the sake of simplicity, this extra demand has not been taken into account and is assumed that the heat integration supplies all the required heat. To minimise the LCOD, LT DAC FLh should be fixed at 8000 FLh, as shown in Fig. 6. However, for consistency, in this section DAC FLh follows power-to-gas (PtG) FLh and the costs of SNG under different PtG FLh have been illustrated in Fig. 11. For such a configuration, the LCOG of a coupled DAC-PtG system with 4000 FLh would be 148, 84, 63 and 52 €/$MWh_{th,HHV}$ in 2020, 2030, 2040 and 2050, respectively. As can be seen, unlike DAC units, by increasing the FLh of PtG units, the levelised cost of gas (LCOG) increases. This is because PtG is relatively less capex intensive than DAC and the higher LCOE net for higher FLh has a bigger impact on the final LCOG. It should be noted that in this simplified system, DAC, electrolyser and methanation units have been coupled and no CO_2 or hydrogen storage has been included.

The cost share of LT DAC-based CO_2 (conservative scenario) of LCOG for 4000 FLh under respective LCOE is illustrated in Fig. 12. As can be seen, CO_2 cost share would be about 27% in 2020, which would drop to 21%, 19% and 19% in 2030, 2040 and 2050, respectively.

It is important to emphasise that a decoupled system with higher DAC FLh would have a significantly lower LCOD, LCOG and consequently lower CO_2 cost share. For example, a decoupled system with 8000 DAC FLh and 4000 PtG FLh would result in lower LCOD and LCOG of 133, 60, 40 and 32 €/t_{CO2} and 132, 76, 58 and 48 €/$MWh_{th,HHV}$, respectively. In addition, the absolute cost of CO_2 and its respective share would be even lower in the DAC base case scenario. Therefore, the costs of CO_2 DAC may not have a decisive

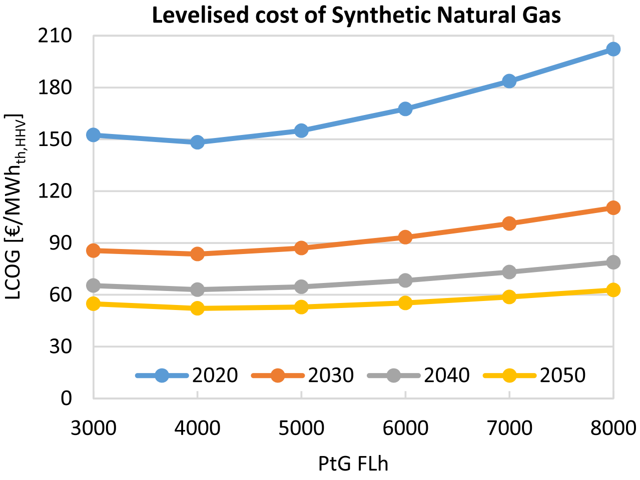

Fig. 11. The impact of PtG FLh on LCOG.

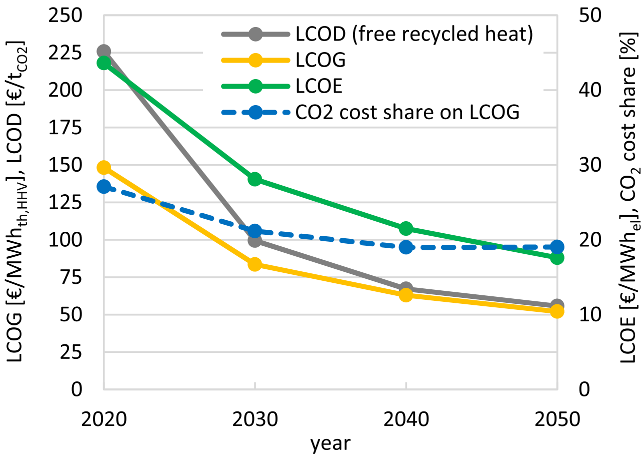

Fig. 12. CO_2 cost share of LCOG cost development for DAC and PtG with 4000 FLh.

impact on the introduction of synthetic natural gas to the market. This simplified model and its results do not represent the condition for all climates or synthetic products.

6. Conclusions

Large-scale CO_2 DAC systems are needed to meet the Paris Agreement targets by mid-21st century, even in a world with high levels of defossilisation and PSCC implementation. It is estimated that 3, 470, 4798 and 15 402 Mt_{CO2}/a DAC capacities are needed by 2020, 2030, 2040 and 2050, respectively. A literature review on DAC technologies is performed and the available technologies are categorised from an energy system perspective. High temperature aqueous solution-based direct air capture (HT DAC) and low temperature solid sorbent-based direct air capture (LT DAC) are the two main categories of commercially available technologies which are further analysed for the period 2020 to 2050, technically and economically. Although the energy demand of a LT DAC system is higher, for high FLh, its total energy demand could be met at about the same cost, as the major share of energy demand could be supplied by relatively cheaper low-grade heat supplied by heat pumps. In addition, although the capital expenditure of both technologies is at the same level, the LT DAC technology is the more favourable option today and in future, due to its potential for extensive cost reduction by utilisation of waste heat from other sources. Moreover, the LT DAC system shows a high modularity, and has no demand for external water.

The LCOD development in the decades to come, mainly depends on the learning curve of capital expenditures, its energy demand and the cost development of renewable electricity. In a conservative scenario with 10% learning rate of capex and the realisation of half the required DAC capacities at each time step, the capex of HT/LT DAC systems are calculated to be 815/730, 378/338, 265/237 and 222/199 €/t_{CO2}·a in 2020, 2030, 2040 and 2050, respectively. While the base case scenario has been defined as 100% implementation of the required capacities with 15% learning curve of capex, in line with the experience from comparable technologies. Under this scenario, the capex of HT/LT DAC systems would shrink to 815/730, 211/189, 119/106 and 89/79 €/t_{CO2}·a in 2020, 2030, 2040 and 2050, respectively. In addition, a 5/10% electricity demand reduction for HT/LT DAC and 14.3% low-grade heat demand reduction is foreseen at each 10-year time step.

As a case study, the CO_2 capture costs in Morocco, supplied by hybrid PV-Wind-battery plants and heat pumps have been investigated. The results show that, despite higher electricity costs, DAC systems with higher FLh would have lower LCOD. In the conservative scenario, the LCOD of HT/LT DAC systems with 8000 FLh are calculated to be 268/222, 133/105, 91/69 and 71/54 €/t_{CO2} in 2020, 2030, 2040 and 2050, respectively. While in the base case scenario, the costs would be reduced to 268/222, 111/84, 72/53 and 54/38 €/t_{CO2}, respectively. Based on the discussion in section 5.3., it can been concluded that such results are in line with results of major publications and companies' targets as of today and in the long term. However, such cost reductions could be expected only if the technology implementation starts in 2020 according to the defined scenarios. In addition, access to free waste heat could further decrease the LCOD of LT DAC by 40–57%, depending on the year and applied scenario. At such costs, DAC is competitive to PSCC with less restrictions on capacity and location. Whereas, fossil fuel based CO_2 may induce further costs than only the capturing costs, since later emissions to the atmosphere are most likely to be included, in particular for a net zero emissions system, so that the capturing costs may be the minor cost fraction for PSCC. Such freedom could further increase the competitiveness of DAC in projects associated with CO_2 storage or utilisation, by minimising the transportation costs.

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