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Faculty of Tropical AgriSciences

Czech University of Life Sciences Prague
Faculty of Tropical AgriSciences

Carbon Dioxide as a Resource and Fuel

BACHELOR'S THESIS

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Author: Jan Faktor

Supervisor: doc. Ing. Bc. Tatiana Ivanova, Ph.D.

Declaration

I hereby declare that I have done this Thesis entitled “Carbon Dioxide as a Resource and Fuel” independently, all texts in this Thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague 15th of May 2020

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Jan Faktor

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Abstract

The persistent increase of CO_2 and other Greenhouse Gases (GHGs) levels in the atmosphere is a very actual topic and an alarming problem of the modern world. Set of new technologies is being introduced to tackle this situation. Useful utilization or sequestration of CO_2 by capturing it from the industrial sources of air pollution or the atmosphere itself, can be applied in many different ways as resource/feedstock and fuel, e.g. for power generation, production of chemicals, fourth-generation biofuels, as well as carbon capture storage (CCS) for example method of carbon mineralization that can be used in agriculture, food and building industry. CO_2 transformation is one of the important instruments on how to reduce global warming. However, many obstacles as high costs, need for further development of technologies and lack of governmental support lye in its way.

This Bachelor's Thesis entitled "Carbon Dioxide as a Resource and Fuel" was written in a form of literature review mostly based on information from scientific articles published by various well-established scientific web databases as well as on numerous reports provided by different international organizations. The Thesis reviewed, compared, and summarized facts concerning carbon capture and utilization (CCU) and CCS. It was divided into four main chapters where each of these was dedicated to a particular part of the process from capture storage, its transportation & storage to utilization and last chapter of this Thesis was mainly focused on outlooks of these technologies.

Keywords: CO_2 storage, carbon capture and storage, negative emissions technologies, carbon utilisation, advanced biofuels, carbon mineralization

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List of the abbreviations used in the Thesis

CC – Carbon Capture

CCS – Carbon Capture and Storage

CCU – Carbon Capture and Utilization

CCUS – Carbon Capture Utilisation and Storage

CO – Carbon Oxide

CO_2 – Carbon Dioxide

CO_2-EOR – Enhanced Oil Recovery utilizing Carbon Dioxide

EOR – Enhanced Oil Recovery

EOR+ – Method combining CO_2-EOR with CCS

GHG – Greenhouse Gas

GS – Geological Storage

GtC – 1 GtC=1 billion metric tons of carbon equivalent

H – Hydrogen

H_2 – Molecular Formula of Hydrogen

H_2O – Water

H_2S – Hydrogen sulphide

IEA – International Energy Agency

IGCC– Integrated Gasification Combined Cycle

t – tonne

km – kilometre

m – metre

kW – kilowatt

MW – megawatt

N_2 – Nitrogen

NG – Natural Gas

NH_3 – Ammonia

NH_4 – Ammonium

NO_3 – Nitrate

NO_x – Nitrogen Oxide

OF – Ocean Fertilization

OXC – Oxyfuel Combustion

PCC – Post Combustion Capture

PO_4 – Phosphate

Pre-CC – Pre-Combustion Capture

R&D – Research and Development

SO_x – Sulphur Oxides

UNCLOS – United Nations Convention on the Law of the Sea

UNFCCC – United Nations Framework Convention on Climate Change

1. Introduction

The extensive presence of GHGs in the atmosphere is one of the major global problems of the present-day world. According to Cebrucean et al. (2014) industrial and power plants that use fossil fuels as their main feedstock are accountable for the release of more than 12 billion tonnes of CO_2 each year. This has primarily been caused by previous and ongoing long-lasting extensive use of fossil fuels in the energy production sector as well as in various types of industrial plants and transportation.

Although the situation with the use of non-renewable energy sources has improved in the recent years as new renewable types of energy sources have emerged and the results are evident in the structure of the world's energy sources (wind energy, biomass-fuelled plants, geothermal as well as solar power). It is projected that the use of non-renewable energy sources will decrease significantly in the next decades. This change is rather slow, even though it is enhancing, and the change is following the right direction, there is still substantial room for improvement in the future. Fossil fuels account for 80% of all the resources for energy production and this number is expected to decrease further to 75% by 2035. Therefore, CCS and other CO_2 utilisation methods could be a good example of how to continue in the use of fossil fuels and at the same time reduce CO_2 emissions (Wilberforce et al. 2019).

Carbon Capture Utilisation and Storage (CCUS) could be potentially very important in mitigating GHG emissions alongside with other methods, for example, using renewable energy sources, improving the effectiveness of current fossil fuel plants, phasing out old power plants and using nuclear energy or cleaner energy sources, for instance, gas or biomass as a feedstock instead of traditional coal or oil (Feron & Hendriks 2005).

Captured CO_2 offers a variety of useful applications such as production of advanced biofuels, enhanced oil recovery as well as it can be converted into the feedstock for agriculture, food-processing industry, pharmaceutical purposes, improving aquacultures with algae biomass and many other sorts of utilization.

The knowledge about this interesting and important topic is presented in the Thesis.

2. Aims of the Thesis

The main objective of this Thesis was to analyse and summarize current scientific findings and information regarding Carbon Capture Utilization and Storage. Subsequently, the goal was to review different technologies used for Carbon Capture, Carbon Storage likewise various applications of CO_2 emissions, including discussion of their advantages and disadvantages as well as a description of possible obstacles that might arise in the future. Furthermore, it aimed to confront the ideas and conclusions from various experts on this modern issue.

3. Methodology

This Thesis was written as a literature review consisting of four main chapters that were further divided into sub-chapters. The Thesis was elaborated in accordance with the manual of the Faculty of Tropical AgriSciences for writing Bachelor's Thesis and all references included in this Thesis were cited according to the Citation Rules of the FTA for Theses in English (2017 manual). The methodology of the Thesis was based on the study of secondary data sources (mainly articles) obtained from the scientific databases such as ScienceDirect, Elsevier, Web of Science, EBSCO and Google Scholar including other literature sources (e.g. reports from European Commission and International Energy Agency), which were found by using specific keywords. The scientific information search was completed through the keywords such as: carbon capture and storage, carbon utilisation, carbon dioxide removal, geological storage, oceanic storage, greenhouse gases, algae biofuel, direct air capture, carbon capture and utilisation, and others with the application of Boolean operators. Subsequently, the analysis and processing of selected articles, technical reports, etc. related to the Thesis topic followed.

4. Literature Review

4.1. Carbon Capture

De Coninck et al. (2009) state that CCS is one of the modern methods to achieve the reduction of the amount of CO_2 being released into the atmosphere by capturing its particles from the source of pollution, which are mainly heavy industry plants (cement, steel, refineries, chemical) and power plants that utilise fossil fuels, and later safely transport the substances into a secure storage location such as onshore or offshore geological or underwater oceanic storages, where these will be stored for long-term. Most of the authors (Herzog & Golomb 2004; Benson & Orr 2008; Gibbins & Chalmers 2008) agree on the statements mentioned above. In addition to this, the deployment of CCS projects on various levels ranging from research projects to fully operational projects has been gradual, as in the recent years the numbers have increased to 37 commercial large-scale projects from which 17 are operational, 4 are being constructed and the rest is at various stages of development (Bui et al. 2018). Furthermore, in 2019, 51 large-scale facilities were reported, raising the number to 19 operational plants, 4 under construction, 10 in advanced development and 18 in the early development phase (Global CCS Institute 2019).

Figure 1 shows the countries involved in the CCS operations and the current projects around the globe, dividing the countries into 8 different groups according to the technology or the combination of technologies they use and maturity of projects ranging from pilot-scale to full-scale operational projects.

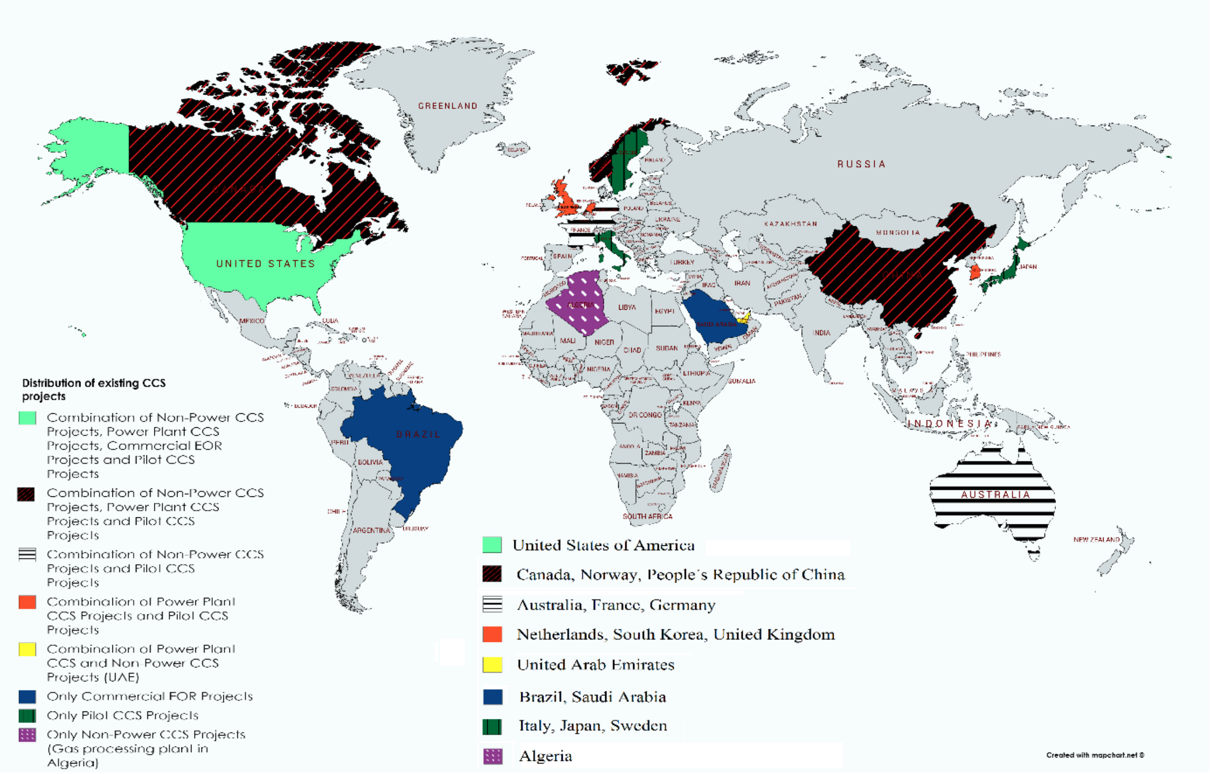


Figure 1. World map of CCS projects and divisions according to technologies used

Source: Adjusted by the author based on data from the MIT (2016)

These storage places have considerable potential, as their vastness can accommodate at least 2,000 Gt of the undesired substance, i.e. CO_2. This fact clarifies why CCS could be one of the possibilities of how to reduce the presence and impact of the most common GHG in the atmosphere (Benson & Orr 2008). Furthermore, Metz et al. (2005) published that the number could be possibly even higher (than this), allowing to sequestrate a greater volume of CO_2 in geological storages, with the numbers ranging somewhere between 1,000 and 10,000 Gt of CO_2.

Secondly, CO_2 can be extracted directly from the air without any need for the system to be attached to the actual source of emissions, as it is accomplished by improving and boosting natural processes, e.g. photosynthesis that closes off CO_2 in biological matters such as flora, ground or the seafloor (Benson & Orr 2008).

The authors divide the methods of carbon capture into three main types. This division is determined by the type of the process, the environment in which it occurs and the period in the process when the extraction of CO_2 occurs. The following are the three methods: Post-combustion Capture or, in other words, Flue Gas Separation (Herzog &

Golomb 2004), Pre-combustion Capture and Oxyfuel Combustion (Benson & Orr 2008; Gibbins & Chalmers 2008; Finney et al. 2019), referred to as Oxy-combustion as well (Wilberforce et al. 2019).

Figure 2 summarises possibilities involved in carbon capture, utilisation, and storage.

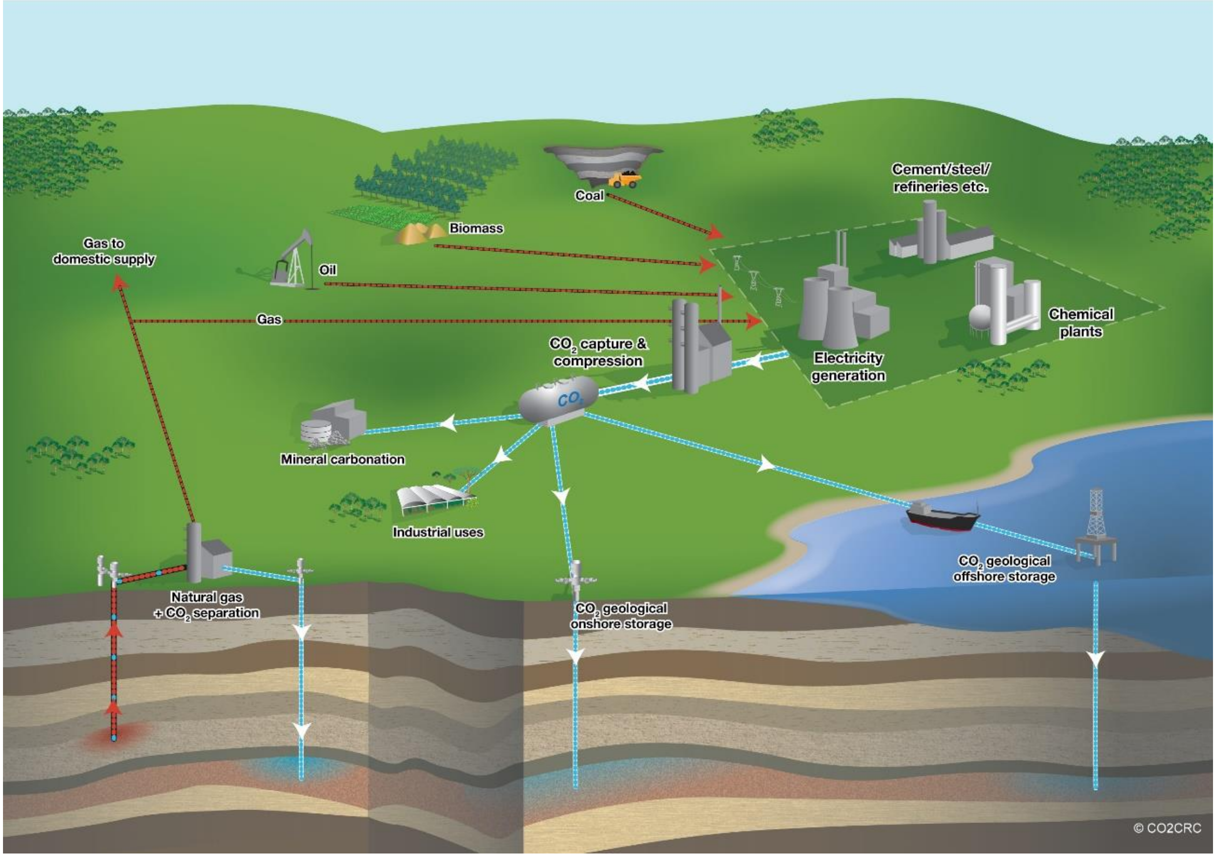


Figure 2. CCS and CCU technologies and facilities overview

Source: CO2CRC (2017)

4.1.1. Types of Capture Technologies

4.1.1.1. Post-Combustion Capture (PCC)

As the name of this process already suggests, it takes place after the actual ignition of the fuel. Therefore, the extraction and isolation of molecules of CO_2 are conducted from the stream of the flue gas, which is released out after the completion of the fuel's combustion (Cuéllar-Franca & Azapagic 2015; Plasynski et al. 2009; PowerPlantCCS 2010).

Most importantly, the separation of CO_2 from the flue gasses, that mostly comprise of CO_2 and N_2, is accomplished by chemical absorption in absorber tower, where most of the CO_2 will be absorbed in the solvent and other particles will escape creating a solution made of the solvent and CO_2. This solution will be separated in the stripper tower where it will be later heated to approximately 100-120°C (Herzog & Golomb 2004). The elevated temperature causes the solvent and CO_2 to separate. The separation enables recollection and subsequent reuse of the solvent (Oexmann & Kather 2009; PowerPlantCCS 2010; Wang et al. 2017).

A Solvent-based method (Benson & Orr 2008) using ammonia and ammine based solvents, most commonly monoethanolamine (Cuéllar-Franca & Azapagic 2015; Zhang et al. 2018), is currently one of the most advanced methods available (Finney et al. 2019) which also enables to use membranes to achieve selective partition of molecules (Bui et al. 2018).

There is still an ongoing research effort to find the optimal solution and possibly improve the methods that are already in use. The feedstock used can vary from non-renewable (Zhang et al. 2018) to renewable fuels, for example, biomass. One of the authors solely focuses on, this matter as a possible option of even cleaner energy for the future by using a combination of CCS attached to biomass-fired plants (Finney et al. 2019).

Most authors agree on the fact that PCC is highly beneficial, as it offers the broadest options for later use since it can be retrofitted to older plants that were not outfitted with these technologies before. This could significantly reduce the costs of equipping such facilities in the future (Benson & Orr 2008; Bui et al. 2018; Zhang et al. 2018; Finney et al. 2019).

Due to the energy-intensive nature of chemical absorption, scientists are continually motivated to reach the envisioned goal of decreasing costs of capture processes. Therefore, it is believed that separation based on membranes, which is simpler and is made of a lower number of components, could produce the desired results and reduce energy intensity while it could be even more environmentally friendly (Wang et al. 2017).

Some of the authors agree on the fact that PCC is possibly the most energetically efficient method. Therefore, it would reduce electricity costs connected with the process since other forms are more demanding on energy in terms of capture of CO_2 (Gibbins & Chalmers 2008; Zhang et al. 2018).

4.1.1.2. Pre-Combustion Capture (Pre-CC)

The method is based on separating CO_2 from the feedstock ahead of ignition (Cuéllar-Franca & Azapagic 2015; Zhang et al. 2018). It has been stated that it could be available at lower prices and its efficiency could be better, but at the same time, there are significant changes that need to be implemented when mounting a Pre-CC system to a plant (Benson & Orr 2008).

Firstly, the fuel must be transformed into a gas by the presence of high pressure and mixed with the air coming from the air separation unit where oxygen and nitrogen have been isolated. The outcome of this process will be synthetic gas, also called syngas, that mostly comprises of CO, CO_2, H_2O, and H (Gibbins & Chalmers 2008). After achieving this, CO is directed towards a catalytic reactor named shift converter in which steam is added and these two components react. The main outcome of such reaction is CO_2 and H_2. CO_2 is later separated by using synthetic absorbents finally producing feedstock flow rich on H_2 (Scholes et al. 2010; Clean Air Task Force 2020), as another advantage of this method is that it can be used with natural gases, as well as generating power in combined cycle (Zhang et al. 2018).

4.1.1.3. Oxyfuel Combustion (OXC)

The main difference of this technological approach is that the ignition of feedstock happens in a setting without normal air. Unlike other approaches, it uses an environment that purely consists of oxygen, therefore, there will be no further need to remove the N_2 from the fumes as it was done in the air separation unit beforehand (Benson & Orr 2008; Cuéllar-Franca & Azapagic 2015). In some cases, this environment can consist not only of oxygen but can be mixed with the reused flue gas which mainly consists of CO_2 and H_2O (Zhang et al. 2018). Removing N_2 from the cycle allows having a cleaner and under pressure easily separable mixture of water and CO_2 (Gibbins & Chalmers 2008). The flue gas is later recirculated into the boiler to control the temperature and is gradually cooled in a condensation unit where CO_2 can be separated by the condensation of water and later compressed for transport (Zheng 2011; Stanger et al. 2015).

It is stated that even in this case it could be possible to retrofit this method into older plants, although further research would be needed to confirm these claims as well as the financial viability of such projects (Benson & Orr 2008).

In March 2015, experts from Australia and Japan finished the construction of the world´s first oxyfuel full-scale demonstration project, Callide oxyfuel project, thanks to the financial support of the governments. This technology can be attached either to power plants or industrial sites (CS Energy Ltd 2020).

4.1.2. Comparison of Capture Technologies

4.1.2.1. Deficiencies of Different Methods

Regarding the PCC, the process of solvent regeneration is the most demanding part of the process in terms of energy consumption (Herzog & Golomb 2004; Wang et al. 2017). Energy consumed can reach up to 3.8-4.0 GJ per one tonne of CO_2 capture in the case of a 600 MW coal-fired power plant (Wang et al. 2017). Major efforts are concentrated on operation optimization, modifications of processes and improving solvents (Cebrucean et al. 2014; Kuckshinrichs & Hake 2015; Wang et al. 2017; Zhang et al. 2018; Wilberforce et al. 2019). At the same time, the research should be focused on the degradation of amine-based solvents as it is considered to be one of the weaknesses of this method (Kanniche et al. 2010).

One of the major drawbacks is the high implementation cost and questionable flexibility of operation of power plants featuring PCC. Secondly, efficiency losses must be taken into consideration as they range from around 9–14% (Kuckshinrichs & Hake 2015). Moreover, Wang et al. (2017) state that these efficiency losses are higher, reaching up to 14-16%. In previous estimates, these numbers amounted to 25% (Benson & Orr 2008).

Pre-CC has the same problem with an excessive energy debt, although it is smaller than in the case of PCC (Zhang et al. 2018). The efficiency losses in the case of Pre-CC specifically using the Integrated Gasification Combined Cycle (IGCC) power plant based on the method of physical CO_2 scrubbing is between 9-12% in Kuckshinrichs & Hake (2015) and 5-11% in Cebrucean et al. (2014). Another issue associated with IGCC power plants is the fact that these plants are highly complex and extensive costs apply to them, excluding CC equipment, therefore the costs would rise even further. Due to this fact, some of the planned projects have not been initiated (Kuckshinrichs & Hake 2015).

As in the case of PCC, one of the main disadvantages of OXC is the high initial cost and questionable flexibility of operation. Another problem is the fact that it is still unclear if OXC can be retrofitted (Kuckshinrichs & Hake 2015).

Compared to the PCC, the efficiency losses of OXC are slightly lower, ranging between 8-11% (more like Pre-CC). It is due to a demanding air separation which causes efficiency loss of 7% on its own. Improvements in air separation units would be needed to reduce losses (Thimsen et al. 2011; Cuéllar-Franca & Azapagic 2015; Kuckshinrichs & Hake 2015; Zhang et al. 2018), in some reviews, the loss connected to air separation reaches almost 10% (Cebrucean et al. 2014).

As such, OXC technology could encounter problems with air discharge because of improper non-airtight instalment. Problems connected with material deterioration and corrosion have been filled (Zhang et al. 2018).

4.1.2.2. Benefits of Different Methods

Kuckshinrichs & Hake (2015) state that some of the major benefits of PCC are: a deep understanding of the process (Zhang et al. 2018), the possibility of improvements in efficiency, commercial availability of equipment (Wang et al. 2017), easy retrofitting to existing power plants (Benson & Orr 2008; Wang et al. 2017) and the fact that no fundamental changes to power plant process are necessary. Lastly, a very important beneficial factor is the highest purity of captured CO_2, which is very close to 100% (Kuckshinrichs & Hake 2015).

According to Kuckshinrichs & Hake (2015), one of the advantages of Pre-CC is the commercial use of a physical scrubbing method on an industrial scale, therefore a lot of extensive knowledge has been obtained. Achieving high purities of CO_2 is another positive aspect of this method. One of the other major advantages of Pre-CC from IGCC plants is the possibility of generating power and at the same time providing other products from syngas, e.g. methanol and synthetic fuels.

The Pre-CC technology is energy-efficient compared to PCC and OXC and uses less water because of the usage of a lower amount of gas in an environment with higher pressure and higher supply of CO_2 (Zhang et al. 2018).

High-efficiency potential, commercial availability of necessary technical components, availability of large-scale air separators sufficient for oxygen production and lastly no need to dispose of any by-products are the most considerable advantages of OXC (Kuckshinrichs & Hake 2015).

Benson & Orr (2008) state that there would be a possibility of retrofitting of OXC technology to power plants, but according to Kuckshinrichs & Hake (2015), it is still unclear whether this will be possible in the future. Zhang et al. (2018) add that retrofitting should be possible.

In comparison to other methods, OXC reaches the lowest discharge amounts of pollutants. Another factor is its applicability to a variety of fuels. It has very high efficiency in eliminating CO_2. It excels in small size, compatibility with conventional steam cycle and highly developed method of air separation (Zhang et al. 2018).

4.1.2.3. Financial Prospects of Different Methods

IEA (2015a) has also focused on other industries such as processing natural gas (NG) as well as fertiliser, bioethanol, and hydrogen production in which the costs can be as low as US$5-20/t of CO_2 avoided. In steel or cement production the prices are close to US$60/t.

According to Gibbins & Chalmers (2008), the total electricity costs of PCC could be lower than those in the case of Pre-CC in use with natural gas plants. On the other hand, Pre-CC from IGCC plants is projected to possibly produce electricity at lower costs than in the case of PCC used in combination with coal. This fact is mainly supported by high initial costs of PCC operations as well as frequent change of the solvent.

In some regions, transfer from coal to gas would be beneficial because of low gas prices and the fact that it produces less CO_2. The amount of CO_2 emissions doubles in case of coal-fired plants from 400 kg/MWh to 800 kg/MWh. A possible addition of the CC technology to coal-fired plants could increase power generation costs by 40-63% to approximately US$100/MWh. Despite this fact, it is still considered to be competitive with the prices of solar photovoltaic and offshore wind costs. Furthermore, the energy can be produced according to a current demand (IEA 2013).

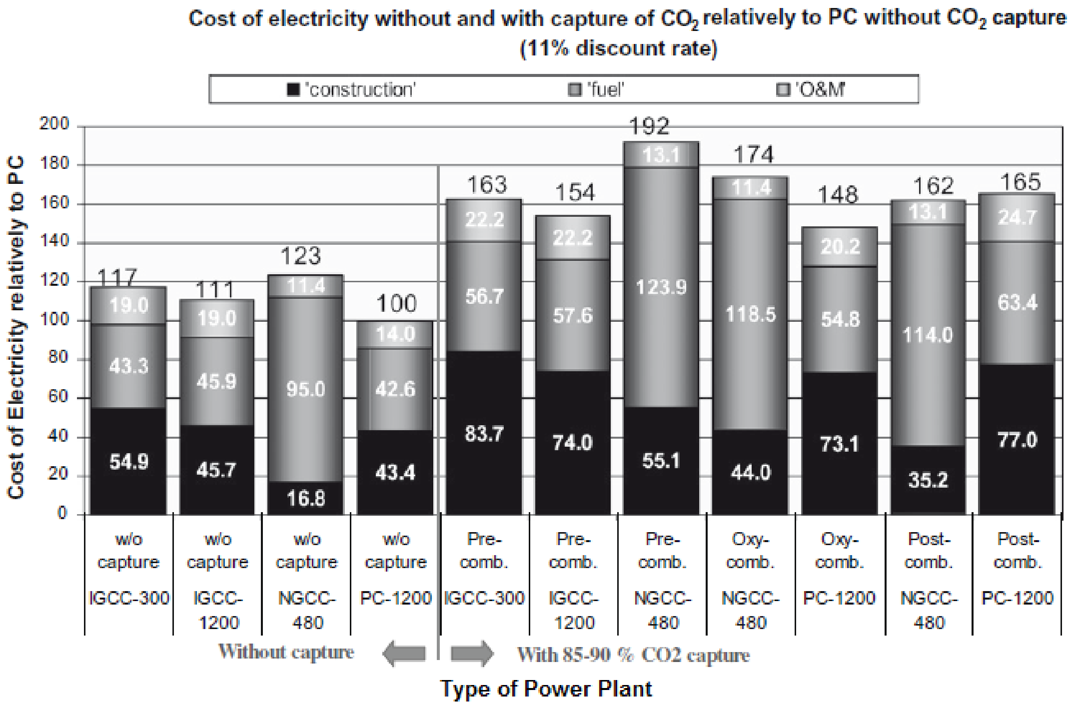
Because of the size of the PCC plants, this correlates with the higher purchase and operational costs. Solvent-based capture is financially demanding in terms of equipment (Zhang et al. 2018).

According to predictions and calculations made by Wang et al. (2017) in case of Pre-CC, the price would rapidly rise for one kW produced from €980/kW without CC equipment to €1,865/kW with CO_2 capture. Naturally, fuel prices, interest rates and time of operation must be taken into consideration.

The cost of Pre-CC is substantially higher than of a conventional coal power plant (Zhang et al. 2018). The main factor of production costs in the case of natural gas-fuelled plants is the fuel price. On the contrary, in the case of coal-fired plants, the main factor is the investment cost of the plant (Feron & Hendriks 2005).

OXC is financially the most promising method as the capital costs of the division of air from oxygen and other processes are cost-efficient (Zhang et al. 2018). Thimsen et al. (2011) concluded that the initial costs of the OXC method were slightly lower compared to those of PCC. PCC has significantly higher final purity of CO_2 compared to OXC, therefore it is reflected in the overall cost of capture methods. At the same time, OXC eliminates almost 100% of CO_2 and in the case of PCC, it results in 90% of CO_2 captured.

Figure 3 illustrates the electricity costs concerning different types of power plants with and without CC (including additional nomenclature). From the figure is visible that the lowest price was reached with PC-1200 plant which is not equipped with CC technology and the highest cost was in the case NGCC-480 plant where Pre-CC was applied, moreover, PC-1200 with OXC technology proved to be the cheapest option within the range of power plants equipped with CC technology.



Nomenclature

IGCC	Integrated gasification combined cycle
IGCC-1200	IGCC of quench type delivering 1200 MWe as gross power output
IGCC-300	IGCC of radiant type delivering 300 MWe as gross power output
NGCC	Natural Gas Combined Cycle
NGCC-480	advanced NGCC delivering 480 MWe as gross power output
PC	Pulverised coal power plant
PC-1200	PC delivering 1200 MWe as gross power output

Figure 3. Comparison of total costs of energy in various types of power plants in %

Source: Kanniche et al. (2010)

4.2. Transport and Storage of Carbon Dioxide

4.2.1. Transport of Captured Matter

As the capture of CO_2 might not take place at the exact location where it will be stored, a transportation system needs to be developed. Several options for transportation of CO_2 arise. Mainly pipelines have been considered as well as other options: shipping, road, or rail transportation. This will primarily be decided based upon the distance (Tan et al. 2016), availability of infrastructure as well as the scale of the capture operation that will be connected to the storage site (Lokhorst & Wildenborg 2005).

Plasynski et al. (2009) state that pipelines are generally the most viable solution for CO_2 transportation in commercial CCS projects because of the large volumes of the transported material. This has been confirmed as the most common method for such transport by Tan et al. (2016). The method mentioned has already been applied in the Weyburn project, which has a length of 320 km. This pipeline supplies Enhanced Oil Recovery (EOR) operations with CO_2 and it can transport up to 5,000 t/day of 95% pure CO_2. According to Bui et al. (2018), there is already more than 6,500 km of operational offshore and onshore CO_2 pipelines in the world. At the same time, considering storage with other undesirable gases such as H_2S, SO_X, NO_X, such action would require special design of the pipeline to enable mixed stream transportation. Transportation of CO_2 requires compression of the matter to 100 bar into a liquid state (Benson & Orr 2008), but these numbers vary, as it is 150 bar according to Plasynski et al. (2009) and 80 bar according to Tan et al. (2016). The pipelines should also be appropriately sized according to the size of the CCS facility and its annual output (Tan et al. 2016).

To avert pipeline corrosion, dehydration of CO_2 needs to be conducted before its transportation. Another preservation is assured by cathodic protection of the pipeline. The experience from established petroleum or natural gas pipelines has been beneficial and applied to the development of CO_2 pipelines mainly using already developed construction methods in an undersea environment. Some of the disadvantages of underwater pipelines are the depth limits for construction, maintenance, positioning and anchorage of such system, with limits of approximately 450 m in manned diving operations and 1,000 m in automated dives conducted by a robot (Adams et al. 1995).

Should the depth exceed these limits, discharge from floating platforms, that are equipped with vertical pipes attached to the sea bottom, can be used instead. In this case, liquified CO_2 would have to be shipped by tankers to the platforms and consequently injected. One unfavourable factor for this method is its very high cost of building ships for this purpose and secondly the volume of CO_2 that power plants would produce which would result in a large number of trips that would need to be undertaken to deliver such volumes to the platforms (Adams et al. 1995).

In some circumstances shipping could be considered as well, mainly because of its flexibility as well as the fact that over long distances, the costs would be reduced significantly. The research and development (R&D) phase would have to be employed as there are numerous factors to consider in ship transport, for example, pressure, temperature, and density of transported material as these would impact the design of the support and thickness of the tank and material used, because of the temperature and lastly the tank insulation (Tan et al. 2016).

Lastly, economic factors affect the decisions, as the costs of each method vary greatly. In the case of the pipeline, it is mostly determined by the length, the terrain, and the depth. If economic viability were calculated using over 10 million metric tons annually (that could be produced by a 1,500 MW coal plant) pipelines cost would be estimated at US$0.50/t/100 km where on the other hand the cost of road transport would be significantly higher reaching US$6/t/100 km (Herzog & Golomb 2004). Adams et al. (1995) have previously estimated the price of 100 km offshore pipeline reaching the depth of 1,000 m being at US$300,000,000 and this amount would exclude land transport.

4.2.2. Storage of Captured Matter

After the capture and the transport of the molecules of CO_2, subsequent storage in a place that prevents the substance from leaking must follow. Such action prevents the return of CO_2 into the atmosphere. Storage is one of the possibilities to dispose of this undesired GHG. Another possibility is to utilize the captured CO_2 (Benson & Orr 2008). CCU will be reviewed and summarized in the next chapter.

Carbon Storage projects are already operational on different levels ranging from research-oriented pilot projects to full-scale commercial projects. The oldest of the large-scale storage projects is situated in Norway. The Sleipner project has been operational since 1996 and it has been under the control of Equinor. It is capable of injecting 1 million tonnes of CO_2 annually (Furre et al. 2017; Ringrose 2018; Equinor 2019). Since 2008, this project has been accompanied by another Norwegian Carbon Storage project in Snøhvit to decrease CO_2 emissions from natural gas extraction operations reaching up to 700,000 t of CO_2 captured annually (Equinor 2008; Cebrucean et al. 2014; Offshore Technology 2020). Other projects that are worth mentioning due to their long operation of more than 10 years are Canadian Weyburn-Midale project, Algerian In Salah project and the US Salt Creek project (Metz et al. 2005; Cuéllar-Franca & Azapagic 2015). Norwegian projects inject CO_2 into deep saline aquifers. Canadian, US and Algerian projects use depleted oil and gas reservoirs (Cuéllar-Franca & Azapagic 2015).

4.2.2.1. Geological Storage

Geological Storage (GS) has a very high potential as the available underground storages are vast. Therefore, large amounts of CO_2 could be sequestrated in the future (Gibbins & Chalmers 2008; Cuéllar-Franca & Azapagic 2015; IEA 2015a). IEA (2015a) highlights the fact that although there are a large number of locations suitable for storage if a commercial deployment is to be implemented from the 2020s, more effort must be put into characterization and transformation of the chosen locations into functional storage sites. Ideal places for such storage of CO_2 are depleted fossil fuel reservoirs, deep coal seams that are not suitable for mining, caverns and mines or saline aquifers (Lokhorst & Wildenborg 2005; Benson & Orr 2008; Cuéllar-Franca & Azapagic 2015). There is insufficient knowledge about the injection of CO_2 into coal bed formations, therefore more research needs to be conducted on this topic (Metz et al. 2005; Shi & Durucan 2005; Cuéllar-Franca & Azapagic 2015).

In general, the techniques already known from oil drilling have been implemented. This fact supported the increase of the efficiency and improvements in monitoring and modelling of CO_2 storage sites. Technologies undertaken from oil drilling include well-drilling, injection of undesired CO_2 and computer monitoring and various simulation methods that predict future events. These strategies have been further tested to ensure that they prove reliable when used in CO_2 storage, making it currently one of the most promising storage technologies (Metz et al. 2005; Gibbins & Chalmers 2008; Cuéllar-Franca & Azapagic 2015).

The storage itself is based on the safe injection of the compound into a carefully selected porous geological rock formation. The depth of such formations varies, but in general, CO_2 is stored between 0.8 and 2 km beneath the Earth's surface. The storage is necessarily accompanied by the correct temperature and pressure to ensure that it stays in a liquid or supercritical form which is met at 31.1°C and 73.8 bar (Cuéllar-Franca & Azapagic 2015). The density of the compound in these conditions prevents easy leakage. After the injection of CO_2 into depths, various physical and geochemical trapping mechanisms prevent migration of the compound back to the surface. One of the common trapping mechanisms is the use of caprock, as the liquified gas tends to move upwards through the storage site until it reaches the impermeable layer of rock. Caprock usually consists of mudstone or clay. These materials trap CO_2 in a process called structural storage. This reaction will later help to bind CO_2 chemically to the surrounding rock in an irreversible reaction, so-called mineral storage (Metz et al. 2005; Cuéllar-Franca & Azapagic 2015; Kuckshinrichs & Hake 2015; Wilberforce et al. 2019).

However, safety measures must be implemented to prevent leakage. According to Lilliestam et al. (2012), this leakage should not be detrimental to the environment, but it would inhibit the mitigation of CO_2 emission. Cuéllar-Franca & Azapagic (2015) mention that the rate of leakage varies from 0.00001% to 1% depending on the conditions of storage and other various factors. Therefore, monitoring of storage site is essential to prevent any cracks and following re-emission of CO_2. Mapping the paths that could lead to fast leakage is important as well (Metz et al. 2005; Lilliestam et al. 2012; Kuckshinrichs & Hake 2015). Finney et al. (2019) state that one of the main challenges will be to eliminate impurities (moisture, acid gases, metal aerosols, etc.) as these could potentially influence the safety of storage of the compound because of its reaction with and degradation of materials used during the transport and storage phase. According to Wilberforce et al. (2019), the possibility of heightened seismicity due to CO_2 injection exists.

4.2.2.2. Ocean Storage

Ocean storage is established on the fact that the ocean itself is already the biggest natural carbon sink on the planet containing approximately 40,000 GtC. The number is incomparably higher than the volume which is found in the atmosphere and the biosphere combined which equals mere 2,950 GtC (Herzog & Golomb 2004). Vastness of the ocean could provide significantly higher numbers of stored CO_2 if deep ocean storage or dissolving of CO_2 in the water column is to be implemented. Additionally, these processes would only accelerate the natural process of carbon exchange between the atmosphere and the ocean (Herzog & Golomb 2004; Bui et al. 2018). This would allow the sequestration of CO_2 from the atmosphere for centuries (Tan et al. 2016). However, ocean storage has never been tested on a large-scale, even though it has been studied theoretically in laboratories and various modelling projects for over 30 years (Metz et al. 2005; Sheps et al. 2009; Cuéllar-Franca & Azapagic 2015).

First of these methods relies on the use of steady pipeline or a mobile tanker (Metz et al. 2005; Benson & Orr 2008) from which the CO_2 would be injected and subsequently dissolved into the water column. This approach disperses and dissolves liquified CO_2 droplets into the ocean, later becoming a part of the global carbon cycle. According to

Benson & Orr (2008) and Herzog & Golomb (2004), using a diffuser could lead to a faster dissolution of CO_2. Depths of injection vary, usually reaching 1,000-3,000 m (Herzog & Golomb 2004; Metz et al. 2005; Benson & Orr 2008; Plasynski et al. 2009; Tan et al. 2016). The depth must not be less than 500 m as the pressure lower than 50 bar would allow liquified CO_2 to vaporize and return into the atmosphere. In deeper waters, liquified CO_2 has a lower density than seawater, enabling it to ascend due to its buoyancy. The main advantages of this method are the availability of the technologies and minimization of impacts on the surrounding environment (Herzog & Golomb 2004).

Secondly, a deep-water release method can be used in combination with a pipeline or offshore platform that delivers CO_2 onto the seabed with depths exceeding 3,000 m. Such depth guarantees higher density of CO_2 compared to the surrounding water, therefore forming a “lake” (Metz et al. 2005; Adams & Caldeira 2008; Benson & Orr 2008; Tan et al. 2016) which entraps CO_2 in created CO_2 hydrates surrounding the molecule of CO_2 with water molecules due to pressure and temperature (Herzog & Golomb 2004). Some authors state that ocean circulation, tides, and currents could cause a partial return of CO_2 into the atmosphere. However, this fact is very site-specific and it would be a question of centuries or millenniums (Benson & Orr 2008; Sheps et al. 2009; Tan et al. 2016). According to Sheps et al. (2009), deep ocean storage is one of the most economically feasible options.

Other methods such as dry ice disposal, CO_2-seawater mixture injection (Adams et al. 1995; Herzog & Golomb 2004) or Ocean Fertilisation (OF) were considered. The OF process relies solely on enhancing natural processes by adding a fertilizer in the form of iron to improve photosynthesis executed by phytoplankton leading to a higher absorption rate of CO_2 (Sheps et al. 2009; Bui et al. 2018).

Ocean storage is still in the early stages of development, therefore not much is known about its possible ecological impacts (Metz et al. 2005; Bui et al. 2018). The main concern is leakage and consequential damage that a concentrated CO_2 stream could cause to the surrounding marine environment (Metz et al. 2005; Plasynski et al. 2009; Cuéllar-Franca & Azapagic 2015; Kuckshinrichs & Hake 2015). The main issue is the acidification of seawater which lowers the current pH and long-term exposure to such conditions (Herzog & Golomb 2004; Metz et al. 2005; Plasynski et al. 2009; Sheps et al. 2009; Kuckshinrichs & Hake 2015). According to Plasynski et al. (2009), these might be the reasons why implementation of the technologies is so slow and difficult from the environmental and legal side as there are several treaties and national laws restricting ocean storage of CO_2. However, Herzog & Golomb (2004) estimate that if all man-made carbon dioxide would be injected into the deep ocean it would change the pH level of the ocean only by 0.15 units.

In Figure 4 graphical presentation of the ocean, storage can be seen.

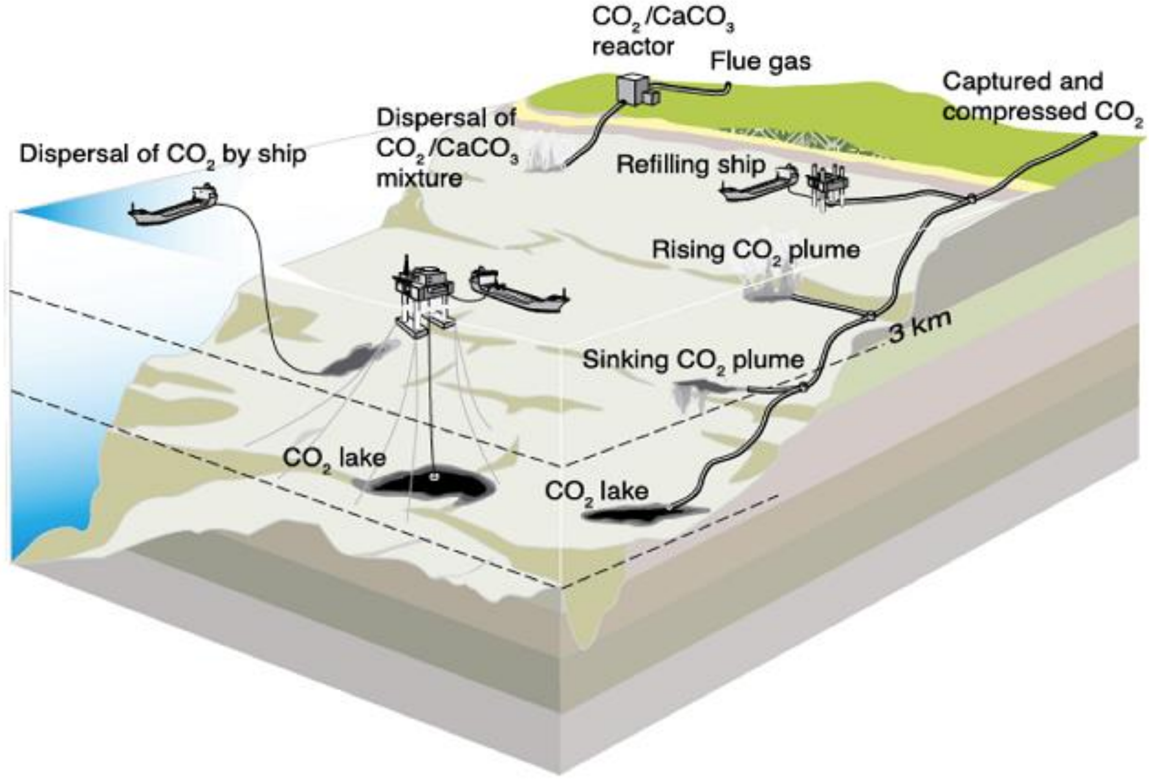


Figure 4. Different methods of CO_2 injection into the ocean

Source: Metz et al. (2005)

4.3. Carbon Utilisation

Carbon utilisation is an important part of carbon reduction strategies as the process adds value to the undesired compound. Therefore, its market value could lead to a broader spectrum of utilization opportunities and would increase demand for carbon utilization and at the same time, it would help to mitigate GHG.

4.3.1. Enhanced Oil Recovery

Enhanced Oil Recovery utilizing CO_2 (CO_2-EOR), a technology that achieved the highest maturity level (Gozalpour et al. 2005; Bui et al. 2018), is a tertiary recovery method. In this process, injection of liquified CO_2 into the basin increases oil extraction by up to 15% (Kuckshinrichs & Hake 2015), based on pressure and enhancement of oil properties due to reaction with CO_2, leading to easier flow (Metz et al. 2005; IEA 2013; Global CCS Institute 2016; Tan et al. 2016; Bui et al. 2018).

CO_2-EOR is widely distributed throughout the USA since the 1970s (Lokhorst & Wildenborg 2005; Metz et al. 2005; IEA 2015b). Approximates in the amount of CO_2 pumped below the surface ranges from 30 Mt (Metz et al. 2005) to 60 Mt of CO_2 annually (IEA 2013). According to (Global CCS Institute 2020) a method combining CO_2-EOR with CCS called EOR+ can reach lower emissions by 50% compared to traditional oil recovery methods.

However, the major part of CO_2 used for these operations is naturally occurring, reaching up to 70% (Global CCS Institute 2020). Plasynski et al. (2009) suggest the usage of CC and CO_2-EOR in regions lacking natural CO_2 to effectively utilize anthropogenic CO_2.

More than half of injected CO_2 stays in the basin and the rest is brought back to the surface with extracted oil. Afterwards, it is separated and recycled for further use in EOR. Therefore, the operation functions as a closed circuit (Gozalpour et al. 2005; IEA 2015b; Bui et al. 2018). In the end, the CO_2 should remain sequestrated as in the case of Weyburn (Metz et al. 2005). Herzog & Golomb (2004) warn that the end of the process involves "blowing out" phase that releases part of the CO_2 back to the atmosphere to maximize oil recovery.

Figure 5 contains a visualization of the closed-circuit principle, where CO_2 is captured, utilized for EOR, and subsequently recycled from extracted oil for further use.

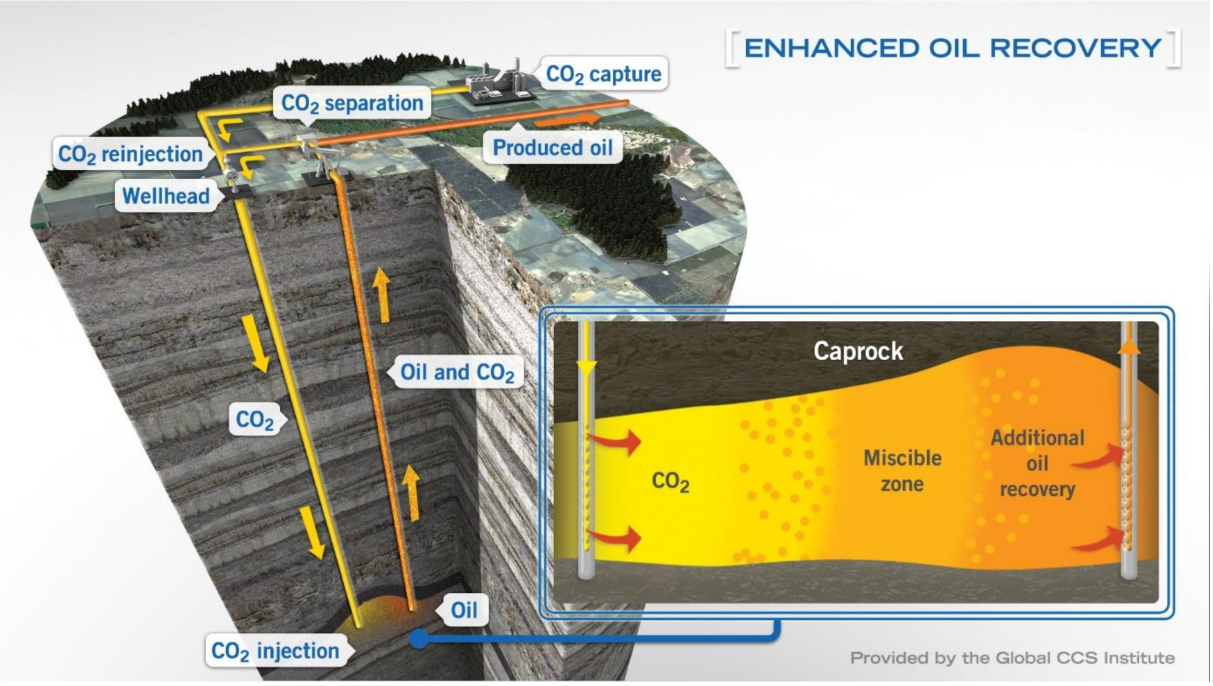


Figure 5. EOR technology scheme

Source: Global CCS Institute (2018a)

Nonetheless, CO_2-EOR insufficiently concentrates on CCS as its major goal is to augment oil production. Significant changes in operation would have to be introduced in risk and site assessments, and monitoring if EOR+ is to be implemented (Lokhorst & Wildenborg 2005; IEA 2015a; Bui et al. 2018), because not much attention was given to safe storage in EOR operations (Kuckshinrichs & Hake 2015). In the case of EOR minimum amounts of CO_2 were demanded to produce the highest amounts of oil for operation efficiency. On the other hand, in EOR+ maximization of both would be required (Lokhorst & Wildenborg 2005; Plasynski et al. 2009; IEA 2013; Bui et al. 2018). IEA (2013) and Bui et al. (2018) add the fact that there are 140 such projects around the globe from which only approximately 6 are EOR+. Even though EOR+ operations would reach negative emissions (case-specific), storage in saline aquifers is more efficient as it does not produce any additional CO_2 (IEA 2013).

Gozalpour et al. (2005) summarize the major benefits and obstacles to technology. CO_2 is considered as the best gas to use in EOR due to its properties. Offshore CO_2-EOR operations were suggested as these could be safer due to the behaviour of CO_2 in depths.

Farajzadeh et al. (2020) researched the exergetic efficiency of EOR+ and it considers the whole cycle. The main findings are the need for the cost of CO_2 separation reduction, high emissions of CO_2 during the whole process as with current technology it would produce more CO_2 than it would store. Claiming that this technology is unsustainable, as it consumes more energy than is produced from the obtained oil, as 35-50% of the extracted oil would have to be used for capture, transport and storage.

The approach could have the potential of storing from 70 up to 360 Gt depending on intensity but it admits that it might be a very optimistic assessment (Rystad Energy 2017; Bui et al. 2018). Future implementation of EOR+ would vitally need financial incentives, higher oil prices (to compensate the cost of CCS), and lower costs of CO_2 (Gozalpour et al. 2005; Metz et al. 2005; Bui et al. 2018).

4.3.2. Advanced Biofuels

Due to unlimited demand for fossil fuels and various government support schemes for biofuels mainly in the USA and EU, a favourable environment was established for prospective research, expansion and improvements in the creation of plant-based biofuels of newest generation mostly based on photosynthetic microalgae and cyanobacteria (Alam et al. 2012; Jones & Mayfield 2012). However, macroalgae as seaweeds have high potential as well (Sahoo et al. 2012). The flexibility of the algae-based biomass to produce various biofuels like bioethanol, biodiesel, biogas, likewise biohydrogen increases its significance as diversification of production could improve its economic outlook (Jones & Mayfield 2012).

These biofuels, produced from lipids and carbohydrates, are a result of photosynthetic reactions in various algae species that can produce high amounts of oil and achieve high biomass yields (Alam et al. 2012; Jones & Mayfield 2012; Alalwan et al. 2019).

The 1st generation of biofuels lacked efficiency related to growth. Its cultivation jeopardizes biodiversity and creates an issue as arable land is occupied with energy crops instead of food production leading to food shortages. In the case of 2nd generation costly transformation operations were the main deficiency. The 3rd and 4th generations do not interfere with these operations (Alam et al. 2012; Jones & Mayfield 2012; Sahoo et al. 2012; Alalwan et al. 2019). According to (Alalwan et al. 2019) 4th generation of biofuels will involve (genetically modified) microorganisms as microalgae, yeast, fungi, cyanobacteria with a desire to minimize emissions. At the same time, it would include technologies especially used in combination with the latest generation of biofuels as pyrolysis and gasification. However, technology is still in the early development stage.

Even though 1st and 2nd generation of biofuels are not as effective as algae, they are still recommended as a part of CO_2 mitigation efforts as the crops e.g. corn, rice, and sugar cane can still decrease the amounts of atmospheric CO_2 with a beneficial impact on climate change (Alam et al. 2012; Cheah et al. 2016; Moreira & Pires 2016).

The capture of CO_2 and its utilization through algae biomass can be applied to industrial sources of CO_2. Suresh et al. (2011) and Cheah et al. (2016) agree on the fact that direct seepage of flue gases into the algae reservoir needs further examination as it could unfavourably affect the organisms due to its high concentration of CO_2 in the stream, high temperature, and presence of toxic SO_x.

The big advantage of this method is the option of direct air capture of CO_2 from the atmosphere by algae and its fixation in the organisms. Direct air capture from flue gases could lead to a 70% cost reduction due to elimination of CC costs (Sahoo et al. 2012). Cheah et al. (2016) state that conversion into biofuels and bioenergy is a better option compared to CCS technology.

Open system cultivation is established in naturally occurring or artificial bodies of water. It is used for cultivation of algae for biofuel production and CO_2 removal. Construction and operation of such facilities are easy, however, poor utilization of solar radiation, high evaporation rate, the release of CO_2 back to the atmosphere and possible contamination of other waterways with genetic material in case of genetically modified algae are major drawbacks (Alam et al. 2012; Sahoo et al. 2012; Abdullah et al. 2019).

Closed system cultivation or photobioreactor (Alam et al. 2012) occurs in the artificially built environment, which has the benefits of high productivity rates, low risk of contamination, large surfaces for proper illumination, thus improving the conditions for algae growth (Alam et al. 2012; Sahoo et al. 2012; Abdullah et al. 2019). Adeniyi et al. (2018) consider photobioreactor as the most effective method due to its high productivity and its enhanced environmental conditions, however, it has very high costs, and there are environmental risks involved.

4.3.2.1. The versatility of production from algae biomass

Due to low lignin content and high amount of sugars in algae, implementation of fermentation procedures to produce bioethanol are possible. Development in saccharification processes is needed to enhance sugar yields from agar as nowadays it is difficult to extract. Especially green algae have high potential as these accumulate high levels of polysaccharides and starch that can be used for transformation into bioethanol (Alam et al. 2012; Jones & Mayfield 2012; Cheah et al. 2016; Alalwan et al. 2019). According to Alalwan et al. (2019), it is easier to obtain ethanol from algae than it is in the case of energy crops.

Biodiesel can be obtained on account of transesterification processes as these transform lipids which are used by algae for storage purposes and are found in high amounts of up to 50-60% measured in dry weight (Jones & Mayfield 2012). After the transesterification process is accomplished, lipids become very much alike as other oils obtained from energy crops. Cost issues occur, but these could be decreased with further research (Alam et al. 2012; Jones & Mayfield 2012; Cheah et al. 2016; Suganya et al. 2016; Alalwan et al. 2019).

Biodiesel produced from algae is perceived as a very potential biofuel (Alam et al. 2012; Jones & Mayfield 2012; Alalwan et al. 2019). Alalwan et al. (2019) add the fact that the biodiesel could have slightly lower heating value compared to fossil fuel. Furthermore, Sahoo et al. (2012) declare that nitrogen deficiency in algae production could have beneficial impacts on oil quantity and quality.

However, not only liquid biofuels can be obtained from microalgae, as even gaseous biofuels are a viable option. Other significantly competitive biofuels obtained through anaerobic fermentation are biohydrogen and biogas (biomethane), that can be utilized as fuel or for energy production. Algae are ideal due to their lack of structural lignin; therefore, they are easier to digest. Although further development of pre-treatment technology for process optimization is required (Jones & Mayfield 2012; Cheah et al. 2016; Suganya et al. 2016; Moravvej et al. 2019). Biohydrogen can be obtained through photofermentation as well (Jones & Mayfield 2012; Rastogi et al. 2018).

Production of biogas is carried out by anaerobic digestion which transforms biomass into volatile fatty acids and methane that can be later used as biogas (Jones & Mayfield 2012; Moreira & Pires 2016; Suganya et al. 2016). After the digestion, methane can be captured at the pressure of 1 bar and when it reaches purity exceeding 95%, it can be subsequently transported as Compressed Natural Gas. During the processes, other compounds as H_2S, NH_3, O_2, N_2, and CO can be created (Moreira & Pires 2016). According to Jones & Mayfield (2012), biogas production could potentially decrease impacts of detrimental algal blooms to be used for biomethane production instead, yet the production is still limited due to technical immaturity. Cheah et al. (2016) mention that the highest efficiency in net energy gain is achieved within the biomethane.

In Figure 6 visual representation of the production versatility can be seen.

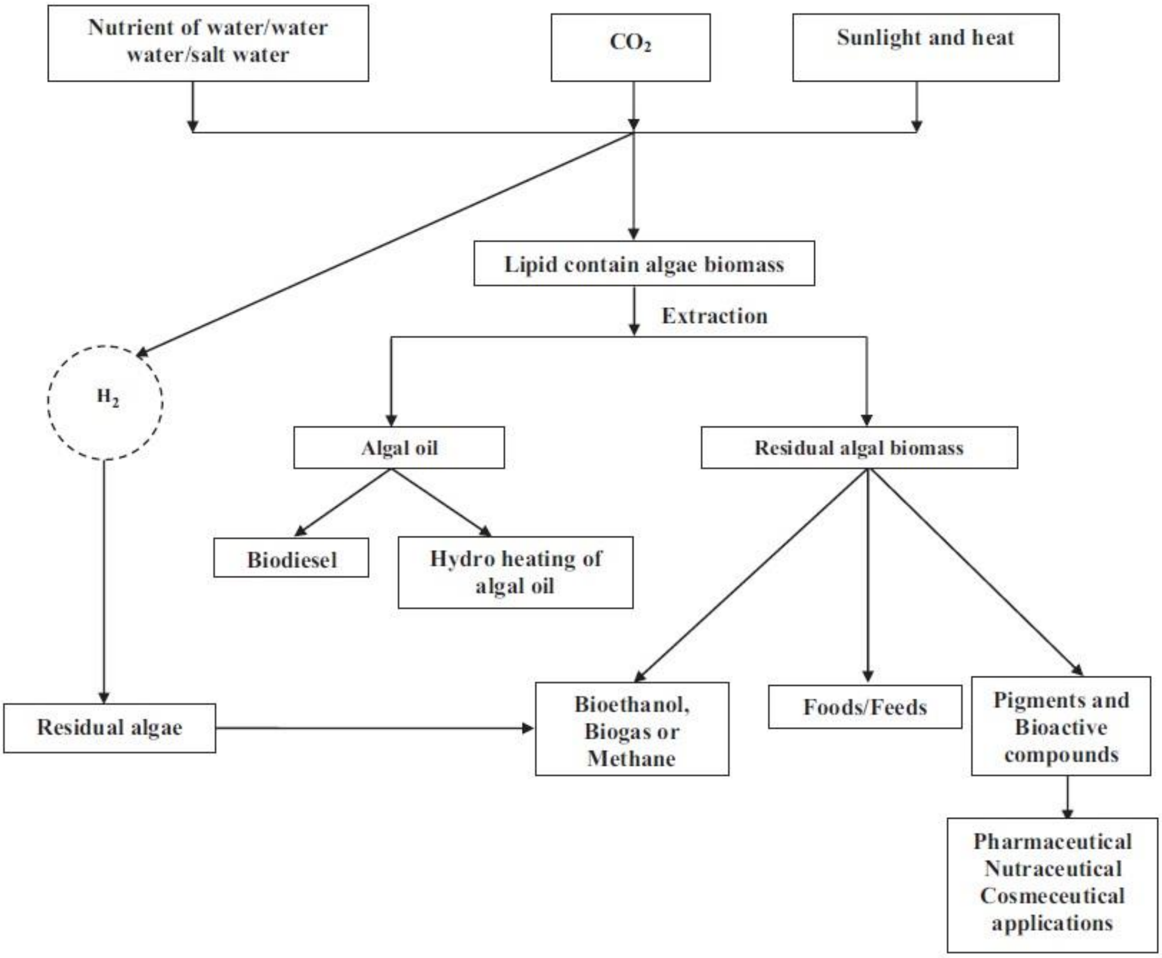


Figure 6. Opportunities of biorefinery for future utilization of algae biomass

Source: Suganya et al. (2016)

Further utilization of algae biomass is possible in various directions. Mainly in the chemical production of many dyes, polyunsaturated fatty acids, polysaccharides, antioxidants, and other bioactive compounds as they contain substantial amounts of lipids and carbohydrates that can be utilized, thus, enabling commercialization of biomass within fields of pharmacy, nutritional additives, food, and cosmetics (Alam et al. 2012;

Sahoo et al. 2012; Adeniyi et al. 2018; Alalwan et al. 2019). Another very favourable consequence of the presence of algae is the impact on marine life as it provides shelter, retention of biodiversity, and supply of nutrients which results in higher fish productivity (Moreira & Pires 2016). Additionally, it can remove NH4, NO3, PO4 from wastewater (Alam et al. 2012).

4.3.2.2. Strengths and weaknesses of advanced biofuels

Microalgae have very serious potential as benefits overweight their negatives. The main positives of these organisms are fast growth where the harvest of microalgae can be reached as soon as in 1 to 10 days and can double their body mass within 24 hours (Alam et al. 2012). No limitations exist on the number of harvests compared to terrestrial crops (Suresh et al. 2011; Alam et al. 2012; Suganya et al. 2016).

Its significant impact on global warming is decisive as this technology could potentially mitigate CO_2 emissions due to its advanced carbon fixation ability leading to net-zero emission balance of energy production (Suresh et al. 2011; Alam et al. 2012; Jones & Mayfield 2012; Sahoo et al. 2012; Moreira & Pires 2016; Alalwan et al. 2019) as photosynthesis reaches much higher solar efficiency than in terrestrial plants (Alam et al. 2012). Moreira & Pires (2016) state that phytoplankton already accounts for up to 50-70% of global carbon fixation and commercial utilization could increase it.

The great productivity of lipids and carbohydrates makes algae the perfect candidate for biofuel generation. Oil content can reach up to 15-80% in dry matter of the algae biomass (Alam et al. 2012; Alalwan et al. 2019). In comparison with energy crops, algae biofuels could produce up to 300 times more oil (Sahoo et al. 2012; Alalwan et al. 2019). Algae or seaweeds can annually produce up to 19,000 litres of biofuel per acre whereas in the case of soybean it is only 180 litres (Sahoo et al. 2012).

Another of its benefits is the fact that algae can survive in various environments as it has very low demands. Therefore, seawater, non-potable water, wastewater and placement on non-arable land in artificial reservoirs can be used for its production and H_2O, CO_2, solar energy, inorganic salts, and temperatures around 20-30°C are vital for its cultivation (Alam et al. 2012; Jones & Mayfield 2012; Sahoo et al. 2012; Suganya et al. 2016; Rastogi et al. 2018; Alalwan et al. 2019). Chemical composition and performance of algae can be manipulated through adjustments of the environment through control of sunlight, temperature etc. (Alalwan et al. 2019; Moravvej et al. 2019).

Furthermore, it has greater efficiency of admission to nutrients and water due to the aqueous environment (Alam et al. 2012; Jones & Mayfield 2012; Moravvej et al. 2019). Its cultivation does not need pesticides or herbicides (Alam et al. 2012; Sahoo et al. 2012). Jones & Mayfield (2012) affirm that the fertilizer intake process is very efficient in the case of algae.

Algae biofuels can be used in the transport industry, possibly reducing its high emissions (Alam et al. 2012; Jones & Mayfield 2012; SCOT Project 2015). In comparison to fossil fuels, CO_2 emissions could be reduced by up to 90% (Alam et al. 2012).

Alalwan et al. (2019) state that one of the biggest positives about liquid biofuels is compatibility with current engines used in the automotive industry.

On the contrast, the main deficiencies of this technology are complex technological challenges and other difficulties that can be eliminated through further R&D. Furthermore, these are accompanied by financial demandingness of actions as harvest and chemical processes during transformation (Alam et al. 2012; Jones & Mayfield 2012; Adeniyi et al. 2018; Abdullah et al. 2019; Alalwan et al. 2019). Adeniyi et al. (2018) wrote that further improvements in fuel blends and its properties will be needed. Jones & Mayfield (2012) add that high energetical severity is caused by high water content in biomass, as dehydration activities account for up to 69% of energy input. Processes without dehydration process could reduce costs.

Metabolic engineering could influence the performance of organisms involved in the operations and accordingly fuel quality and quantity. Improvements in the production process must be made to commercialize it (Alalwan et al. 2019).

The crucial part of further research will be the selection of the most efficient species for carbon fixation and biofuel generation (Alam et al. 2012; Jones & Mayfield 2012; Moreira & Pires 2016).

Raslavičius et al. (2018) mention that biofuel production from algae will have a significant role, nonetheless, it will be dependable on governmental efforts on climate change mitigation, forthcoming policies and possible financial support, technological advancement as well as socio-economic developments.

4.3.3. Mineral Carbonation

The principal part of mineral carbonation is a chemical reaction between CO_2 and metal oxide e.g. Mg or Ca. The outcome of this reaction is the creation of silica and carbonates such as limestone or magnesium carbonate (Metz et al. 2005; Romanov et al. 2015; Chiang & Pan 2017). Ideal sources of these two compounds are minerals as olivine or serpentine (Metz et al. 2005; Markewitz et al. 2012; Kuckshinrichs & Hake 2015; Chiang & Pan 2017).

This process can be done in two main forms, firstly as an in situ (mineral carbonation) process occurring within silicate rocks where CO_2 can be injected for storage and secondly ex situ (accelerated carbonation) which is an enhanced naturally occurring process of weathering. In situ has lower energy requirements, however, the process itself is much longer but its main purpose is storage and is not supposed for mining operations. For ex situ process various types of waste products from metallurgy, power plants and cement facilities can be used. Additionally in ex situ process mining takes place which enables further industrial processing of the matter (Metz et al. 2005; Romanov et al. 2015; Chiang & Pan 2017). Moreover, it offers reuse of materials, low materials costs and high availability of storage sites (Chiang & Pan 2017).

Cuéllar-Franca & Azapagic (2015) add that one of the benefits of this process is the fact that there is no need for usage of high purity CO_2 stream and that it can contain residues from flue gases. With such low demands, costs can be decreased since the purification process is not needed. Another beneficial factor is the high abundance of such metal oxides that exceed the volume which is needed for mitigation of emissions produced by fossil fuels (Metz et al. 2005).

Such fixation of CO_2 is desired as it results in long-term storage without any environmental risks as in the case of geological or oceanic storage where leakage can occur. Products of this reaction can be stored in silicate mines or can be recycled into construction materials (Markewitz et al. 2012; Romanov et al. 2015; Chiang & Pan 2017). Furthermore, Romanov et al. (2015) suggest the usage of the products such as lime in various industries including road constructions and mostly cement industry stating that such action could lead to further cost improvements as commercial deployment would decrease mining operations but the chemical transformation of limestone into lime would create further CO_2 emissions. However, as in the most technologies mentioned in this

Thesis very common issues as high cost and the need for further refinement of technologies arise due to its high energy penalty (Metz et al. 2005; Cuéllar-Franca & Azapagic 2015).

4.3.4. Other Opportunities for Carbon Utilization

According to Kuckshinrichs & Hake (2015), approximately 130 million tonnes of CO_2 are utilized annually. A very important part of CO_2 utilization is its conversion into chemicals as it accounts for the largest amount of commercially utilized CO_2. As it sums in annual consumption of 107 million tonnes of CO_2 to produce urea and 2 million tonnes is used for methanol production (Metz et al. 2005; Markewitz et al. 2012; Kuckshinrichs & Hake 2015). Thus, its main purpose is fertilization in agriculture but it can be used in other industries like pharmaceutical, tobacco, power plants and even transportation where demand surged in recent years as AdBlue became widely used for the intent of NO_x reduction (Kuckshinrichs & Hake 2015). Furthermore, polymers and polyurethanes can be obtained through catalytic reactions (Metz et al. 2005; Kuckshinrichs & Hake 2015; Chiang & Pan 2017). These materials can be used as construction material in the future (Kuckshinrichs & Hake 2015).

Many industrial plants around the world already utilize produced CO_2 through various chemical processes. As in the case of Marsden Point oil refinery in New Zealand, which is the country's only source of refined oil and I had the privilege to visit. Its operations include CO_2 capture and purification stage since the year 2016 and it can purify up to 50,000 t of CO_2 which can be subsequently used in the food processing industry for drink carbonation, altered atmosphere packaging solutions and refrigeration in meat and dairy products (Chemicals Technology 2016).

Furthermore, CO_2 can be used as a preservative and it can assist in decaffeination and flavour extraction processes. Apart from food and beverage industry CO_2 with high purity from refineries and ammonia plants can be used in many other industrial branches as pharmaceutics mainly for synthesis purposes and low-temperature transport (Metz et al. 2005; Cuéllar-Franca & Azapagic 2015; Kuckshinrichs & Hake 2015; Chiang & Pan 2017).

CO_2 can be utilized in many other industries, e.g. metallurgy where it can be used for protection of materials or gas elimination in non-ferrous metallurgy. In paper production and waste, treatment CO_2 can establish the desired pH balance. Furthermore,

CO_2 can find many applications as cooling medium or enhancing conductivity in electronics production (Metz et al. 2005; Kuckshinrichs & Hake 2015). Lastly, CO_2 is very often used for fire extinguisher production as certain aspects allow better performance in fighting fires where water cannot be used (Metz et al. 2005; Markewitz et al. 2012; Kuckshinrichs & Hake 2015; Chiang & Pan 2017).

4.4. Future of Carbon Capture Utilisation and Storage

This chapter summarizes current and future R&D programmes, obstacles in implementation of CCUS, as well as recently introduced policies. It is mainly focused on European projects as these are most significantly related to the Czech Republic. Another reason for this is the fact that the EU is one of the most advanced actors in environmental initiatives, policies, and laws, considering CCUS technologies as a very important part of the CO_2 emission reduction strategy for 2030 and 2050 (European Commission 2017a, 2019a; ZEP 2019).

4.4.1. Research & Development Projects in CCUS

Various national programmes and research activities funded by the EU, Norway Grants, or in some cases nationally-funded, concentrate on expanding the knowledge and improving the methods of CCUS are underway in 13 European countries (European Commission 2019b).

The SITECHAR project identifies key steps for improving large-scale project implementation. RISKS addresses potential threats imposed by CO_2 storage. PANACEA improves the predictability of storage operations. The last of these efforts is the IMPACTS project solely focused on the impact of impurities on materials involved in transportation and storage of CO_2 (Cebrucean et al. 2014).

The NORDICCS project aims at the research of the storage capacity and exploration (European Commission 2019b). However, 80% of the storage spaces found in Germany are in the states that do not allow storage (Kuckshinrichs & Hake 2015; European Commission 2019b). Further expansion in exploration and storage activities is expected as Spain, Norway, Netherlands, and France have obtained or applied for new permissions (European Commission 2019b).

ERA-NET ACT (Accelerating CCS Technology) and the European Strategic Energy Technology Plan (SET Plan) link efforts of various projects to improve their efficiency. The projects such as The North Sea Basin Task Force and the Baltic Sea Region CCS network create an environment where countries can cooperate in the development of joint transport and storage projects on a regional level providing access to these technologies to the countries that do not have such options (European Commission 2019b).

Proper financing of CCS projects is vital for their further distribution. EU tries to support such projects through funding tools such as Horizon Europe (2021-2027), Connecting Europe Facility (2014-2020), and lastly Innovation Fund (2020-2030) (ZEP 2019). A predecessor funding programme was NER 300 (2012-2018) provided support to the demonstration of innovative low-carbon technologies like CCS and renewable energy on a commercial scale totalling for €2 billion. However, only one CCS project was selected (European Commission 2017b; ZEP 2019).

R&D actions grew significantly in the recent years even in the USA and Australia, where these technologies are considered a vital part of national CO_2 emissions reduction strategies as in the case of EU. Each of these countries has invested over US$2 billion into the research of CCUS (Wilberforce et al. 2019).

4.4.2. Policies

An important part of the implementation of CCS and CCU technologies is based on good international and national policies. These should lead to promotion, easier implementation, and better support of CCS and CCU projects (IEA 2015a; European Commission 2017a, 2019a, 2019b; Zapantis et al. 2019).

However, IEA (2015a), Global CCS Institute (2019), and Atlantic Council (2020) agree on the fact that the measures employed by the governments are not sufficient and further advancements in policies must be made as CCUS is considered to be one of the most important technologies for CO_2 emissions mitigation. Otherwise, the technology might not be available on a scale that is needed for the timely emissions decline. Stating that financial investments must be increased substantially, and direct policies must be introduced. Acceleration of these processes is crucial. Even Wilberforce et al. (2019) correspond that global co-operation will only increase the efficiency of the development process and consequently reduce the costs enabling broader implementation of these technologies as they would be more appealing and higher investments would be provided.

UN Framework Convention on Climate Change (UNFCCC) supports the method of ocean storage as one of the main CO_2 sequestration technologies. However, the UN Convention on the Law of the Sea (UNCLOS) is sceptical because of possible impacts on the environment (Metz et al. 2005). Interestingly, the division between the two UN projects is evident.

The Global CCS Institute examines the development of policies implemented by governments for faster deployment of CCS technologies to alleviate the impacts of climate change. The Global Policy Indicator (CCS-PI) comprises of 9 main observed areas and measures the advancement of implemented policies on a scale from 0 to 100, where higher scores signify more developed policies. In 2018, Norway attained the highest rank of all the countries with a score of 56/100. It divides the nations in four bands (A, B, C, D) according to development of their policies from where those in Band A are the most developed and includes countries such as Norway, Canada, UK, USA, China, and Japan (Global CCS Institute 2018b).

4.4.3. Barriers and Challenges of CCUS implementation

According to the European Commission (2017a), one of the main drawbacks of CCS technologies is the fact that they are financially very demanding, and this might be one of the future most difficult hurdles for implementation, mainly considering the high costs of capture processes. However, these costs can be reduced by further improvements to technologies through R&D (European Commission 2017a). The high costs are even related to retrofitting operations (European Commission 2019b)**.**

Wilberforce et al. (2019) add that the major future challenges include cost reduction of the processes involved. Mainly costs of construction, retrofitting costs and costs of electricity in the case of plants equipped with CCS. Surprisingly, energy from outdated plants retrofitted with CCS technology is still cheaper than in the case of newer plants mounted with CCS. Other challenges include high-efficiency losses in PCC processes and the expansion of CO_2 storage operations.

Wilberforce et al. (2019) also identify the loss of biodiversity, fertile land and ecosystems as another serious problem that needs to be addressed before construction of future capture, transportation and storage facilities as these activities could cross important biodiversity hotspots on land as well as below water where certain species respond adversely to the increases of CO_2 in their environment. Possible leakage could lead to degrading the quality of groundwater as well (Lilliestam et al. 2012; Wilberforce et al. 2019).

Another future obstacle will be enforcing important safety regulations and standards to ensure safe and environmentally friendly solutions for securing long-term sequestration of CO_2, and reducing the overall risks of the whole operation from capture to storage. This desired framework was provided by the CCS Directive of the EU (European Commission 2017a).

The London Convention from 1972 is another obstacle for ocean storage as it bans materials produced or manufactured on land to be stored in the sea. An exemption to this rule is disposal of CO_2 which arises from production or processing operations carried out on the sea. In 1996 other exemptions were introduced in the Marine Pollution protocol but CO_2 was still not included as the technology was very recent (Metz et al. 2005; Sheps et al. 2009). On the other hand, an amendment from 2009 to Article 6 was granted in 2019, allowing exports of CO_2 to other countries for transport and subsequent offshore geological storage (Global CCS Institute 2019).

Lilliestam et al. (2012), Kuckshinrichs & Hake (2015) and Tcvetkov et al. (2019) mention that one of the main issues is the fact that in some countries people have very little knowledge about CCS and CCU, which could lead to misconceptions, possibly causing a negative attitude towards these technologies. Therefore, information should be provided to the public to eliminate at least one of the barriers of mass implementation which is negative public opinion itself. As it was proved in Norway, informed individuals tend to trust more and believe technology not to be harmful. However, as time passes people are more aware of these technologies as well of their impacts and risks. IEA (2015b) states that this has been managed well in the case of EOR operations across North America.

5. Conclusions

To conclude, CO2 emissions present a significant threat to the world, as we know today that consequences of global warming without any further action could drastically change our home, the planet Earth. Therefore, teams of experts and researcher worldwide work on the development of new technologies that focus on abatement of excessive amounts of anthropogenic CO2 in the atmosphere. CCUS technologies prove their crucial importance in efforts of CO2 mitigation.

As various methods of CC emerge (Pre-CC, OXY, PCC), reductions in the amount of emitted CO2 are expected as these technologies showed their ability to be even retrofitted to older industrial plants (PCC) as these can be the biggest sources of air pollution, and at the same time full-scale capture facilities (Pre-CC, OXY, PCC) are already available for deployment in new power or heavy industry plants.

Large amounts of captured CO2 can be stored in different geological formations most commonly saline aquifers or depleted oil and gas fields. The storage of CO2 in the ocean is possible as well. In this case, it could be dissolved in shallow water or stored in the depths. However, many people doubt that these storage options are viable as there is a possibility of leakage that could have detrimental impacts on the environment. Therefore, various safety measures must be improved beforehand.

Additionally, undesired CO2 can be utilized in many ways. EOR is one of them, where sequestration of CO2 takes place and simultaneously it enhances the efficiency of crude oil production. Yet CO2 can be used to create favourable products for daily use as it covers a wide range from biofuels, chemicals, fertilizers, pharmaceutical products, building materials and many other applications.

Nevertheless, CCUS technologies are unfortunately not widely distributed yet. As they have many common issues. One of the main deficiencies is its low-efficiency rates and high implementation and operation costs, which result in limited application to developed nations. Therefore, in most cases, further R&D is needed to improve its performance. Followed by environmental concerns as some of the technologies are still in development, therefore not much is known. To improve this situation targeted policies, governmental cooperation, and incentives are needed to be applied.

The main contribution of this work is embodied in summarization and analysis of available scientific literature and other important current sources of information associated with CCUS technologies in May 2020.

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