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Master's Thesis

TECHNO-ECONOMIC ASSESSMENT OF ATMOSPHERIC CO_2 CAPTURE PLANTS

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ABSTRACT

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Climate change is attracting more and more attention. Despite already taken actions towards its mitigation, concentration of greenhouse gases (GHG) in the atmosphere is continuing to grow. Emerging innovative technologies, like capturing CO_2 from the ambient air, in other words, direct air capture (DAC) can help mankind to fight this crucial problem and keep global temperature rise well below 2 °C compared to preindustrial levels. DAC finally makes it possible to close the carbon cycle by capturing and further converting CO_2 from the atmosphere into synthetic fuels that can replace conventional liquid fuels widely used nowadays in the transportation sector. Currently, there are a few commissioned DAC pilot plants in the world. The purpose of this research is to gather available information about technologies capturing CO_2 from the atmosphere and precisely DAC plants, perform in-depth analysis of energy requirements and associated capital and operational expenses and deliver a detailed overview of up-to-date available technological solutions. The conducted research proves that it is technically possible and economically feasible to build DAC plants nowadays. Additionally, the scientific contribution of the research consists in holistic descriptions of key technical and estimated economic parameters of two final DAC plants' models that one can use for further investigation or as input for synthetic fuels production systems.

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BECCS	Bioenergy with Carbon Capture and Storage
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
Capex	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDRA	Carbon Dioxide Removal Assembly
CO_2	Carbon Dioxide
crf	Annuity Factor
DAC	Direct Air Capture
DI	Disruptive Innovations
FLh	Full Load hours
FT	Fischer-Tropsch
fuel	Fuel Costs
GHG	Greenhouse Gas
HT	High Temperature
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KOH	Potassium Hydroxide
kWhel	kilowatt hour electrical power
kWhth	kilowatt hour thermal power
LCOD	Levelised Cost of CO2 Direct Air Capture
LR	learning rate
LT	Low Temperature
MOF	Metal Organic Frameworks
N	Lifetime

Na_2CO_3	Sodium Carbonate
NaOH	Sodium Hydroxide
NASA	National Aeronautics and Space Administration
NG	Natural Gas
OPEX	Operating Expenditures
PR	progress ratio, defined as unity minus LR
PV	Photovoltaic
RE	Renewable Energy
RE-SNG	Renewable Synthetic Natural Gas
SNG	Synthetic Natural Gas
USD	United States Dollars
WACC	Weighted Average Cost of Capital
€	Euro

1. Introduction

This part of Master´s Thesis project examines the rationale of the research topic and includes such parts as research background, research scope and objectives, scope and limitations and introduces the overall structure of the study. The methodology is presented in a separate section.

1.1. Background

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 rapidly increased from 280 ppm in the preindustrial period (Pielke, 2009) to 403 in 2016 with an annual growth rate of 2 ppm/year (IEA, 2017). Paris Agreement, signed in December 2015, aims to mitigate the climate change and to keep temperature rise well below 2 °C in comparison to the preindustrial age by united efforts of all countries (UNFCCC, 2015). To achieve this goal, along with sharply cutting anthropogenic GHG emissions, actions will be needed for active CO_2 removal.

A range of options is available for CO_2 emissions removal. CO_2 emissions can be captured from point sources such as flue gases of conventional power plants or non-energetic sectors such as cement plants. However, this method has not yet been actively implemented in the world. In addition, 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. A large number of small emitters, such as in the transportation sector, which account for 50% global GHG emissions, are just impossible to neutralize by conventional CO_2 capture applications (Seipp et al., 2017). These facts lead to the undeniable necessity to find additional solutions that are capable of capturing CO_2 independent from the origin and location.

Another solution for climate mitigation is capturing CO_2 directly from the atmosphere. So far, plants have been doing it naturally to some extent. However, they cannot keep up with the increasing anthropogenic emissions. Afforestation, bioenergy with carbon capture and storage (BECCS) and enhanced weathering were introduced to capture CO_2 from ambient air (Williamson, 2016). However, their commercial attraction is limited. All of these measures associated with risks. BECCS and afforestation on the large-scale threaten biodiversity, water and food security because both are characterised by huge land requirements (Smith et.al., 2015). Enhanced weathering provokes rising pH values in rivers and changing the chemistry in oceans (Kohler et al., 2010).

CO_2 Direct Air Capture (DAC) is the other option for capturing CO_2 from ambient air. DAC represents the removal of CO_2 with the use of chemicals from the atmosphere, diluted gases and distributed sources of carbon (Broehm et al. 2015, Choi et al.;2011). DAC is a relatively new and innovative technology on early commercial stage, which in a long-term perspective, alongside with conventional technologies, can help humankind to control and mitigate climate change (Lackner, 2009; Sanz-Perez et al., 2016). One of the latest DAC technologies commissioned by Climeworks in 2017 is compact with zero water requirements (Climeworks, 2018).

The first application of capturing CO_2 from the ambient air was introduced in the 1930s (House et al., 2011). Back then, the need of the technology was not recognized and only later it found its application in life supports systems of manned closed systems such as space stations and submarines. The first systems dated back to 1965 were not regeneratable (Isoble et al., 2016). Modern space shuttles are all equipped with regeneratable Carbon Dioxide Removal Assembly (CDRA) that helps to maintain habitable environment for crewmembers (NASA, 2006). The experience and knowledge gained in the field of removing CO_2 form the ambient air could be transferred and used in many industrial processes and help to stabilize climate change (Satyapal et al., 2001).

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 may be needed, which could be energy and cost-intensive (Knoope et al., 2014; Aspelund and Jordal, 2007; Johnsen et al., 2011).

1.2. Research scope and objectives

Research background has shown that climate change mitigation is important issue that is not yet being fully taken under control. Hence, the aim of the current study to perform extensive techno-economic analysis of up-to-date technologies capturing CO_2 from diluted gases, such as ambient air, that has a potential to significantly contribute to the reduction of HGH in the atmosphere.

Therefore, the goal is to present a comprehensive overview of all available technologies and estimate the feasibility of direct air capturing plants. Accordingly, the first objective is to analyze mass balance, energy performance and efficiency of the plants, while the second one it to estimate capital and operational expenditures of the plants and evaluate the final price of ton CO_2 captured from ambient air.

The main research question (MRQ) of the study is "*It is feasible to build and operate direct air capture plant today and by 2050*?"

In order to get an extensive answer to this question two sub-questions were formulated:

RQ1: "*What are the existing technologies for CO_2 capture from the ambient air?*".

RQ2: "*What are the cost and efficiency of the technologies today and in future?*".

The answers to these questions imply combined quantitative and qualitative research methods based on secondary data gathering such as scientific publications and articles, conference publications, open access materials from companies, technology overviews. Narrative analysis alongside with summarizing, categorizing, structuring of data is used as main methods in the current study.

1.3. Limitations

Current Master´s Thesis has faced several limitations. One of the major limitation is associated with the maturity level of the analyzed technology. The amount of plants that have been commissioned is rather small. Additionally, the technologies utilized by companies are highly innovative and has a strict non- disclosure nature, hence, some of the technological aspects are kept under strict secret. Moreover, some results presented in scientific papers are based on experiments and laboratory testing which leads to the high possibility that operating parameters of big scale plants will differ from reported in the literature.

One can argue that results delivered upon secondary data is not reliable or does not cover all substantial areas of the proposed research. However, in-depth analysis of all available data in open access was conducted to ensure that the study comprises and accumulates all necessary information within the scope of analysis.

Another considerable limitation is related to the assumption used for data estimation presented in the literature. Some of the papers are dated back to the beginning of 2000s when not even a single plant was commissioned, so that presented results are in most cases hypothetical and based on theoretical assumptions and benchmarking to similar in some extent technologies from different industries. Furthermore, the background and methodology of assumptions used in the literature are not always clear. Thus, during the research, these issues were kept in mind. In order to avoid misleading result, the final models of each technology are based on the aligned and recalculated parameters from different sources.

1.4. Structure of the study

In this Master´s Thesis a techno-economic assessment of main CO_2 direct air capture technologies, from an energy system point of view, has been carried out. The remaining sections of the project are organized as follows.

Section 2 describes the methodology and process of data gathering. The aim of the chapter is to familiarize the reader with the adopted methodology in details, introduce the approach of data collection and explain the approaches used for recalculation and aligning technical and economic parameters which are a big value for current research.

In section 3 literature review is presented. Scientific papers in the field of CO_2 capturing from the ambient air are discussed in a chronological way so that the reader can easily follow the evaluation path of technology and get a basic understanding of the systems that are described in detail in the following Result section. In addition, literature review of disruptive innovations and the ways of managing it were carried out to substantiate innovative nature of examined technology.

Results are presented in the section 4 where all up-to-date technologies are categorized based on the working principle, described in much details, including both technical and economic parameters. The summary of the findings allowed to present the final models for each of the approaches with input and output figures, in addition, long-term estimations and sensitivity analyses for the most valuable parameters are carried out.

In section 5 the main contributions of the study are highlighted and possible further research directions are discussed. The crucial parameters of CO_2 capture plants are addressed and the role of the technology to the climate change mitigation alongside with other approaches is argued.

Section 6 draws the conclusions based on performed evaluations of the innovative technology and indicates directions for further research.

The complete list of the materials such as academic literature, theoretical materials, conference publications and materials from companies, which are in open access, is provided in the references section.

2. Methodology

An extensive review has been performed. Literature published from early 2000s to present time are included in the research. Research were conducted in the following manner: Data gathering via such platforms as Science Direct, Scopus, Google Scholar, ResearchGate, official websites of companies and international governmental 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. Sensitivity analysis of the most valuable variables is made. DAC was compared to the most competing technology, point source CCS.

Cost numbers from different years presented in USD were converted to euros by using a fix exchange ratio of 1.33 USD/€, the long-term average exchange rate. Values in other currencies were converted to euros based on exchange rates of the corresponding year.

The equations (1)-(4) below have been used to calculate the levelised cost of CO_2 DAC (LCOD), the levelised cost of electricity (LCOE), the levelised cost of heat (LCOH) and the subsequent value chain. 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.

$$LCOD = \frac{Capex_{DAC} \cdot \text{crf} + Opex_{fix}}{Output_{CO_2}} + Opex_{var} + \frac{DAC_{el.input}}{LCOE} + \frac{DAC_{heat.input}}{LCOH} \quad \text{Eq. (1)}$$

$$LCOE = \frac{Capex \cdot \text{crf} + Opex_{fix}}{FLh} + Opex_{var} + \frac{\text{fuel}}{\eta} \quad \text{Eq. (2)}$$

$$LCOH = \frac{Capex \cdot \text{crf} + Opex_{fix}}{FLh} + Opex_{var} + \frac{\text{fuel}}{\eta} + \frac{LCOE}{COP} \quad \text{Eq. (3)}$$

$$\text{crf} = \frac{\text{WACC} \cdot (1 + \text{WACC})^{\text{N}}}{(1 + \text{WACC})^{\text{N}} - 1} \quad \text{Eq. (4)}$$

Maturity level of the technologies is also taken into consideration. The focus of 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 is identified. As a result, up to date data is used for long-term estimation of key parameters for time periods 2020:10:2050.

The research also includes short techno-economic analysis of point source CCS as it is believed to be the main competing technology to DAC. The analyses of point source CCS are presented in the way of overview including key performance parameters and cost analysis. Once the cost and energy demand per ton of captured CO_2 is calculated it is possible to compare two different technologies.

Overall methodology for the research is as following:

1. Reviewing of available data and making a database
    - focus on scientific publications in the field of DAC
    - analysis of company activities and press releases
    - establishing target parameters and merging all finding in one database

2. Recalculation and aligning of the findings
    - conversion of the currencies
    - recalculation and putting data on comparable scale (energy requirement and capital expenditures per ton of CO_2 capturing capacity)
3. Comparison of DAC to the most competing point source CCS technologies
    - conducting a brief techno-economic analysis of point source CCS
    - reviewing the options for CO_2 compression; storage and transportation

3. Literature review

This chapter presents important theories and models related to the topic of this study. First, innovations are discussed, after which specific attention is paid to disruptive innovations, as DAC is said to be potentially disruptive. Finally, the last sub chapter increases the understanding of how disruptive innovations can be managed.

3.1. Innovation

Innovation is a commonly used word in business and academic life. It is ‘’generally understood as the successful introduction of a new thing or method (Luecke and Katz, 2003). Luecke and Katz (2003) add that ‘’innovation is the embodiment, combination, or synthesis of knowledge in original, relevant, valued new products, processes or services’’. Other definitions of innovation underline the novelty aspect while also linking innovation to business or commercial value. For instance, Narvekar and Jain (2006) see an innovation as an element of novelty which adds commercial value, while Assink (2006) calls it ‘’the process of successfully creating something new that has significant value to the relevant unit of adoption’’.

Aforementioned definitions of innovation still leave space for interpretation. New things, methods, or novelties can entail a wide variety of aspects. Hence, in order to be more specific one can distinguish between technical, administrative, process or product innovations (Van de Ven, 1986). The Organisation for Economic Cooperation and Development (OECD, 2010) points out that technology is strongly combined to innovation, implying that ‘’a new thing or method’’ or ‘’an element of novelty’’ not incidentally relates to technology.

Typically, innovations are categorized as either incremental or radical, whereas incremental innovation refers to evolutionary innovations and radical innovation to something completely new and revolutionary (Christensen, 2003). Similarly, innovations can be seen as either incremental or breakthrough (Tushman and Anderson, 1986). Satell (2017) provides a more comprehensive overview of innovation types by distinguishing between four different types, including both disruptive and breakthrough, which thus are not exactly the same. The four types of innovation are categorized based on how well the problem is defined and on how well the domain is defined, resulting in basic research, breakthrough innovation, disruptive innovation and sustaining innovation, as depicted in Figure 1. One of the purposes of the matrix is to provide managers of innovation with guidance on how to deal with each kind of innovation, which explains the possible actions mentioned in the figure. In despite of this original purpose, the model shows different kind of innovations.

How well is the problem described?			
	Well	**Breakthrough innovations** Mavericks Stunk Works Open innovation/prizes	**Sustaining innovation** Roadmaping R&D labs Design thinking Acquisitions
	Not well	**Basic research** Research divisions Academic partnership Journals and conferences	**Disruptive innovations** VC model Innovation labs 15%720% rule Lean launchpad
		Not well	Well

How well is the domain defined?

Fig. 1. Four types of innovation (picture from Satell, 2017)

Basic research derives from the idea that ‘’innovations never arrive fully formed’’ (Satell, 2017). Hence, basic research and a critical approach could ultimately lead to something totally new. Breakthrough innovations refer to ‘’unique or state-of-the-art technological advances in a product category that significantly alter the consumption patterns of a market’’ (Wind and Mahajan, 1997). Sustaining innovations ‘’make good products better in the eyes of an incumbent’s existing customer’’ (Christensen, Raynor and McDonald, 2015).

As the technology upon which this paper is based is generally considered as disruptive, disruptive innovations deserve special attention. Therefore, the next subchapter elaborates on this phenomenon.

3.2. Disruptive innovation

Disruptive innovation (DI) has received abundant attention in academic literature from very different points of view. One of the earliest papers dedicated to the theory of DI dates back to 1985 (Abernathy and Clark, 1985). More recently, extensive explanation of the theory and fundamental principles of DI were firstly introduced to the audience by Christensen (1997), when he described a DI as a technology that differentiates itself from mainstream technologies though creating new value chain. In early stage all DI based technologies are able to satisfy only narrow market segments with particular not standard values. Advanced value is a driver for further development of DI which in the end leads to creating the whole new market and by that time the technology become widely available to the broader audience. Further, Christensen (1997) agrees with previous authors that DI is most appealing to customers whose needs are not yet fulfilled.

Kostoff et al. (2004) have characterized DI as a technology that exponentially increases the value received by the customers, can facilitate development and growth of existing industries and potentially create new markets. Moreover, he emphasized the importance of identifying DI in an early stage in order to facilitate the development and implementation. The importance to identify DI is furthermore underlined by Danneels (2004) even though his main research focus was on distinguishing the market or niche where the DI will most likely appear in short terms.

Even though many authors theoretically described DI in-depth, in practical life it remains difficult to distinguish DI among other types of innovations. Yu and Hang (2011) have stated that challenging nature and importance of DI in technology is rather underestimated by industrial companies. The authors spotted the research gap between specific strategies and creation of technological DI. Intensive study was conducted to conclude that one can intentionally create technologies to become DI in research and development laboratories if such strategies as miniaturization, simplification, augmentation and exploitation for another application are implemented by management group. Moreover, it can be used in two ways, as a direct guidance for action or as a tool for benchmarking with competitors. Implementation of these strategies will help the companies to become disruptive and achieve high performance because purposely created technologies based on DI are believed to be the key advantage in high developing and constantly changing world. Misunderstanding of the reasons lying behind disruption based technology led to confusion and misusing of the term, which was also investigated by Christensen et al. (2015). He has explained the specific characteristics of DI based on examples from real life. Based on his theory DI are continuous and represents a process of evaluation of the technology rather than emerging point of the product and often appears after small scale laboratory experiments.

3.3. Managing disruptive innovation

Nagy et al. (2016) raise essential questions addressing managing DI on the organizational level. This predictive approach not only can help to better understand the strategy of DI that brought the technology to wide success. In addition, it can help existing companies to adopt the changing or new created market.

The relationship between DI and the process of technology inception was addressed by Li et al. (2017). This question is in high interest of academic world but still requires deeper investigation. The research was based on literature review and understanding fundamental concepts of emerging and disruptive technologies. It was highlighted that even though there are broad theories and abundant scientific publication explaining in detail both of the concepts it is still can be applied inaccurately due to interchangeable misleading nature based on common features such as novelty and uncertainty.

Mahto et al. (2017) in his study presented DI as a measure that helps markets to evolve, to overcome scarcity and to achieve abundance. However, it is not as easy as it might look like as DI in the early stage of development are associated with major barriers such as poor quality and high prices of the innovative product. Nevertheless, the authors suggest that by encouraging and creating appropriate environment for development of DI.

History of DI development has shown that decent amount of DI has ended up in a failure. That was the reason for Vecchiato (2017) to investigate why companies tend to fail to find appropriate markets when introducing DI. Based on examples of companies operating in mobile industry he has shown that mistakes of managerial group in terms of finding appropriate marketplace for DI can be fatal for the new technology.

Latest works dedicated to DI have investigated if it is possible to fight GHG emissions and manage climate change by utilizing DI. Wilson (2018) has introduced DI as an undeniable contributor to the future negative emission world. He summaries characteristics of DI and, precisely disruptive low-carbon innovation, providing criteria based on which one can help identify low carbon disruptive technologies in the mainstream markets. In his work he also presented the list of potential disruptive low-carbon innovation in the field of mobility. The author strongly believes that DI has a huge potential to promote worldwide energy transition towards low emission energy system and consequently to highly desired climate mitigation.

Tyfield, (2018) has also analyzed low carbon DI on the example of China where low-carbon transition is an urgent global priority due to high growing rates of GHG emission. In particular, he analyzed low carbon DI from the perspective of complex power/knowledge systems. The author emphasized emerging opportunities of collaborations with technical enterprises and highly possible political barriers that are common in capitalist countries.

Literature review allows to conclude that DI is not always successful and moreover have huge amount of challengesin identifications and obstacles while competing with mature business models and often end up in failure. In most of cases emerging DI is expensive and have low quality, people are not willing to widely utilize it until it is improved. When the consumers are satisfied with both economic and technical part of the innovation they eagerly adopt it. This is the way disruptive innovations bring the prices down on the market.

DAC plants are also can be seen as an example of emerging DI. Currently it is on the stage where technology is still expensive, however the investigation has proven that price is going down whereas the technology is improving. Nowadays the plants are able to fulfill the needs of synthetic fuels productions which represent a small market niche. Further investigation of the topic has the aim to prove technical and economic feasibility of DAC plants implementation, which will not only significantly contribute to climate change mitigation but also create a new market where CO_2 will be a raw material for synthetic fuels production.

3.4. Available DAC technologies

Due to ultra dilute concentration of CO_2 in the atmosphere chemical sorbents with strong binding characteristics became widely discussed in the literature. Aqueous solution of strong bases is used in conventional point source CCS technologies and many researchers investigated its applicability to DAC. Keith et al. (2005) analysed physical and economic limits of BECCS and aqueous solution-based DAC and concluded the second option to be a feasible near-term option. However, the 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 industrial scale. In addition, he has benchmarked the system with two previous studies on thermodynamic level. Stolaroff et al. (2008) discussed optimization 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 conventional CO_2 capture methods with system based on the work of Baciocchi et al. (2006). Zeman (2014) investigated the APS report and proposed final cost reduction by using CO_2 free energy and minimizing plastic packing materials of the contactor part. Canbing et al. (2015) suggested utilizing the system proposed in early work of Zeman by using wind power and battery as the energy input. All 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 performing 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 causticization 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.

Another major group of scientific publications is focused on systems based on solid sorbents. Temperature swing adsorption (TSA) is the main DAC method in this category, which has been described by Kulkarni and Sholl (2012) and Sinha et al. (2017). Unlike aqueous solution-based system, the regeneration happens at relatively lower temperatures (100 °C), which is cheaper to produce or available as the byproduct of some industrial plants. Derevschikov et al. (2013) suggested using composite solid sorbent for DAC and using renewable energy (RE) to produce methane on the site. Lackner (2009) examined the possibility of CO_2 capture by moisture swing adsorption 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.

Rather 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 rather novel approach based on crystallization of CO_2 molecules with a guanidine sorbent with low temperature requirements on the level of 80-120°C. Even though preliminary results of this approaches are promising, a deeper investigation is needed.

In order to estimate potential cost of DAC, Simon et al. (2011) conducted a research where a generic DAC technology was examined only based on such assumptions as energy inputs, land and water use. The study claims that it is possible to capture CO_2 for 225 €/t_{CO2}, however points out that substantial research into the kinetics and thermodynamics of capture chemistry is needed to prove it.

In addition, several papers have presented an overview of available technologies. Goeppert et al. (2012) discussing capturing CO_2 from point sources, raised the question why DAC is needed, summarised and discussed on technical level all available technologies and listed active companies. It was concluded that DAC is theoretically feasible, but technically challenging, because it requires 2 to 4 times as much energy as CO_2 capturing from point sources, however, nevertheless indispensable for stabilising climate change. Broehm et al. (2015) divided all available technologies into three groups (aqueous solution of strong bases, amine adsorption 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 one based on 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.

There are several companies who are active in the DAC field. Climeworks, was founded by Gebald and Wurzbacher in 2007 in Zurich, Switzerland (Climeworks, 2018a). The company utilises an amine-based approach that release CO_2 at a temperature around 100 °C. The company in a partnership with Audi launched in 2014 a pilot plant based in Dresden-Reick that captures CO_2 from air and converts it into synthetic diesel afterward. In 2017 the company has commissioned another commercial scale DAC plant which provides CO_2 for nearby located greenhouse, there is not much information about its current performance, however in the long-term the company is targeting production costs to be around 75 €/t_{CO2} (Climeworks, 2018b). Another leading company, Carbon Engineering, was established by Keith in 2009 in Canada, Squamish, (Carbon Engineering, 2018a). The approach used by the company is based on a strong aqueous solution of KOH and $Ca(OH)_2$ combination and operates at high temperatures of about 900 °C. The demonstration plant was introduced in October 2015 with a capacity of 1 t_{CO2}/day and the current goal of the company is to establish a broad commercial deployment of synthetic fuels production based on DAC (Carbon Engineering, 2018b). Another company which is developing advanced technology is Global Thermostat that was formed in 2010 by Eisenberger in New York, USA (Global Thermostat, 2018). The company has announced ambitious plans to deliver CO_2 at a cost of 11-38 €/t_{CO2}, however information about real up-to-date performance of the company and its technology are rather limited (Broehm et al., 2015). Antecy is another European DAC company that was founded in 2010 by O´Connor in Hoevelaken, Netherlands (Antecy, 2018). Its technology operates in a moderate temperature requirement of 80-100 °C but regeneration is happening only with pressure reduction (Roestenberg, 2015). All companies are presented in visualized way in *Appendix 1*.

4. Results

4.1. Description of technologies

Basic air capture models consist of contacting area, sorbent and regeneration module. Contacting area exposes sorbent to ambient air and facilitates airflow through the model, increasing the absorption of CO_2 molecules. Sorbent must be easy to handle, resistant to contamination and should not vanish during the process, as its properties determines the whole process. The main DAC systems have been described below.

4.1.1. High temperature aqueous solution

Aqueous solution consists of two cycles that can happen simultaneously. The basic example of the approach is illustrated in Figure 2. In the first cycle, known as absorption, ambient air is brought into contact with sprayed sodium hydroxide (NaOH) as the aqueous solution 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 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 2, according to the 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 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).

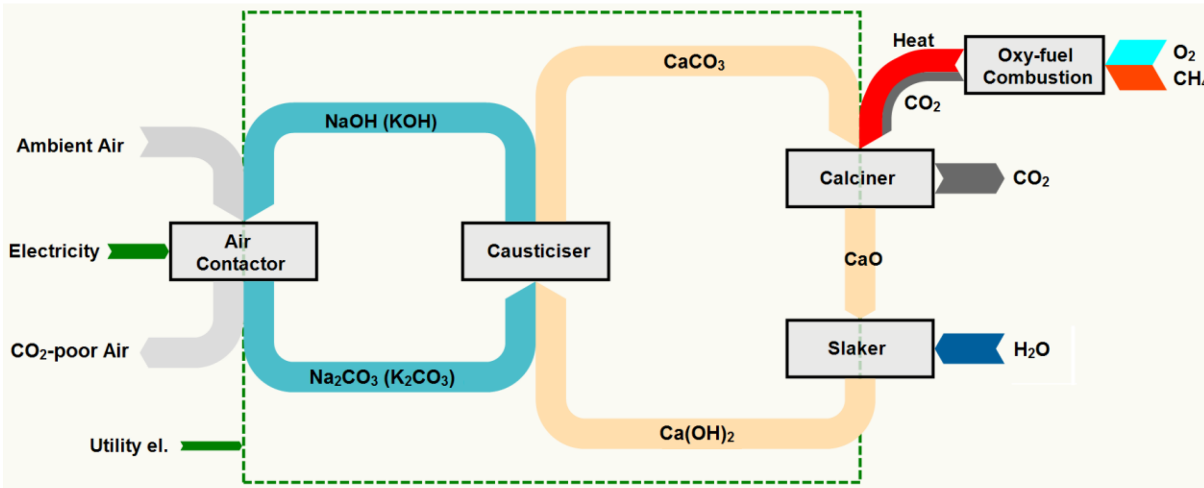


Fig. 2. Example of CO_2 direct air capture based on aqueous solution of sodium hydroxide (NaOH) and potassium hydroxide (KOH) as an alternative.

contactor	$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$	Eq. (5)
causticiser	$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$	Eq. (6)
calciner	$CaCO_3 + heat \rightarrow CaO + CO_2$	Eq. (7)
slaker	$CaO + H_2O \rightarrow Ca(OH)_2$	Eq. (8)

Besides heat, the system also needs electrical power for pumping the air through the contactor, spraying the aqueous and moving the solutions from one unit to another. In the literature, electrical power is presented in the range of 440-764 kWh_{el} per ton CO_2. This also includes the energy demand for CO_2 compression, to the mentioned pressures in Table 1, prior to transport or storage.

As can be seen in Table 1, in earlier literature, natural gas (NG) has been mainly suggested for the supply of the high-grade heat demand. However, this would not be a sustainable solution. Providing 2000 kWh_{th} high-grade heat by oxy-fuel combustion of NG with 90% efficiency for capturing 1 ton of atmospheric CO_2, would release 0.44 ton of direct NG-based CO_2 emission, not even considering its life cycle emissions. One of Carbon Engineering (2018c) DAC technologies fully powered by NG 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 the 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 by 2030 electrolyser technology (Fasihi et al., 2017). This is a huge increase in the primary energy demand and the production cost due the high costs of SNG production. Thus, a fully sustainable and affordable system should be fully electrified, which has been discussed in relatively newer studies. Carbon Engineering (2018c) has already developed a fully electrified system phase with total 1500 kWh_{el} demand for both power and heating demand, in order to capture 1 ton of atmospheric CO_2. Thus, the fully electrified Carbon Engineering technology has been chosen as the final model for aqueous solution technology in our study. The outlet pressure of CO_2 in the Carbon Engineering technology is set to 150 bar. However, in our study, to have a common ground for comparison between different technologies, the CO_2 compression step is not needed. According to Socolow et al. (2011), CO_2 compression from ambient air to 100 bar would need 420 MJ_{el}/t_{CO2} (117 kWh_{el}/t_{CO2}). The maximum pressure in the Carbon Engineering process at 150 bar is higher than in the APS model discussed by Socolow et al. (2011), which could lead to higher electricity demand by compressors. Nevertheless, in the absence of information about the electricity consumption of CO_2 compression in the Carbon Engineering system, the total electricity demand has been lowered by 120 kWh_{el}/t_{CO2} in 2020 and has been set to 1380 kWh_{el}/t_{CO2}. In this technology, NaOH has been also substituted by potassium hydroxide (KOH), which is non-toxic and has no hazardous impact on the environment (Carbon Engineering, 2018c).

Table 1. HT aqueous solution DAC specifications

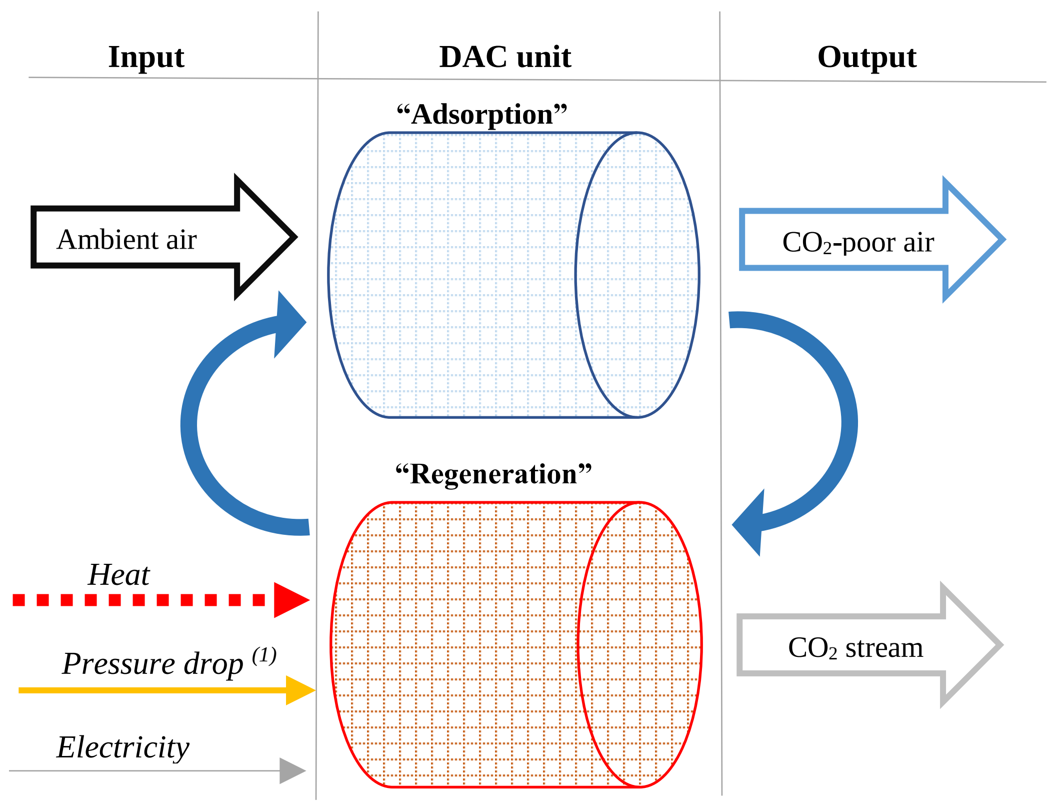
type	1st cycle sorbent	2nd cycle sorbent	CO_2 concent.	maximum temp. demand (°C)		energy demand			outlet pressure	CO_2 purity	reference
			ppm	absorption	desorption	kWh_{el}/t	kWh_{th}/t	via	bar	%	
2-cycle	NaOH	$Ca(OH)_2$	-	ambient	900	-	-	NG	100		Keith, et al. (2005)
			500			440	1678	NG	58		Baciocchi et al. (2006)
			380			764	1420	NG/coal	-		Zeman (2007)
			-	-		1199 -24612 [1]		-	-		Stolaroff et al. (2008)
			500	-		494	2250	NG	100		Socolow et al. (2011)
				ambient		2790		wind + battery [2]			Li et al. (2015) [3]
	KOH		-	-		10 GJ fuel [4]		NG	150		Carbon Engineering (2018c)
						1500		el.			
	NaOH	$Na_2O.3TiO_2$		ambient	850		(5)		15 [6]	pure	Mahmoudkhani and Keith (2009)
1-cycle	-	CaO	500	365-400	800-875			CSP		99.9	Nikulshina et al. (2009)
2-cycle	**KOH**	**$Ca(OH)_2$**	**500**	**ambient**	**900**	**1380**		**el**	**>ambient**		**Final Model (this study)**

(1) based on different contactors
(2) based on Zeman (2007), without heat recycling
(3) the heat generation method unclear
(4) heat and electricity generation and their ratio unclear
(5) 50% less high-grade heat than conventional causticization
(6) CO_2 separation at 15 bar and then compression to 100 bar

4.1.2. Low temperature solid solution

Technologies in this group have only one solid system unit. Adsorption and regeneration are taking place at the same unit consistently one after another. In general, at the first step the system is open, ambient air goes through naturally or with the help of fans. At the room temperature, CO_2 chemically binds to the filter and CO_2 depleted air leaves the system. This step is finished when sorbent is fully saturated with CO_2. In the next step, the fans are switched off, the inlet valve is closed and the system pressure is decreased by vacuum. 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 further use. 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 hereinafter.

Amines are known for their selective ability to absorb CO_2 molecules from diluted concentrations. Climeworks proposed filter made of special cellulose fiber that is supported by amines in a solid form, which binds CO_2 molecules alongside with air moisture so that 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 1500-2000 kWh_{th}/t_{CO2}, which can supplied by low-grade or waste heat, as demonstrated in the recent respective pilot plant (Climeworks, 2018b). In addition, it needs 200-300 kWh_{el}/t_{CO2} for the fans and control systems. Output of the reaction is 99.9% pure stream of CO_2 that can be collected. Climeworks claimed that the target cost for large scale plants is less than 75 €/t_{CO2} (Climeworks, 2018b), however no electricity price or financial assumption has been provided. Figure 2 shows the basic example of the system.



(1) Optionally, depends on the system

Fig. 3. Example of a LT solution DAC system

The system proposed by Kulkarni et al. (2012) is different in the way that desorption of the sorbent silica (TRI-PE-MCM-41) is occurring by introduction of steam at the temperature of 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). System has the same cycles, but due to high possibility that MOFs can be oxidized at higher temperatures, vacuum is necessary before heating. Cooling is achieved by water evaporation from the surface. He concludes that among two MOFs options the one based on magnesium (Mg) is more favorable due to lower electricity and heat demand which is 997 kWh/t_{CO2} (Sinha, 2017).

Roestenberg (2015) has presented technology utilized by Antecy, a company that actively works in the DAC field. CO_2 is absorbed 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 100°C by low-grade heat. Derevschikov et al. (2013) introduced a DAC system based on K_2CO_3/Y_2O_3 sorbent powered by wind energy that regenerated at the temperature of 150-250 °C. The sorbent is rather sensitive to height temperatures and can be easily destroyed. Table 2 summarizes main technical characteristics gathered from the literature by the sources.

Table 2. Solid one-cycle solution technical specifications

sorbent	CO_2 con.	maximum temp. demand (°C)		desorption pressure	energy demand			cooling		CO_2 purity	reference.
	ppm	adsorption	desorption	bar	kWh_{el}/t	kWh_{th}/t	via	by	°C	%	
amine-based	400	ambient	100	0.2	200-300	1500-2000	waste heat	air/water	15	99.9	Climeworks (2018b); Vogel (2017)
TRI-PE-MCM-41			110	1.4	218	1656	steam			88	Kulkarni and Sholl (2012)
MOF (Cr)			135-480	1	1420		HT steam	water evaporation	pressure reduction	-	Sinha et al.(2017)
MOF (MG)					997						
K_2CO_3/Y_2O_3			150-250		-	-	el. heater	-	-	-	Derevschikov et al. (2013)
K_2CO_3	-		100	-	-	-	waste heat	airflow	ambient	-	Roestenberg (2015); Antecy (2018)
	400	**ambient**	**100**		**250**	**1750**	**waste heat**				**Final Model (this study)**

4.1.3. Other technologies

In addition to the described major models, new approaches have been suggested in literature. As these technologies have not been developed on a pilot scale, they have not been further discussed in this paper. Eisaman et al. (2009) suggested electrochemical CO_2 capture and modified-fuel-cell approaches at ambient temperature. However, no cost assumptions have been presented.

Ion-exchange resin also captures CO_2 by one-cycle system. Lackner (2009) and Goldberg et al. (2013) have investigated identical techniques. Thin resin sheets are exposed to ambient air to facilitate free flow of the air through the material. When loading is finished the sheets is moved to closed system. Inside the system, air is removed and moisture is added. 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 drying process. Lackner (2009) claims that the system with natural airflow would only require electrical energy in amount of 316 kWh_{el}/t_{CO2}, including compression for liquefaction, but using fan will add an additional 10 kWh_{el}/t_{CO2}. The system utilises the 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 will turn to a pressurized 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. Some non-amine sorbents are also based on one-cycle systems.

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 the pressure of 100 bar with the final production cost of about 14 €/t_{CO2}. If this approach makes its way to the 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, the 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 crystallization approach could offer the prospect for low-cost DAC technologies, however, no financial data has been provided.

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

Table 3. Technical specifications for other technologies

sorbent	CO_2 con.	maximum temp. demand (°C)		desorption pressure	energy demand			cooling		CO_2 purity	reference
	ppm	Adsorp.	Desorp.	bar	kWh_{el}/t	kWh_{th}/t	via	by	°C	%	
ion-exchange resin	400	ambient, dried resin	by moisturising	-	316	-	self-heating	drying	45	-	Lackner (2009)
					423-631	-	wind power				Goldberg et al. (2013)
K_2CO_3 [1]		-	25	10-100	2209	-	-	-	-	-	Eisamam et al. (2009)
Na_2CO3 & PyBIG		-	80-120	-	-	-	-	-	-	-	Seipp et al. (2017)
Nanofactory-based [2]			-	-	333	-	solar power	-	-	100	Freitas (2015)

(1) electrodialysis-based CO_2 capture system
(2) molecular filters

4.2. Economics of CO_2 DAC

Most articles are focused on technical parameters and only a few of them 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 reviewed in this study was 376 €/t_{CO2} by Keith et al. (2005), however plant's cost or energy demand are not presented. 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 equipment investment cost, they introduce an optimistic and realistic scenario, associated with the installation cost factor. The optimistic scenario is based on the installation multiplying factor of 4.5, used in point source CCS. Considering the novelty of the DAC technology, a multiplying factor of 6 has been used for the installation cost of the system in a realistic scenario. This has increased the total reported cost 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 cost could be lowered by 2.4% and the annual Opex could be reduced from 4% to 3%.

Taking into account the possible optimisations proposed by Mazzotti et al. (2013) and Zeman (2014), the installation Capex of the final model in this study for 2020 has been set to the optimistic Capex level from Socolow et al. (2011). This also implies 9 additional years for advancements of the technology and experience in the field to reduce the costs to that level. In addition, as was mentioned in *section 4.1.1.*, to have a common ground for comparison with LT solid sorbent DAC technology, the extra compressors to deliver high pressure CO_2 have been avoided in this study, which could also help to reduce the capital costs. On the other hand, the CO_2 concentration in studies related to HT aqueous solution technologies is set to 500 ppm, while studies on LT solid sorbent DAC technologies are usually based on 400 ppm atmospheric CO_2 concentration. Assuming a 400 ppm CO_2 concentration as the common ground for comparison between LT and HT technologies could increase the cost of air contactor, as the most expensive part, in the HT aqueous solution technologie. Not knowing the exact relation between CO_2 concentration and the air contactor cost, this factor has not been included in this study. Moreover, although the capital cost of the Socolow et al. (2011) model has been taken into account, the energy model is based on the fully electrified system of Carbon Engineering (2018) with a different heating system and air contacting solution (KOH), which could also have an unknown impact on the final cost. The annual Opex has been set to 3% based on Zeman (2014). Although Nemet and Brandt (2011) considers a lifetime of 50 years, a lifetime of 30 years has been chosen according to Simon et al. (2011).

The economic data about LT systems based on solid sorbents is more limited. Although Climeworks is the forerunner of LT swing solid sorbent DAC technology, ANTECY's Capex estimation of 730 €/t_{CO2}·a is the only valid public data found. Even though both technologies are from the same main category, the sorbents and the regeneration processes are slightly different. The desorption in ANTECY's model can happen at a slightly lower temperature of 80-100 °C, due to the moisture-aided process. Although ANTECY claims to benefit from both low-cost material and low energy demand from other DAC technologies (ANTECY, 2018), no future information about its energy demand has been provided. Thus, Climeworks' energy demand has been selected as the energy demand for the LT DAC technology in this study. Despite of lack of information about the lifetime and operational cost, a typical 30 years of lifetime (comparable to HT DAC's lifetime) and 4% annual Opex have been assumed for the final model of this study in 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.

In contrary, House et al. (2011) in a skeptical approach, investigated in an empirical analysis the energetic and capital costs of existing DAC systems 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 the ambient air, the work requirement and, to a larger scale, the capital cost of CO_2 DAC would be more than of those proposed in the literature. In addition, carbon-free electricity with a cost of 75-150 €/MWh in a foreseeable future has 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, the fully electrified technology of Carbon Engineering is already available on a commercial scale with a total power consumption of 1500 kWh_{el}/t_{CO2}. Such differences in capital cost are also probable. In addition, with the ongoing sharp decline in the cost of renewable electricity, the assumed LCOE is too high as well.

The cost numbers from literature are not comparable, due to lack of the transparency of technology descriptions, different output conditions (e.g. pressure) 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 20 €/MWh_{el}, low-temperature heat of 8 €/MWh_{th} (<100 °C), high-temperature heat cost of 50 €/MWh_{th} (900 °C) and FLh of 8000 h. In case of lack of data, a lifetime of 30 years and an Opex of 4% of Capex have been assumed. The recalculated costs are presented in Table 4. The cost recalculation was only possible for the systems of Socolow et al. (2011) and Lackner (2009), as the crucial data such as input energy or capex is missing from other models' specifications. According to the results, it can be seen that the final costs reported by Socolow et al. (2011) are recalculated to 358-432 €/t_{CO2}, representing 39-49 €/t_{CO2} lower costs in comparison to the original report. In the contrary, the cost of Lackner´s system is lowered from 144 €/t_{CO2} to 90 €/t_{CO2}. The difference of 54 €/t_{CO2} could be possibly related to a higher rate of Opex for the first prototype, or cost of electricity.

Table 4. Economics of DAC as reported and recalculated

technology	Capacity	Capex	Opex	Lifetime	el. Demand	el. Price	Heat Demand	Indicated time of cost	Cost reported	Cost recalculated	Type of source [8]	reference
	t_{CO2}/a	€/t_{CO2}·a	%	Years	kWh_{el}/t	€/MWh_{el}	kWh_{th}/t	Year	€/t_{CO2}			
aqueous solution (HT [1])						-		2005	376		O	Keith et al. (2005)
	1 000 000	-	-		-	60	-		258	-	O	Holmes and Keith (2012)
	1 000 000	1583 [2]	4 [4]	20	494	53	2250	2011	309	355	O	Socolow et al. (2011)
		2086 [3]							395	429		
	1 000 000					53	1840	2013	300		O	Mazzotti et al. (2013)
									298			
									283			
	1 000 000	**1583**	**3**	**30**	**1380**		**-**	**2020**	**-**			**final model (this study)**
solid sorbent (LT [5])	360 000	730	-	-	-	-	-	?		-	O	Roestenberg (2015) (ANTECY)
	300	-	-	-	200-300	-	1500-2000	2014	-	-	O	Climeworks (2018b)
	-	-	-	-	-	-	-	long-term [7]	75	-		
		730	**4**	**20**	**250**		**1750**	**2020**				**final model (this study)**
solid sorbent (moisture swing)	365	421		10	306	38	-	2009	144	62	O	Lackner (2009)
	-	41			N.A.	N.A.		long-term	23			
generic	400	900	2.5	30	125	-	-	2011	220 [6]	-	R	Simon et al. (2011)
	-	-	-	-	3156	75-150	-	2011	750	-	R	House et al. (2011)
								2050	225			
	500 000	330	4	50	-	-	-	long-term	45	-	R	Nemet and Brandt (2011)
	-	-	-	-	-	-	-	Long-term	30 [9] 71 105		R	Broehm et al. (2015)

(1) 900 °C
(2) optimistic
(3) pessimistic
(4) Additional 2.88 €/t_{CO2} as Opex variable
(5) 100 °C
(6) wind power cost included
(7) large scale
(8) (O) original source and (R) review article
(9) optimistic, realistic and pessimistic assumption

4.2.1. Long-term estimation of main specifications

Currently DAC is in the early stage of development. Most of the research has been done on experimental or laboratory scale, which makes it difficult to predict real plants specifications. In addition, the costs are the main target for long-term predictions, whereas estimation of technical specifications is hard to predict because of the disruptive nature of technology development, thus it is rarely discussed in the literature. However, it is assumed that maintenance cost will be reduced along with the equipment capex due to mass production and it is to lower energy consumption in the long-term (Lackner, 2009; Simon et al., 2011).

The future of HT aqueous solution DAC was discussed by following papers. Keith et al. (2005) have mentioned a factor of three to be the range of accuracy for any estimation of DAC plants. While suggesting 376 €/t_{CO2} as an achievable cost with todays' technology, they also assume that in the future the price will go down and could be on the same range with point source CCS. Socolow et al. (2011) emphasised that significant amount of uncertainty makes it hard to predict the performance of the plant that would be commissioned in the future. Hereby he has estimated final costs based on optimistic and realistic assumption of main technical and operational estimations. Optimistic final cost is 323 €/t_{CO2}, whereas realistic is 414 €/t_{CO2}.

While the current CO_2 DAC capture costs for LT solid sorbent technologies are rather unrevealed, Climeworks has stated that in a long-term, they are targeting to deliver CO_2 for costs below 75 €/t_{CO2}, achieved by economies of scale, improved performance and based on the experience gained for over 10 years of active development (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 device as well. It is projected that this, together with the economies of scale and decrease in the cost 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.

As mentioned in the previous section, in the most skeptical research, House et al. (2011) pointed out that the current costs of CO_2 capturing from ambient air have been underestimated and could be possibly at the range of 750 €/t_{CO2}. However, the study suggests that technological breakthrough can dramatically improve DAC technology, which could make it possible to reduce the production cost 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 a 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 (2011). They performed a sensitivity analysis of the appropriate techno-economic environment for DAC implementation on a large scale, estimated competitive cost of DAC and the effect it will make on conventional type of liquid fuels. They pointed out that after commercialization of DAC, which is likely in the near-term future, the cost will be go down rapidly due to economies of scale and learning by doing. They consider a learning rates of 0.101 for capital cost, 0.135 for energy cost 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 point source CCS (the closes analogy to DAC). Nemet and Brandt (2011) conclude that under this assumption, by 2029, DAC will reach the cost floor of 45 €/t_{CO2} with further reduction to 23 €/t_{CO2} and 14 €/t_{CO2} in 2050 and 2100 respectively. In addition, Nemet and Brandt (2011) suggest a lifetime of 50 years for a generic DAC system, which exceeds any other lifetime assumption in the literature by 20 years.

4.3. Estimate on DAC development in the period 2020 to 2050

4.3.1. Potential cumulative DAC capacity 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*, learning rate, *LR*, applied for the historic cumulative production for specific years, *prod*:

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

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

$$LR = 1 - PR \quad (11)$$

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

The historic cumulative DAC capacity demand, as summarised in Table 5, is estimated for the period 2020 to 2050 for respective DAC demand in the sectors power (power-to-gas, waste-to-energy, sewage plants), mobility (road, rail, marine, aviation), industry (chemical industry, pulp and paper, cement mills, others) and the future additional sector CO_2 removal. 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. (2017) and Ram et al. (2017);
- waste-to-energy negative due to its carbon capture and utilisation (CCU) potential and based on waste resource potential taken from Breyer et al. (2017) and Ram et al. (2017), a

CCU implementation rate assumed to grow from 2% (2025) to 50% (2050), a carbon capture efficiency increase from 60% (2020) to 80% (2050) and a CO_2 content of the waste of 2.44 $Mt_{CO2}/TWh_{th,waste}$ (IPCC, 2003);

- mobility segments are taken from Breyer et al. (2018) for the synthetic Fischer-Tropsch (FT)-fuel demand 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. (2017);
- chemical industry is based on the chemical industry energy feedstock demand growth from 10,280 TWh_{th} (2015) to 19,200 TWh_{th} (IEA, 2009; McKinsey, 2016), a demand coverage growth by naphtha by-product from FT-fuels production from 2% (2030) to 29% (2050) according to Breyer et al. (2018), an estimated 80% energy share of carbon based chemicals and a specific CO_2 DAC capacity demand of 0.28 Mt_{CO2}/a per $TWh_{th,feedstock}$ for 8000 FLh based on Fasihi et al. (2017) for an average of carbon-based feedstock chemicals;
- cement mills negative due to its carbon capture and utilisation (CCU) potential and based on cement production estimate taken from Farfan et al. (2018), a CCU implementation rate assumed to grow from 5% (2030) to 50% (2050), a carbon capture efficiency increase from 60% (2030) to 80% (2050);
- CO_2 removal demand is 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 20% removal share by afforestation and the remaining for CO_2 DAC systems.

The such estimated cumulative CO_2 DAC capacity demand grows from 3 Mt_{CO2}/a (2020) to 16,660 Mt_{CO2}/a (2050), thereof 8000 Mt_{CO2}/a from CO2 removal (2050).

Table 5. Global cumulative CO_2 DAC capacity demand by sector.

Sector		unit	2020	2030	2040	2050
power	power-to-gas	Mt_{CO2}/a	3	7	142.0	363
	waste-to-energy	Mt_{CO2}/a	0	-88	-601	-1002
	sewage plant	Mt_{CO2}/a	0	n/a	n/a	n/a
mobility	road (cars/bus/trucks)	Mt_{CO2}/a	0	242	1714	844
	rail	Mt_{CO2}/a	0	6	67	75
	marine	Mt_{CO2}/a	0	58	1137	3568
	aviation	Mt_{CO2}/a	0	54	1121	3490
industry	chemical industry	Mt_{CO2}/a	0	236	904	1933
	pulp and paper	Mt_{CO2}/a	0	n/a	n/a	n/a
	cement mills (limestone)	Mt_{CO2}/a	0	-69	-428	-611
	others	Mt_{CO2}/a	0	n/a	n/a	n/a
CO_2 DAC, energy system		Mt_{CO2}/a	**3.0**	**447**	**4055**	**8660**
CO_2 removal		Mt_{CO2}/a	0	0	1000	10000
Afforestation		Mt_{CO2}/a	0	0	200	2000
CO_2 DAC, CO_2 removal		Mt_{CO2}/a	**0**	**0**	**800**	**8000**
CO_2 DAC, total		Mt_{CO2}/a	**3**	**447**	**4855**	**16660**

The estimate of cumulative CO_2 DAC capacity demand of Table 5 is taken as input for the DAC capex estimate according to the learning curve approach, for a conservative and a base case scenario. The two scenarios for the 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 (2011) 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 zero GHG emissions in the energy system and an 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 centralized coal-fired power plants, which are finally the basis for the assumed 10% learning rate (Nemet and Brandt, 2011; Rubin et al., 2007; 2004). Highly

modular energy technologies exhibit learning rates around 15%, as documented for electrolysers with 18% (Schmidt et al., 2017), seawater reverse osmosis desalination with 15% (Caldera and Breyer, 2017), lithium-ion battery systems with 12% - 17% (Schmidt et al., 2017; Kittner et al., 2017), which is finally a consequence of a more comprehensive international product standardisation and substantial economies of scale as a consequence of the high modularity.

The results of the learning curve approach for estimating the DAC system capex are summarised in Table 6 and visualised in Figure 4. The DAC system capex are assumed to reach 730 €/t_{CO2}·a (LT) and 1583 €/t_{CO2}·a (HT) in 2020 (Table 4). The capex can decline for LT DAC systems to 196 €/t_{CO2}·a (conservative) and 82 €/t_{CO2}·a (base case) and for HT DAC systems to 426 €/t_{CO2}·a (conservative) and 178 €/t_{CO2}·a (base case) in 2050, respectively.

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

Parameter	**unit**	**2020**	**2030**	**2040**	**2050**
CO_2 DAC, total	**Mt$_{CO2}$/a**	**3.0**	**447**	**4855**	**16660**
thereof 50%, conservative scenario	Mt$_{CO2}$/a	1.5	223	2427	8330
thereof 100%, base case scenario	Mt$_{CO2}$/a	1.5	447	4855	16660
historic cumulative capacity (conservative / base case)	Mt$_{CO2}$/a	1.5 / 1.5	223 / 447	2427 / 4855	8332 / 16662
doublings between periods (conservative / base case)	-	0	7.2 / 8.2	3.4 / 3.4	1.8 / 1.8
capex CO_2 DAC LT (conservative / base case)	€/t_{CO2}·a	730	341 / 192	237 / 110	196 / 82
capex CO_2 DAC HT (conservative / base case)	€/t_{CO2}·a	1583	739 / 416	514 / 238	426 / 178

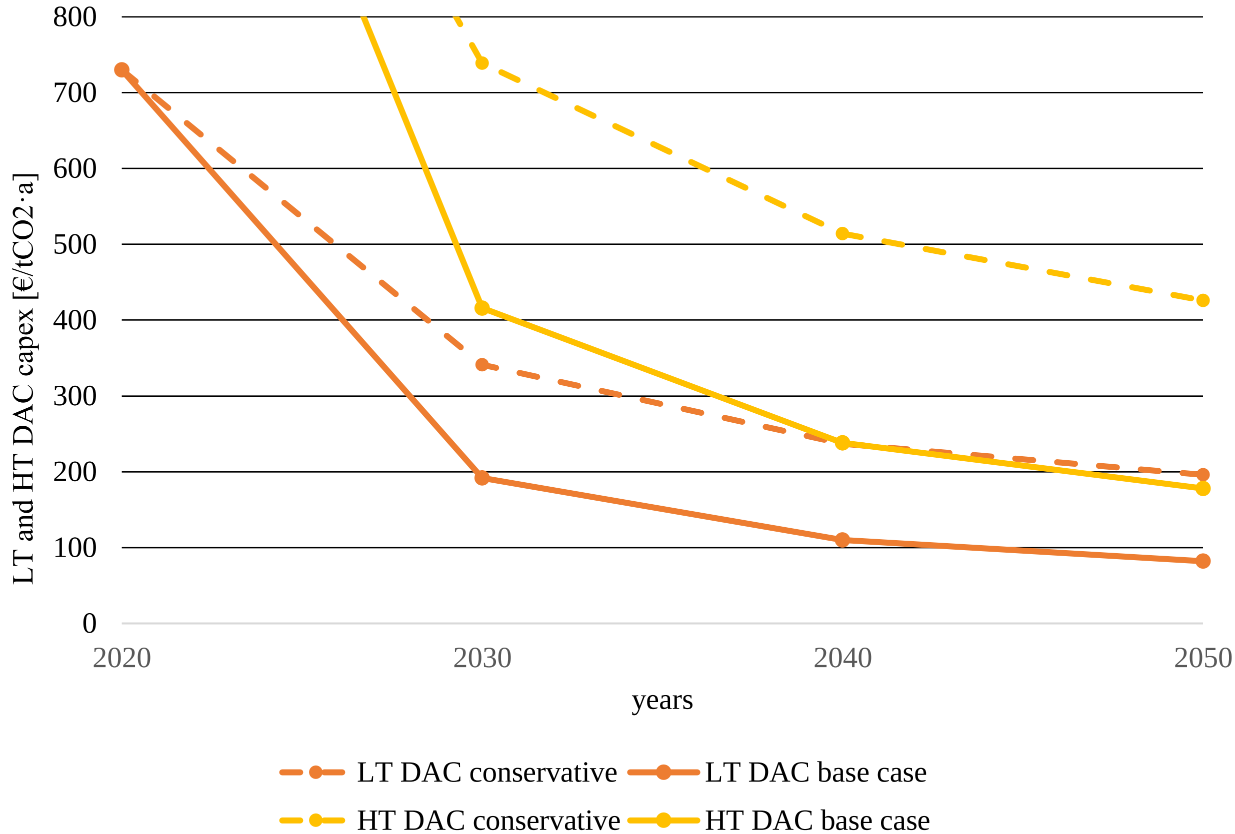


Fig. 4. CO_2 DAC capex development for LT and HT systems based on the learning curve approach and the applied conservative and base case scenarios.

The estimated DAC capex projections are used in the following as input for the cost scenarios for the 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 the long-term development of main specifications based on the ***conservative scenario*** described in *section 4.3.1.*, and are shown in Table 6.

The Capex assumptions for both technologies are based on the cumulative installed capacity and learning rate, 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 that, respectively, according to the long-term estimations for generic DAC plants in the literature. The lifetime of HT DAC has been kept at 30 years through the timeframe of this analysis. In addition, although Nemet and Brandt (2011) suggest a higher learning rate for Opex of DAC systems, it has been kept constant at 4% and 3% of capex from 2020 to 2050 for LT and HT DAC technology, respectively.

In a personal communication with Climeworks (2015), the electricity and LT heat demand for 2030 were estimated to be 10% and 14% less than the current numbers. The same demand reduction rates have been assumed per each 10-year step until 2050. The same electricity demand reduction rate of 10% has been applied to a fully electrified HT DAC system from 2020 onwards, as well.

Morocco was chosen as a potential site for big scale DAC plant implementation with 2400 FLh for single-axis tracking PV system and 3500 FLh for wind technology. Electrical compression heat pumps with a COP of 3 have been used for LT heat generation (DEA, 2016). LCOE, LCOD and LCOH were calculated for 4000 and 8000 FLh conditions and based on the above described assumptions. The results are presented in Table 7.

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

	year	a	2020	2030	2040	2050
LT DAC	capex	€/t_{CO2}·a	730	341	237	196
	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	1290	1109
HT DAC (fully electrified)	capex	€/t_{CO2}·a	1583	739	514	426
	opex	% of capex p.a.	3%	3%	3%	3%
	lifetime	a	30	30	30	30
	el. demand	kWh_{el}/t_{CO2}	1380	1242	1118	1006
4000 FLh	LCOE net	€/MWh_{el}	43.6	28.1	21	17
	LCOH - LT	€/MWh_{th}	31	24	21	19
	LCOD - LT	€/t_{CO2}	280	137	94	76
	LCOD - LT- free waste heat	€/t_{CO2}	133	60	40	31
	LCOD - HT	€/t_{CO2}	443	213	148	120
8000 FLh	LCOE net	€/MWh_{el}	103	57	41	32
	LCOH (LT by heat pump)	€/MWh_{th}	44	28	21	18
	LCOD - LT	€/t_{CO2}	209	101	67	52
	LCOD - LT- free waste heat	€/t_{CO2}	133	60	39	31
	LCOD - HT	€/t_{CO2}	334	161	122	84

Figure 5 illustrates the final contributions for LCOD for the LT and HT DAC systems in 2040 for the conservative scenario. For 8000 Flh the LCOD of the LT DAC system reaches 67 €/t_{CO2}, where the highest shares belong to heat demand at 41% and to DAC capital expenditures at 31%. In case of access to free waste heat, the LCOD could be lowered to about 40 €/t_{CO2}. On the other hand, at 122 €/t_{CO2}, the LCOD of the HT DAC system in 2040 is almost double, where the electricity cost dominates the cost at 50% and the cost share of capital expenditures is about 36%. 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 case of access to very low-cost or free waste heat for LT system, its dependency on very low-cost electricity is relatively lower.

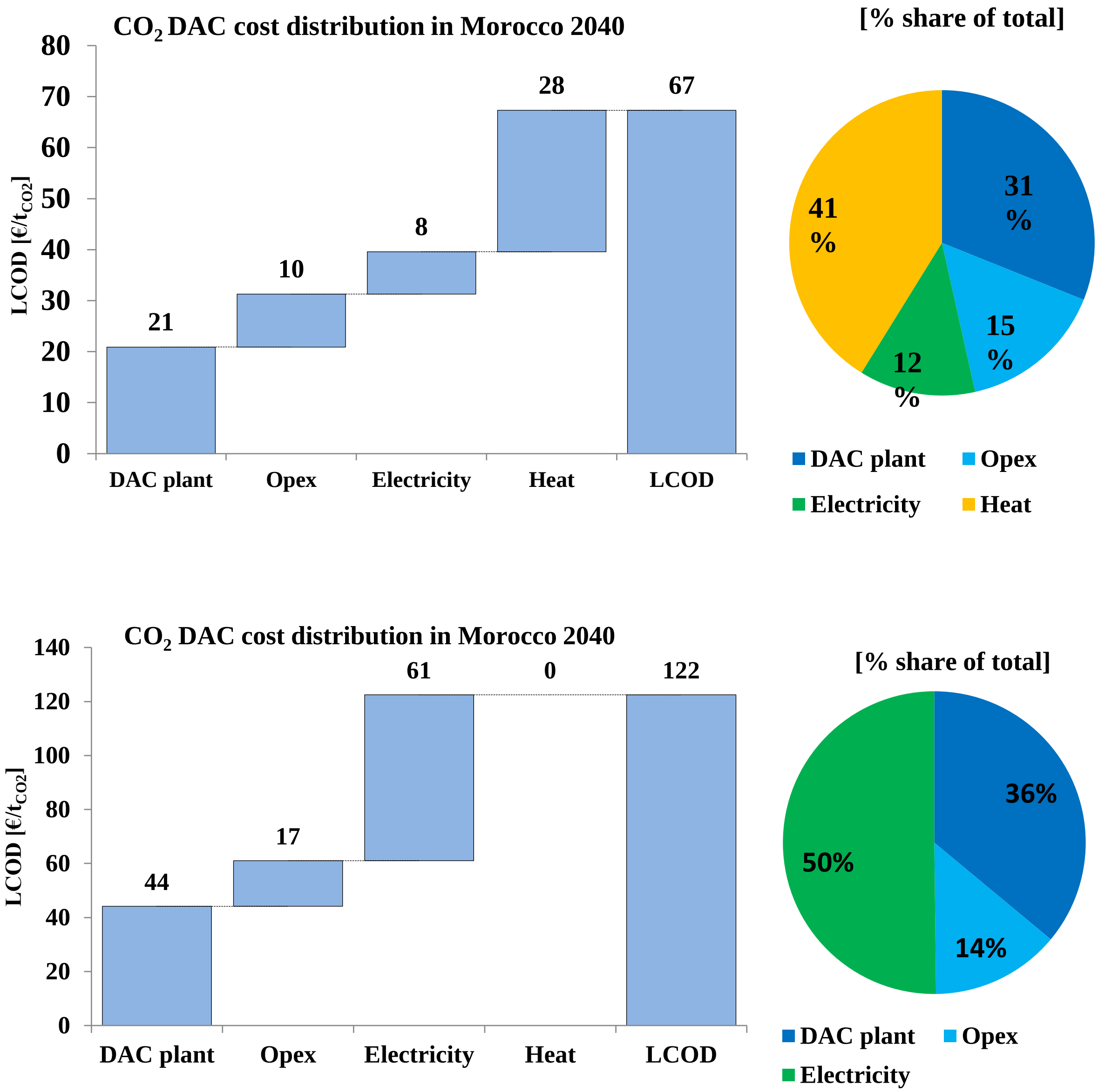
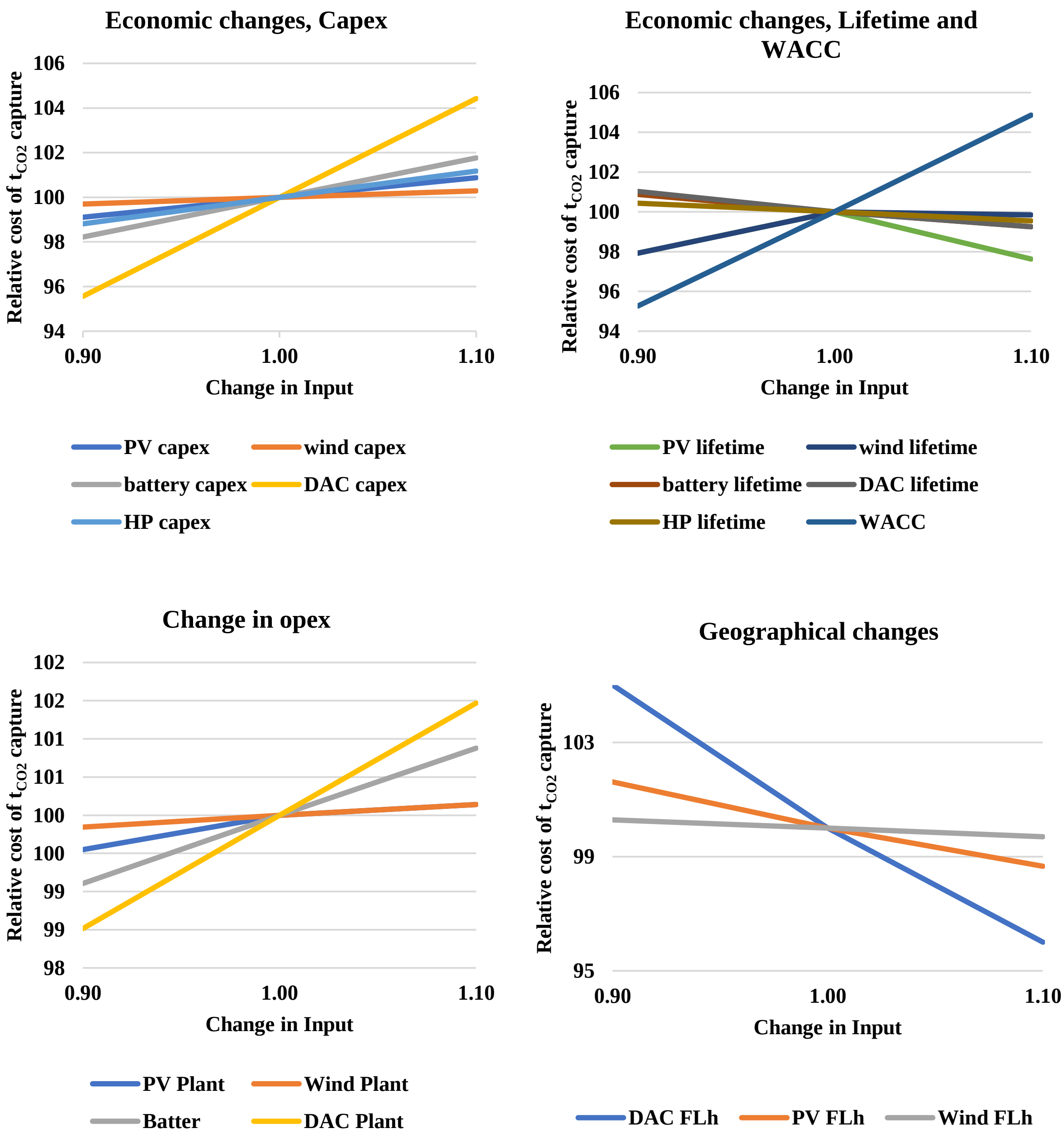


Fig. 5. LCOD cost breakdown for the LT DAC system (top) and HT DAC system (bottom) for 8000 FLh and conditions in Morocco in 2040.

4.3.3. Sensitivity analysis

Due to the uncertainties about the literature-based final DAC system models' specifications and their development 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 which the results for the LT and HT DAC systems are presented in Figures 6 and 7, respectively.



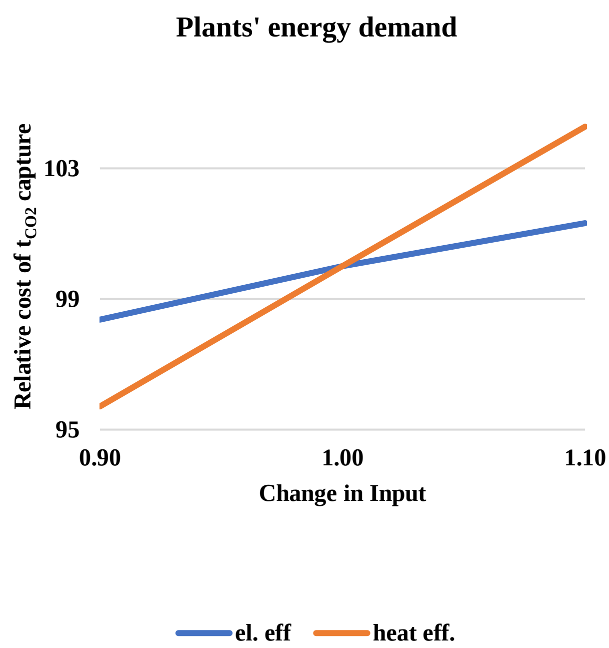
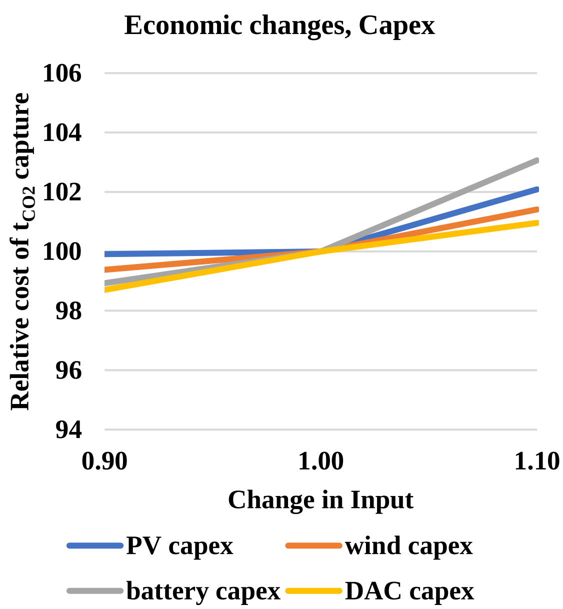
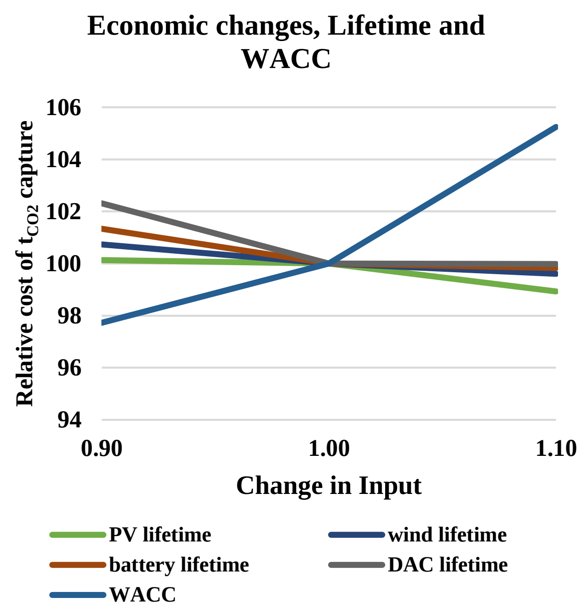


Fig. 6. Sensitivity analysis of input data for the LT DAC system on economic change (top, left), change in plants' Opex (top, right), geographical change (bottom, left) and plant's energy demand (bottom, right) for 8000 FLh.





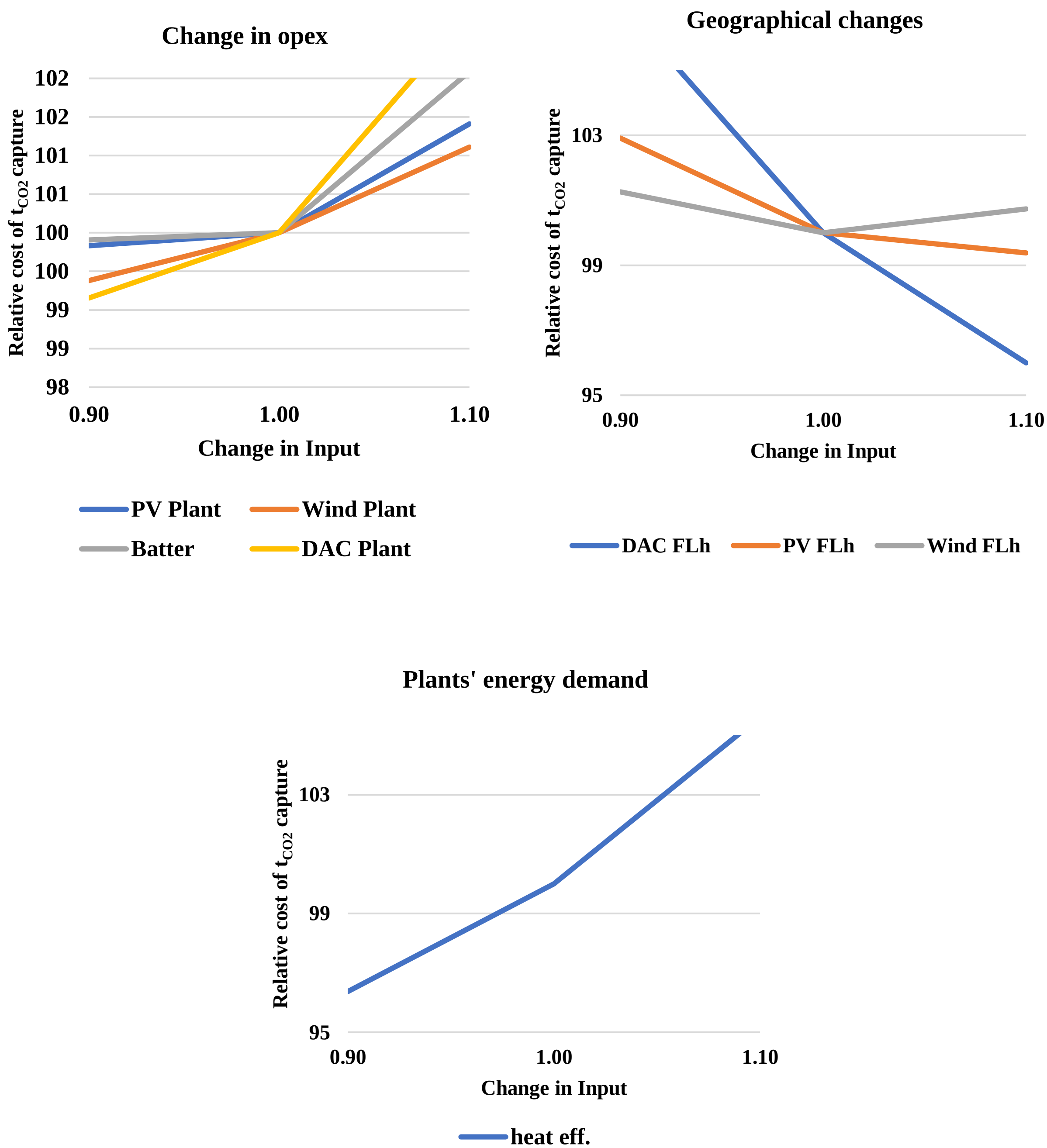


Fig. 7. Sensitivity analysis of input data for the HT DAC system on economic change (top, left), change in plants’ Opex (top, right), geographical change (bottom, left) and plant’s energy demand (bottom, right) for 8000 FLh.

As it can be seen for the both systems change in Capital expenditures and WACC play the most sufficient roles and can result in 10% increase of the final production costs, thus should be addressed and managed carefully. Opex, on the other hand, does not influence much on the final cost production. Overall picture of sensitivity analysis shows in details how single input data can affect CO_2 capture costs. In the world of limited resources, it is important to understand what parameters can be neglected and what has the highest importance so that the DAC plant can be built in any place with the best possible results.

4.4. Compression, transport and storage

After CO_2 capturing, it might need to be compressed to the pressure suitable for further utilisation, transportation (in gaseous or liquid phase) or storage. CO_2 could be liquefied by compression to 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 the other parts of the system (Lackner, 2009).

In DAC systems, captured CO_2 could be directly compressed while in point source CCS it first needs to be cleaned from a wide range of impurities associated with flue gases. Thus, compression station is combined with purification unit (Skaugen et al., 2016). Kolster et al. (2017) reported that the energy requirement for CO_2 compression from point source CCS to 120 bar is on the range of 96-103 kWh/t_{CO2}. Whereas Simon et al., (2011) claimed the minimum energy requirements for CO_2 compression to 138 bar after DAC to be about 62.5 kWh/t_{CO2}, which with a compression efficiency of 60%, would turn to 104 kWh/t_{CO2}. Economic evaluation of compression is not presented separately; however, in most papers, it is already included in the final cost of transport and storage.

CO_2 transportation can be done by different means: pipeline, ship, railways, truck, tank containers or a combination of them. Transportation type strongly depends on the terrain, distance and capacity. Pipeline is well-regulated, safe and mature option for transport of CO_2 (IEA, 2016).

Pipelines are favorable for big amounts of CO_2 with annual transportation capacity of 1-5 million ton and distances on the range of 100-500 km (IEA, 2010).

Ship transport is more cost-effective over long distances (>2400 km) in comparison to transport via pipelines (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 and cannot be used inland so that CO_2 should be somehow delivered from the collection point to the harbour. CO_2 is transported only in liquefied form by ships so that additional pressurisation station at the harbor is needed.

Less attention is dedicated to transport by trucks and trains but for some projects, especially point source carbon capture, it might be the only option. Karjunen et al. (2017) have analysed different sites at the terrain where ship 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 on the range of 4.4-14 €/t_{CO2}. Cost parameters associated with all mentioned means of transportation are summarized and presented in Table 8.

Table 8. CO_2 transportation cost

transportation type	capacity	distance	cost	specific cost	reference
	t_{CO2}/a	km	€/t_{CO2}	€/t_{CO2} per 1000 km	
truck	15-20	1	1	1000	Freitas (2015)
		>100	13	<130	
train	1	100	1.7	17	Freitas (2015)
	1 460 000	598	7.7	13	Gao et al. (2011)
onshore pipeline	1 460 000	300	4.3	14	Gao et al. (2011)
	2 160 000	100	1.34-1.8	13-18	Freitas (2015)
	2 500 000	180	5.4 (2)	30	ZEP (2011)
offshore pipeline	2 500 000	70	28.7 (2)	410	ZEP (2011)
		180	9.3 (2)	52	
		500	20.4 (2)	41	
		1500	51.7 (2)	35	
shipping	40 000	1950	11.8	6	Kujanpaa et al. (2011)
	925 000	300	53	177	Jakobsen et al. (2017)
	1 460 000	300	4.6 (1)	15	Gao et al. (2011)
	2 000 000	750	19	25	Aspelund and Jordal (2006)
	250 000	180	8.2 (2)	46	ZEP (2011)
		500	9.5 (2)	19	
		750	10.6 (2)	14	
		1500	14.5 (2)	10	

(1) Shipping cost does not include liquefaction
(2) Liquefaction accounts for additional 5.3 €/t_{CO2}

Traditional options for CO_2 sequestration (permanent storage) are limited to deep saline formations (1000 to ~10 000 Gt_{CO2}), depleted oil and gas fields (675 to 900 Gt_{CO2}), coal seams (3 to 200 Gt_{CO2}), and basalts, shales, salt caverns and abandoned mines (Svensson et al., 2004; IEA, 2016). However, the best sites for geological storage are limited and soon will be fully used. As a result, transportation distance and associated costs could increase for the future projects. DAC technologies with the purpose of producing synthetic fuel and closing carbon loop need intermediate and seasonal storage with high capacities. Gas tanks can be used for intermediate storage of CO_2. Karjunen et al. (2017) have stated that cost of intermediate storage in cylindrical tanks can be on the range of 10 €/t_{CO2}.

4.5. Land usage and risk of local CO_2 depletion

One of the most common concerns about wide DAC plants implementation is local CO_2 depletion as it may affect the environment and the vegetation. CO_2-poor environment would decrease efficiency of the system and increase final production cost. Thus, it is important to evaluate the recovery time and the minimum distance between DAC plants to avoid these problems. On the other hand, such a distributed system could increase the cost of energy (heat and electricity) delivery and captured CO_2 collection and transportation to the central consumer or storage.

Companies are designing their capture plants in a way that depleted air does not go through the contactors twice. Depletion risk can cause a reduction of capture rate performance of the plant; however, it can be minimised by distributing the system units which leads to higher area demand for DAC plants. Footprint and respective land usage may be a key issue as substantial requirement of land might be a barrier for a large-scale implementation of the technology. Land area needed for a large-scale DAC plant not only accounts for capture units itself but also includes the distance between them and service buildings.

According to Climeworks (2018b) its capture plant has 18 units located in 3 rows on top of each other and it 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. Socolow et al. (2011) claims that for their aqueous based system with the capacity of 1 Mt_{CO2}/a, the total land usage 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. In addition, there is a warehouse for chemical storage and a regeneration unit. However, both sources did not specify how the total land demand or how the minimum allowed distance between units were estimated.

Land requirements were also discussed in less detail by Keith et al. (2005), however in his opinion potential DAC plants can be small as the land between the unit can be freely used for other purposes.

5. Discussion

Many actions were taken in order to reduce GHG emission and stabilize climate change. The Paris Agreement symbolises a common understanding of the extreme situation and actions that are needed to be done. Despite the already taken steps, the rate of GHG emissions is continuing to grow alongside with growth of gross domestic product and population. Breyer et al. (2017) also addressed the issue of increasing harmful emissions and claimed that (RE) in general and solar photovoltaic (PV) in particular are the main weapons against it. In addition, Ram et al. (2017) reported that RE can be utilised in the power sector and successfully fight GHG emissions, while reducing the system cost and creating new jobs. Additional measure for decreasing CO_2 emissions from point sources is point source CCS and attempts to modify transport sector in particular shift to electric vehicles and the substitution of conventional fuels with synthetic ones (Creutzig et al., 2015; Mathiesen et al. 2015). DAC will finally allow to close carbon cycle and in the world where it is not possible to eliminate GHG emissions produced by aviation and marine sector alongside with hard to avoid CO_2 point sources (cement, 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.

Finial price of CO_2 delivered by DAC is the main obstacle and barrier for it worldwide implementation for now. That is true that technologies adopted from point source CCS is rather expensive approach for capturing carbon dioxide from the atmosphere. However, technologies are developing fast and a big scale plant recently commissioned in the 2017 by Climeworks is able to deliver CO_2 for the price of 75 €/ t_{CO2} which does not differ a lot from the cost of point source CCS. This recently implemented plant is a first of its kind, which means it is highly possible that next plants will deliver CO_2 even for lower prices.

Taking into consideration necessarily compression, transport and storage DAC technologies are more favorable compared to point source CCS because capturing CO_2 on the site remove the need for transport. DAC plants can be places as close as possible to the sequestration place or synthetic fuel plant to cut transportation costs completely. In addition, compression and intermediate buffer storage are developed technologies that are available for reasonable prices (Simon et al., 2011; Porter et al., 2017). When transportation accounts up to 50% additionally to the capture price, storage and compression will increase the final cost up to maximum 10%.

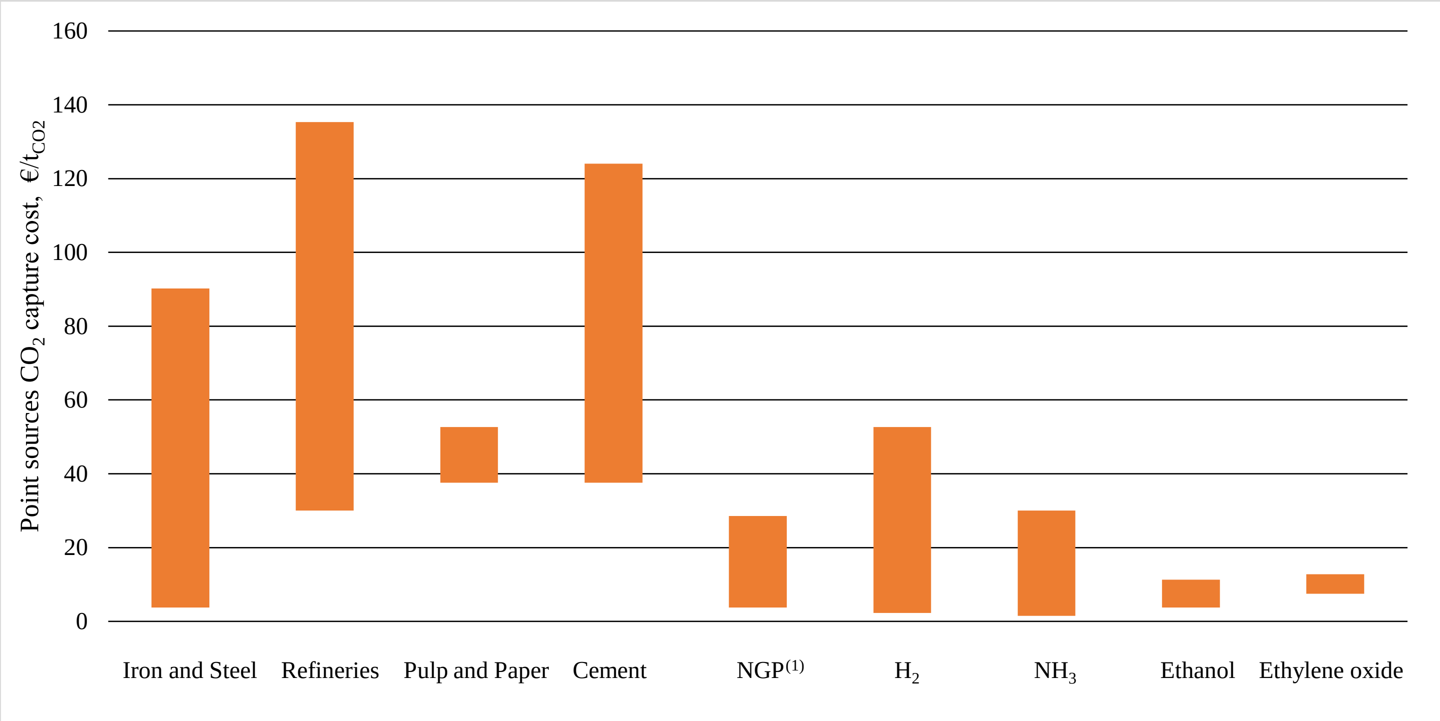
The big variety of materials and models with unique specifications makes it hard to put all proposed approaches on the line and conduct meaningful comparison. Diversity of conclusions and promising improvements in the future does not allow to choose one model and one approach. Special features make some models are more favorable for some conditions or sites but not acceptable for others. Decision should be made by interested parts considering individual goals and available resources. Presented earlier classification and description of technologies is solid enough for one to decide and use input data of mass balance and economics for calculating of individual project performances. Available resources such as amount, type and quality of available energy and abundance of materials can facilitate implementation of more energy intensive technologies, for example. In addition, long-term estimation can show technology development paths and cost reductions over time.

All technologies have strong and weak parts. Solid sorbents adopted from point source CCS have high regeneration temperatures which is hard to provide and as a result cost of captured carbon is super high (around 500 €/ t_{CO2}). When one tries to optimize it by adding additives temperature is lowered but the price is not changing because of the expensive added reagents. Proposed MOFs and some other approaches are sensitive to ambient conditions and despite affordable prices facing high risks of being destroyed by aggressive environment or simply by rain. Only latest proposed technologies based on innovative sorbents, which is intentionally keep in secret by developers, seems to have less disadvantages. Commercial companies are implementing and operating first plants, achieving successful results and proves to the world that DAC is possible and feasible to do.

Energy demand and economics are two main obstacles that are preventing wide implementation of DAC plants. Great amount of cheap and sustainable energy that are needed to run the process and enough financial resources that can enable massive implementation of the technology are two main questions that need to be answered. However, climate change and GHG mitigation is becoming a governmental problem and matches perfectly Paris Agreement targets. It is obvious that as for now main support for DAC implementation on big scale should come from the government with the aim to maintain climate and not making profit. However, on the long-term DAC can become an essential part of synthetic fuel production. Even nowadays closing carbon circle and producing fuels for transport is a main mission of several companies and research groups.

DAC is always compared to point source CCS which is not correct even based on their goals. One may argue that the goal of DAC is not CO_2 depleted air or CO_2 as a product for use on the site but the energy efficient CO_2 capture from ambient air (Broeham et al., 2015). However, from the point of view of Climeworks and Antecy and some other research groups delivering CO_2 as a product in any site of the world for affordable prices is the main goal as it will allow to use it further and produce synthetic fuels for the mobility sector.

Available technologies for capturing CO_2 from different industrial point sources also prove high diversity of the approaches and price ranges. Figure 8 presents the scale of the point source CCS price distribution (Leeson et al., 2017).



(1) Natural gas production

Fig. 8. Scale of the point source CCS cost distribution for different industries

Point source CCS is mature in the oil and gas field where it is used to increase production rates but it has not yet been implemented in substantial scale for avoiding or minimising CO_2 emissions. This technology, however, does not work efficiently and up to 50% of CO_2 is still released to the atmosphere (Leeson et al., 2017).

It is assumed and predicted that the later DAC systems will be more efficient and affordable due to optimisations in the technology, economy of scale and learning curve effects (Nemet and Brandt, 2011). Moreover Broehm et al., (2015) have also concluded that lower CO_2 capture costs are possible due to the same reasons as mentioned above. In addition, the possibility of new radical innovations and complete new approaches and changes in system design should not be eliminated. There is always room for exploring and dedicated development of new brave ideas.

6. Conclusions

DI in CO_2 DAC plants in particular, are in an early stage of development and face many barriers. Nowadays, DAC plants do not have a big market niche, but a limited number of companies, among which Carbon Engineering and Antecy, are highly interested in this technology as their goal is to produce synthetic fuels from the ambient CO_2 and RE on a worldwide scale. In order to reach these goals DAC plants are needed. In addition, the demand for CO_2 capturing is continuing to grow, which makes DAC an undeniable necessity for mitigating climate change. In *Section 4.3.1.* potential cumulative demand for DAC capacity were analysed based on the available data about major CO_2 emitters such as heavy industries; power and mobility sectors. It was concluded that increasing demand for DAC plants will lead to accumulation of the knowledge and experience that will positively influence on the final CO_2 capture costs.

Both the literature review and conducted analysis have shown that it is feasible to build and operate DAC plants nowadays. Currently, there are two main technologies that have a potential to be implemented on the big scale. LT and HT approaches have been tasted in big scale pilot plants. However, due to their high energy demand and expensive costs of novel materials the final production costs are approximately 400 €/t_{CO2}, which is rather high for the nowadays conditions. On the contrary, taking into account the learning curve based on the potential demand for DAC plants it is assumed the costs will dramatically go down in the near future, due to mass production and high learning rates. As the result, estimated main specifications for the long-term period conducted in the S*ection 4.2.2* and generic cost recalculation in the S*ection 4.2.3* show that it will be able to capture CO_2 from the air for lower prices of 67 €/t_{CO2} for LH mode and 122 €/t_{CO2} for HT model by 2050. In addition, a performed sensitivity analysis identified that the Capex of a DAC plant, WACC and FLh are the inputs that affect the final capture cost the most. On the contrary other input parameters do not have a significant effect when adjusted individually. Thus, it shows the input parameters should be addressed all together at the same time.

While one can still doubt and argue the feasibility of DAC pants, several companies have already commissioned and operated big scale plants.

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Appendices

Appendix 1: Companies operating in s DAC field.