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Master's thesis

THE ECONOMIC, ENVIRONMENTAL AND ENERGY PERSPECTIVE OF E-METHANOL

carried out for the purpose of obtaining an academic degree

Graduate Engineer

under the supervision of

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Abstract

Carbon capture and utilization is a term that refers to versatile technological processes in which carbon dioxide (CO_2) is gained from atmosphere or as industrial by-product and converted into value-added products such as e-methanol. There are several carbon capture technologies already present on the market, and the most common ones are: post-combustion capture, pre-combustion capture, oxy-fuel combustion and direct air capture.

The main objective of this study was to compare production of e-methanol to conventionally produced methanol in Austria from energy consumption, environmental and economic perspective. Based on the literature research direct air capture technology was chosen, as promising technology for obtaining CO_2 which would be used for e-methanol production.

The case study used in this work was based on the assumptions of completely replacing conventional methanol production in Austria with e-methanol production.

The methodology for this study includes a cost analysis and environmental assessment, where sensitivity analyses to evaluate production costs under varying electricity prices was done.

The study highlights direct air capture and electrolysis as energy intensive processes, empathizing the importance of renewable energy sources to gain e-methanol's environmental advantages. This case study also shows that the production of e-methanol in the countries with lower electricity prices like Denmark and transportation by train to Austria is economically more feasible than production in Austria, although with a smaller environmental disadvantage.

E-methanol has potential as a renewable fuel, but scaling of production will depend on advancements in direct air capture and proton exchange membrane elektrolyser technologies and investments in renewable electricity.

Keywords: carbon capture technologies, carbon utilization, economic analysis, environmental analysis, energy demand, direct air capture, PEMEL, e-methanol

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Kurzfassung

Kohlenstoffabscheidung und -nutzung (CCU) bezeichnet vielseitige technologische Prozesse, bei denen Kohlendioxid (CO_2) aus der Atmosphäre oder als industrielles Nebenprodukt gewonnen und in wertschöpfende Produkte wie E-Methanol umgewandelt wird. Auf dem Markt gibt es bereits mehrere Technologien zur Kohlenstoffabscheidung, von denen die gängigsten die Nachverbrennungsabscheidung, die Vorverbrennungsabscheidung, die Oxy-Fuel-Verbrennung und die Direktluftabscheidung sind.

Das Hauptziel dieser Studie war es, die Produktion von E-Methanol mit der konventionellen Methanolproduktion in Österreich aus energieverbrauchs-, umwelt- und wirtschaftlicher Perspektive zu vergleichen. Basierend auf der Literaturrecherche wurde die Direktluftabscheidung als vielversprechende Technologie zur CO_2-Gewinnung für die E-Methanol-Produktion ausgewählt.

Die Fallstudie in dieser Arbeit basiert auf der Annahme, die konventionelle Methanolproduktion in Österreich vollständig durch die Produktion von E-Methanol zu ersetzen. Die Methodik dieser Studie umfasst eine Kostenanalyse und eine Umweltbewertung, einschließlich Sensitivitätsanalysen zur Bewertung der Produktionskosten bei unterschiedlichen Strompreisen.

Die Studie hebt hervor, dass Direct Air Capture und Elektrolyse energieintensive Prozesse sind und die Bedeutung erneuerbarer Energiequellen für die Umweltvorteile von E-Methanol unterstreicht. Diese Fallstudie zeigt auch, dass die Produktion von E-Methanol in Ländern mit niedrigeren Strompreisen, wie etwa Dänemark, und der Transport per Bahn nach Österreich wirtschaftlich günstiger ist als die Produktion in Österreich, wenn auch mit geringem Umweltverlust.

E-Methanol hat Potenzial als erneuerbarer Kraftstoff, aber die Skalierung der Produktion wird von Fortschritten in Direktluftabscheidung und Protonenaustauschmembran-Elektrolyse-Technologien sowie Investitionen in erneuerbare Elektrizität abhängen.

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Abbreviations

BECCS – Bioenergy with Carbon Capture and Storage

BMK – Bundesministerium für Klimaschutz, Energie, Mobilität, Innovation und Technologie

CAGR – Compound annual growth rate

CaL – Calcium looping

CAPEX – capital expenditures

CCS – Carbon capture and storage

CCU – Carbon capture and utilization

CEPCI – chemical engineering plant cost index

CLC – Chemical looping combustion

CRF – capital recovery factor

DAC – Direct air capture

EOR – Enhanced Oil Recovery

GHG – Greenhouse gas

HT DAC – High Temperature Direct Air Capture

IEA – International Energy Agency

IGCC – Integrated Gasification Combined Cycle

IPCC – Intergovernmental Panel on Climate Change

LCA – life cycle assessment

LCOD – Levelised Cost of Carbon

LCOE – Levelised Cost of Electricity

LCOH – Levelised Cost of Hydrogen

LCOMeOH – Levelised Cost of E-Methanol

LT DAC – Low Temperature Direct Air Capture

MEA – Monoethanolamine

MeOH – methanol

MOF – Metal organic frameworks

NGCC – natural gas-fired combined cycle

NZE – Net Zero Emission

OPEX – operational expenditures

PC – pulverized coal

PEC – Purchase equipment cost

PEM – Proton Exchange Membrane

PEMEL – Proton Exchange Membrane Elektrolyse

PtL. – Power to liquid

PV – Photovoltaic

RE-SNG – renewable synthetic natural gas

SMR – steam methane reforming

TRL – technology readiness level

WACC – weighted average cost of capital

WGS – Water-gas shift

WP – Wind power

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Figures

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1. Introduction

The issue of climate change has gained the attention of policymakers, scientists, and the public everywhere in the last few years. The emission of carbon dioxide (CO_2) is widely recognized as the primary driver of this concern. As a result, it is possible to argue that reducing these emissions is the solution to reduce climate change [1,2].

The release of greenhouse gases into the atmosphere during the process of industrialization and urbanization has contributed to the phenomenon of global warming, thus leading to climate change. CO_2 emissions, in particular, have been identified as the primary driver, with global emissions reaching more than 36.8 billion tons in 2022 [3]. This surge has substantially increased atmospheric CO_2 concentration, measuring approximately 417 parts per million (ppm) [4]. Figure 1.1 shows the development of CO_2 annual emission from year 1900. From the beginning the industrialization is to notice the strong raise in emission.

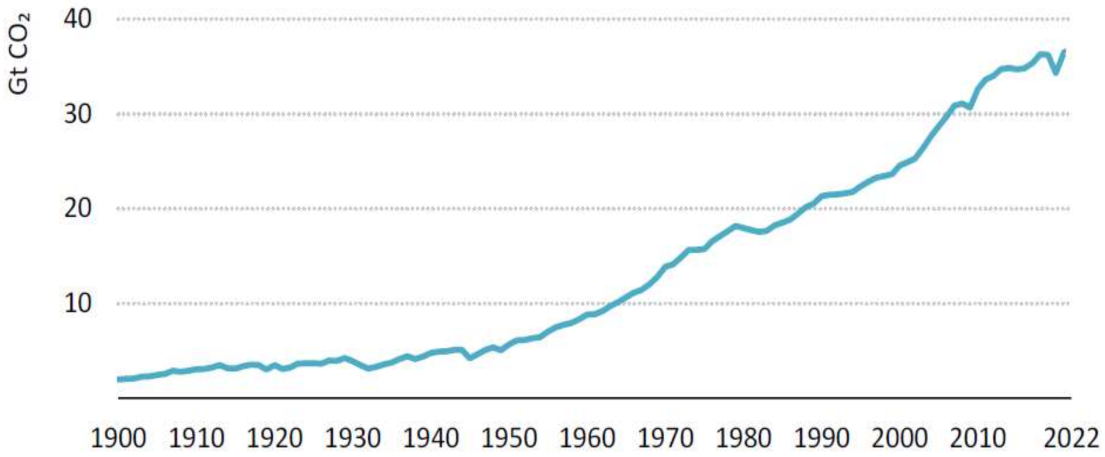

Figure 1.1: Global CO_2 annual emission trend [5]

Carbon capture and utilization (CCU) stands as a potentially disruptive technology that can help in addressing the challenge of climate change by capturing CO_2 from emission sources, including power plants or industrial facilities, and the atmosphere. This captured CO_2 is then harnessed as a raw material for chemical synthesis or other valuable purposes. Carbon capture technology can be integrated into existing coal and gas-fired power plants, helping to reduce emissions while continuing electricity generation. Beyond contributing to the power sector, CCU represents a scalable and cost-effective option for achieving substantial decarbonization in certain industries such as cement, steel, ceramics, glass, and chemical manufacturing, which are significant sources of CO_2 during their production processes. Assessments conducted by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) have indicated that CCU will play a crucial role in achieving the "Net Zero" target by 2050, contributing to a one-sixth reduction in global CO_2 emissions, as mandated by the Paris Agreement, in order to limit the global temperature rise within 1.5°C [6,7]. The Net Zero Emissions (NZE) scenario describes the way to reach the net zero emissions by 2050 and defines the precise plan for

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renewable energy, electrification and energy efficiency, and hydrogen and carbon capture in the future [8]. The share of solar and wind power should increase significantly in this scenario and should account for over 70% of global electricity generation [9]. It has also strong focus on hard-to-abate emissions [8], with solutions like BECCS and DAC playing a crucial role [9]. Reaching the goals by NZE Scenario requires improvements in technological innovation, efficiency and boosting recycling rates both in private and public sector [10].

Failure to effectively implement CCU would result in higher costs for addressing the climate challenge, with China, for instance, facing a 25% increase in expenditure to meet long-term climate change mitigation targets without CCU [11].

CCU not only aims to reduce atmospheric emissions but also seeks to leverage CO_2 for various industrial processes, replacing conventional raw materials [12,13]. Moreover, CCU offers a potential avenue towards a circular economy [14] by recycling waste CO_2 and converting it into valuable materials such as organic compounds [15], concrete [16], and polymeric materials [17].

While these approaches alone may not suffice to achieve the desired objectives, they have the potential to supplement the utilization of carbon-free renewable technologies alongside raising public perception [18].

Most of the captured CO_2 today is used for urea manufacturing (around 130 Mt) and for enhanced oil recovery (EOR) (around 80 Mt). Captured CO_2 is also utilized for the production of CO_2-based plastic and chemicals, synthesis of carbon nanotubes, desalination, algae growth and fish farm fertilization, brewing, etc. Still, markets and scalability issues remain for the most CCU products the biggest issue [19].

Figure 1.2 represent the simplified overview of CCU process. The CCU process consists of capturing and transport of carbon, and its utilization in one of the products. Using that product, CO_2 is released again as part of a natural lifecycle. This is where the circular nature of CCU becomes evident and the process starts over again by recapturing the released CO_2, creating a closed loop of carbon management.

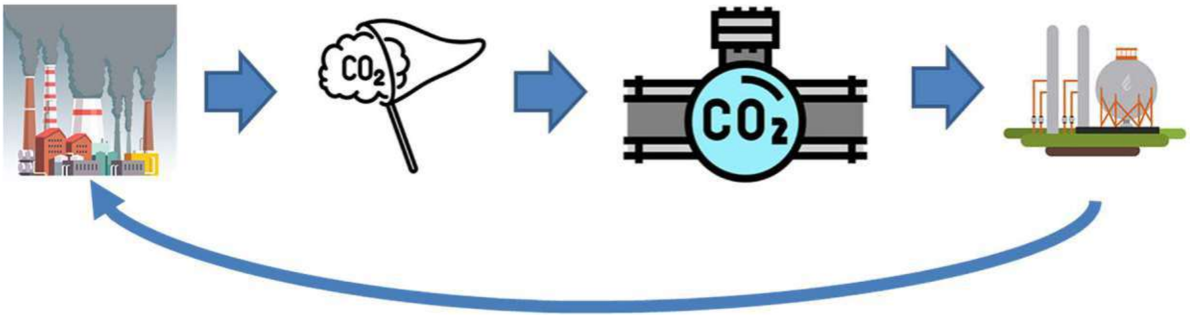

Figure 1.2: Schematic overview of CCU process

The widespread adoption of CCU could lead to job creation, economic growth and the emergence of new industries. Challenges that may arise during the transition process could result in short-term costs for taxpayers and consumers. While carbon markets or taxes could encourage the expansion of CCU, uncertainty in policy is currently hindering private investment. It appears that a combination of government support and

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competitive market forces will be necessary for the successful implementation of CCU [20].

The success of CCU on large scale hinges on its ability to effectively compete with and enhance the transition to renewable energy that is both scientifically and morally necessary. It is important to detect the factors in which CCU can justify its role in achieving significant emissions reductions on a meaningful scale, in order to decide if investing and developing of this technology is needed [21].

Public support will have an important role on the advancement of CCU initiatives. Critics suggest that CCU is being used as an excuse to continue reliance on fossil fuels rather than transitioning to more sustainable energy and transportation alternatives. Additionally, there are concerns regarding the potential environmental risks associated with CO_2 storage, especially underground. It is clear that relying only on CCU alone may not be sufficient to significantly reduce emissions on a large scale. Educating the public about the benefits of CCU and implementing strict safety protocols may help build confidence in these technologies. Despite the complex trade-offs involved, CCU is likely to face opposition from groups advocation for a rapid transition to renewable energy sources [20].

As shown in Figure 1.2, the first process is to capture carbon. The most common carbon capture technologies are post-combustion capture, oxy-combustion capture, pre-combustion capture and Direct Air Capture (DAC). According to the source of CO_2, the suitable capture technologies is used [19].

The main focus in this study regarding carbon capture is DAC technology and according to article from IEA [22], DAC is considered as the most promising technology, because it's not the solution only for the current emissions, but also potentially for all anthropological emissions. Currently, only 0.01 Mt of CO_2 is captured annually by DAC and if all projects, that are planned, are finished by 2030 it should reach around 3 Mt of CO_2. According to NZE Scenario by 2030 there should be 80 Mt of CO_2 captured by DAC, therefore the current development is not even close to meeting the requirements of NZE Scenario.

Although, at the moment, DAC is considered as the most expensive carbon capture technology, it is estimated that by 2030 costs of captured ton of CO_2 should fall below 100 EUR/t_{CO2} [19]. For the purpose of this study the costs of DAC were calculated based on findings of Fasihi et al. [23]. The cost of heat energy were neglected, taking into consideration that the demand for heat energy is going to be covered from methanol synthesis process and production of hydrogen.

The second process in the CCU chain is transportation of CO_2. Transportation of CO_2 is already well established and technology that is used is highly advanced. Depending on distance, quantity or state in which is CO_2 transported, there are few methods: trucks, rail, ships and pipelines [24].

The final process in creating a CCU product is to transform the captured CO_2 into a valuable product. In this study, the chosen CCU product is e-methanol. The capital cost of methanol (MeOH) plant was determined according to Nyari et al. [25], taking into consideration of the purchasing equipment price and the operational costs as a percentage of capital cost. The technical analysis of e-methanol production is described by Pérez-Fortes et al. [26] and it shows the quantity of energy, hydrogen and CO_2 needed for the synthesis of e-methanol. The environmental analysis of e-methanol in this study followed the methodology outlined by Nyari et al. [25], which defines the environmental impact of the CCU process using two key parameters: CO_2 not-produced and CO_2 avoided. These parameters serve as metrics to evaluate and compare the environmental impact of conventional production processes with the production of CCU-derived products.

The production of methanol had doubled in the last decade, and it is estimated that its demand with increased five-fold by 2050 [21]. Methanol is used in different industries, but most important ones are presented in Figure 1.3. As demand grows, production costs are projected to decline. The methodology for forecasting the e-methanol costs is detailed in research article of Radosits et al. [27]. The total investment costs include both the conventional and new components, whereas the cost of new components depends from technological learning.

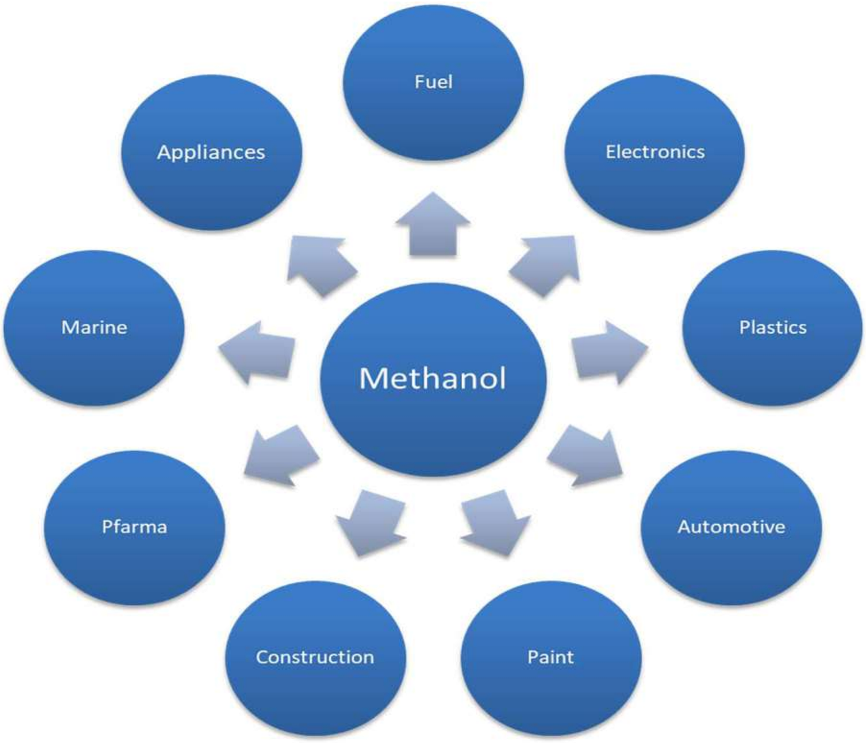

Figure 1.3: Uses of methanol

The main focus of this study was to compare production of e-methanol to conventionally produced methanol in Austria from energy consumption, environmental and economic perspective. The e-methanol and methanol production process selected in this study comprised of power to liquid (PtL) process. In the case of e-methanol, CO_2 captured by DAC technology was utilized, while hydrogen used was obtained by proton exchange membrane (PEM) electrolysis. As both DAC and PEM electrolysis are energy intensive processes, energy acquired would need to come from renewable sources like wind or solar. The energy source is crucial for estimation of the environmental impact.

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This study covered research of the suitable carbon capture technology, associated costs, energy efficiency and environmental impact in order to identify the optimal scenario for implementation of e-methanol production in Austria.

The cost of e-methanol plant located in Austria was calculated for chosen technologies, also with respect to the environmental impact that e-methanol production would have.

The methodology comprised of two main phases: a comprehensive literature review and e-methanol cost calculation for specific analyzed study cases.

A thorough review of the existing literature was conducted in the first phase. Scientific journals, research papers, industry reports, and reputable sources were scrutinized to comprehensively understand carbon capture technologies and e-methanol as one of the CCU products, as also effectiveness, economics and environmental implications of this technology. This study incorporated key findings, statistics, and case studies related to the costs of implementing carbon capture technologies. Transport of CO_2, hydrogen and methanol is discussed, both offshore and onshore, taking cost-effectiveness into consideration, under the assumption that safety standards are fulfilled to provide a comprehensive perspective on production logistics and emissions. Utilization of captured CO_2 and CO_2 usage in various industrial processes is explained, focusing on its potential to reduce emissions while creating economic value. The main emphasis was on production of e-methanol and its potential as a replacement for fossil fuel-based methanol in various industries.

The second phase of the methodology involves the economic and environmental assessment to perform a detailed cost analysis of e-methanol produced with CO_2 from DAC and hydrogen from PEM electrolysis. An input cell was created to facilitate sensitivity analysis of e-methanol pricing, enabling the exploration of various cost assumptions and their impact on overall costs. The sensitivity analysis was focused on the most important factor, the cost of electricity. Variating the electricity costs, the scenarios were developed to compare the production of e-methanol in countries with lower electricity price and Austria, while also taking into account the environmental impact of transport of e-methanol to Austria and additional cost created by transport. For economics, calculations formulas and functions were employed to calculate total costs per ton of CO_2 captured and other relevant metrics. Costs of e-methanol were calculated for the year 2030 and the year 2050, incorporating technological learning curves, advancements in DAC and hydrogen production, and lower electricity prices. Visualizations such as charts and graphs were generated to enhance the presentation of the cost analysis results.

The aim of this study was to analyze the costs associated with CO_2 capture, hydrogen production and e-methanol synthesis, while assessing the potential for reducing greenhouse gas emissions in Austria. To ensure the validity of the e-methanol economics and its alignment with existing estimates, the results were validated against available cost data from literature or industrial reports. Limitations and uncertainties associated with the cost estimation of e-methanol production, including evolving technologies and economies of scale, were discussed.

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2. State of the Art

This chapter provides an overview of the latest advances, challenges, and emerging trends in carbon capture technology and utilization. It explores the main CO_2 capture methods, including post-combustion processes, pre-combustion and oxy-combustion processes, along with the innovative DAC technology. It examines the transportation of captured CO_2, hydrogen and methanol, with a focus on optimizing energy efficiency and economic feasibility. In detailing these technologies and methods, this chapter sets the basic technical context for evaluating the viability and impact of e-methanol production.

2.1 CO_2 capture technologies

The carbon capture process involves the separation of carbon dioxide (CO_2) from flue gas or atmospheric air, which arises from the combustion of fossil fuels or as a by-product during chemical processes followed by its capture to mitigate CO_2 emissions. Extensive research and development endeavors are underway worldwide in the field of carbon capture. The existing body of literature predominantly centers on three primary approaches: post-combustion capture, oxy-combustion capture, and pre-combustion capture and the newest technology that is capturing CO_2 direct from atmosphere: Direct Air Capture. There are also additional technologies that are still in the development stages and not yet ready for industrial implementation. Nonetheless, these processes offer notable advantages, such as significant efficiency potential, when compared to the already established methodologies. All of these techniques are specifically designed to target CO_2 emissions reduction in oil refineries, coal-fired power plants, chemical industries, and steel plants, which feature prominently on the list of major CO_2 emitters. When selecting an appropriate carbon capture system, decision-makers consider three key characteristics of the flue gas [28]:

a) The concentration of CO_2 in the flue gas;
b) The temperature and pressure;
c) The nature of the flue (whether gaseous or solid content).

The process reliability, government incentives and economic evaluation of typical capture systems assist decision bodies in identifying a feasible carbon capture approach.

2.2 Post-combustion capture

Post-combustion capture strategy has taken considerable attention in numerous studies. The schematic representation of this process is illustrated in Figure 2.1. Post-combustion capture refers to implementing carbon capture subsequent to the combustion process, encompassing downstream purification steps for the flue gas, including dedusting, desulfurization, and denitrification. During this process, CO_2 in the flue gas is chemically absorbed utilizing an appropriate solvent. In a subsequent stage, the CO_2 within the loaded solvent undergoes desorption through a change in temperature or pressure (Figure 2.1). The desorbed CO_2 is then cleaned up and compressed to make transportation easier. The solvent undergoes a recycling process, ready to embark on yet another separation cycle, leaving an insignificant trace of CO_2.

This system exhibits significant potential for widespread integration within coal-fired power plants, owing to the relatively straightforward nature of retrofitting existing systems.

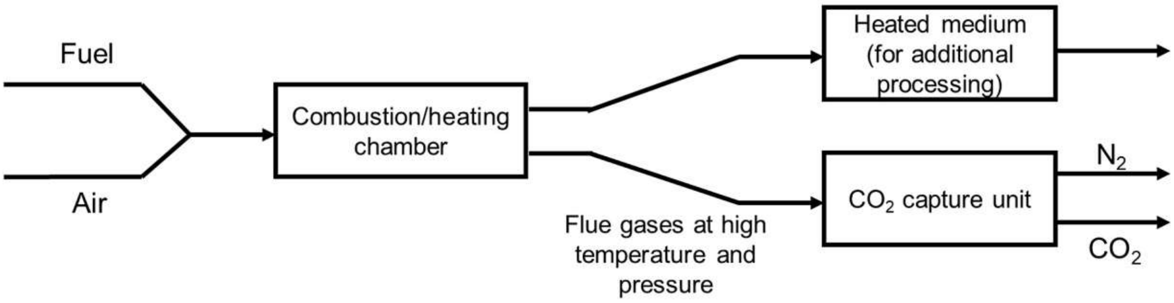

Figure 2.1: Schematic illustration of post-combustion CO_2 capture strategy

The main objective of the CO_2 capture process involves the separation of CO_2 from N_2 to obtain pure CO_2. In flue gas, the CO_2 partial pressure typically ranges from 0.1 to 0.13 bar, with N_2 contributing approximately 75% of the partial pressure and contributions from other pollutants like SO_X, NO_X, and trace metals [28]. Consequently, these additional components consume significant energy during the separation process. This leads to reduced CO_2 capture efficiency and rising CO_2 separation expenses. The treatment of flue gas containing CO_2 often involves conventional chemical adsorption technologies, such as CO_2 wet scrubbing utilizing aqueous amine solutions [29] that offer regeneration advantages. At around 120°C, the solvent liberates CO_2. Subsequently, the solvent undergoes recycling and reuse in the absorption column. Monoethanolamine (MEA) stands out as a commonly used and cost-effective solvent.

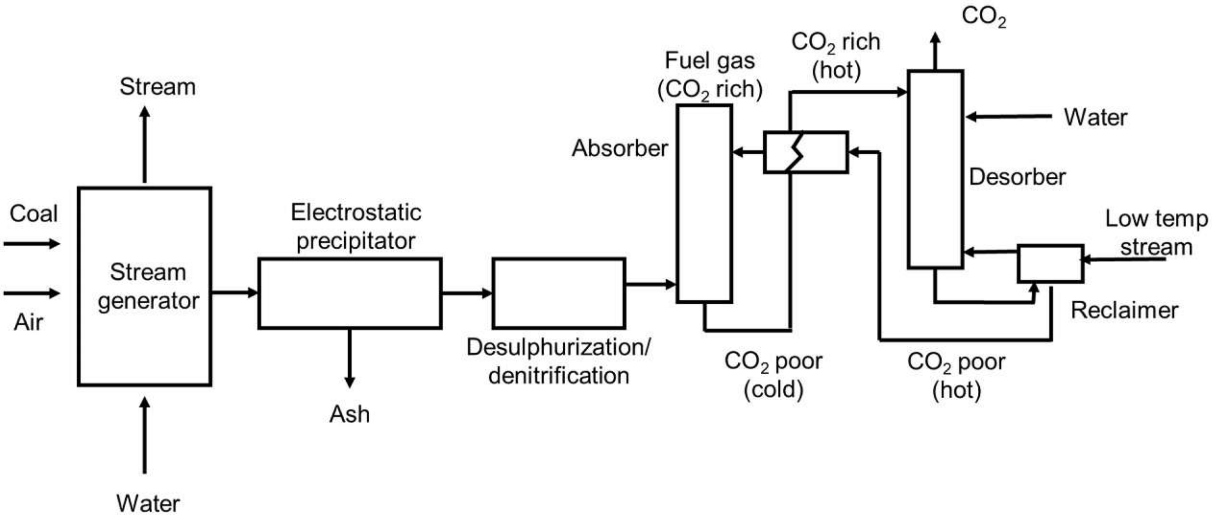

Figure 2.2: Schematic illustration of post-combustion CO_2 strategy with amine scrubbing [29]

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2.2.1 Utilization trends

The primary research and development focus on the identification of appropriate solvents. Alkanolamines, such as MEA, have gained significant experience and found commercial applications in various chemical industrial processes. However, their direct transferability to power plant processes is limited due to the distinct composition and volume flow of flue gas in power plants compared to chemical industrial processes. A crucial development effort objective is minimizing energy needs during regeneration. In this context, the utilization of tertiary or sterically hindered amines shows promise, as they necessitate considerably less desorption energy. However, these solvents encounter challenges during absorption, including decomposition in the presence of oxygen and degradation through sulfur dioxide or nitrogen oxide reactions. Consequently, the solvent needs continuous replacement. Oxygen-induced solvent decomposition can be mitigated by incorporating "inhibitors." Salts are produced as a result of reaction with SO_2 and NO_x and are removed at high temperatures in a unit operation (Figure 2.2). Reducing SO_2 levels in the flue gas prior to carbon capture is necessary to minimize deterioration. It is assumed that SO_2 concentrations ranging from 10 to 25 mg/m^3 can prevent the breakdown impact [30]. As a consequence, the construction of flue gas desulfurization units that are more efficient has become an absolute necessity.

Scrubbing with inorganic solvents is an alternative to the more common amine method. Basic alkaline and alkaline earth solutions have garnered more attention recently due to the fact that they provide great resistance to oxygen, thermal stability, and very low heat needs for absorption and desorption. However, their disadvantage lies in the comparatively slower reaction rate, which can be enhanced by adding additives [31]. An alternative approach revolves around the utilization of ammonia as a potential solution. Through the introduction of water, ammonia can be employed to effectively capture and bind the CO_2 content within the flue gas. This method offers a distinct pathway for addressing the CO_2 emissions and facilitating their removal from the flue gas stream. The ammonia-based process entails low energy demands for both absorption and desorption. Additionally, ammonia serves as a cost-effective absorbent. The chilled ammonia process is a modified version of the ammonia-based method that facilitates CO_2 absorption at significantly lower temperatures. This alternative approach offers distinct advantages compared to traditional ammonia processes, including reduced volume and mass flows. As a result, the chilled ammonia process exhibits lower energy requirements and decreased NH_3 slip [32].

Continuous efforts are underway to explore alternative separation technologies. Novel solvents should exhibit improved performance, higher CO_2 capture capacity, lower energy consumption during regeneration, enhanced rate of sorption, reduced volatility, improved stability, decreased degradation, and lower corrosiveness [33].

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2.2.2 Advanced practices in post consumption

Advanced methods employed in post-combustion operation encompass the implementation of membrane-based and carbonate looping techniques. The concept of carbonate looping unfolds within a dual fluidized bed reactor, where a continuous stream of calcium oxide (CaO) flows as the CO_2 carrier, creating an interconnected loop that binds the carbonator for absorption and the calcinator for desorption, paving the way for efficient carbon capture and release. A high-temperature reaction takes place (600-700°C) in this process, where there is a reversible exothermic absorption of CaO and endothermic calcination of calcium carbonate ($CaCO_3$) occurring at temperatures around 900°C. Unlike traditional scrubbing approaches, this method allows for utilizing absorption heat in the power plant process, thereby improving efficiency. A study estimates efficiency losses of approximately 7.2% when considering CO_2 compression and associated conditioning [34]. Abanades et al. [34] indicate an efficiency loss of about 3% in the absence of CO_2 compression and associated conditioning at a capture rate ranging from 70% to 95%. The process offers advantages such as the potential for achieving high purity and its theoretical suitability for retrofitting.

In the realm of post-combustion processes, membranes emerge as a promising alternative. Polymer and hybrid membranes combining organic and inorganic components are preferred for the selective capture of CO_2 over N_2 [35]. However, membrane-based techniques in the post-combustion route necessitate substantial energy input for compressing the flue gas, creating the required pressure differential for effective gas separation. Membranes lack the requisite qualities, such as selectivity, to attain high capture efficiency and purity in a single-stage membrane setup without imposing high energy demands. To address this challenge, a potential solution involves adopting a multiple-stage configuration comprising membrane setup along with compressors or turbines. Additionally, retentate recirculating can enhance the CO_2 concentration in the feed gas. By employing these innovative concepts, it becomes feasible to restrict efficiency losses to a range of 7.8-9.2% based on the specific membrane properties. Such an approach allows for a capture efficiency of 90% and a purity level of approximately 95% [36].

2.2.3 Efficiency

The efficiency losses associated with post-combustion carbon capture have been estimated at approximately 9-14%, encompassing liquefaction and conditioning [37]. Of these losses, around 2-3% are attributed to the compression and liquefaction of CO_2. To enhance efficiency, several routes can be explored. These include the development of novel solvents and capture processes optimal integration, including CO_2 compression, within the power plant operations. According to Finkenrath et al. [37], if this potential is fully realized, the efficiency losses for the post-combustion process can be decreased to 9.1% (including compression) in the optimal scenario while maintaining a capture efficiency of 90%.

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2.2.4 Advantages and disadvantages of post-combustion processes

The post-combustion process offers notable advantages, leveraging the extensive expertise gained from the utilization of amine scrubbing in chemical industries applications. Moreover, there is significant scope for enhancing its efficiency. This process obtains the highest level of captured carbon dioxide purity (>99.99%) among carbon capture technologies. Incorporating this process into a power plant calls for tailored adjustments in the low-temperature steam section while keeping its overall operation intact, eliminating the need for any big changes at its fundamental. This components integration ensures maximizing efficiency without compromising the plant's existing functionality. All the necessary components are accessible in the commercial market, preventing the need for groundbreaking innovations. This allows retrofits in existing power plants, known as end-of-pipe technology. It is crucial to acknowledge the significant drawback of substantial investment costs. In addition, the operational flexibility of power plants equipped with post-combustion technology is uncertain.

2.3 Pre-combustion capture

Pre-combustion carbon capture represents a promising technological approach aimed at extracting CO_2 from syngas, which refers to a gaseous mixture comprising different proportions of H_2 and CO before the fuel undergoes combustion in turbines. The primary objective of this CO_2 capture technology is to enhance the efficiency of chemical reactions and energy generation. Integration of this technology is most likely to occur in gasification combined cycle (IGCC) or natural gas-fired combined cycle (NGCC) systems. Gasifying fossil fuels in a gasifier generates high-pressure syngas, which consist primarily of CO and H_2, and is the first step in a conventional IGCC process with CO_2 collection. This gasification process entails two principal chemical reactions, which are accompanied by the production of small quantities of SO_2 and NO_X:

$$2C + O_2 + H_2O \rightarrow H_2 + CO + CO_2$$

$$C + H_2O \rightarrow H_2 + CO$$

The syngas, primarily composed of H_2, CO_2, and CO, undergoes a process of moderate cooling followed by subsequent reforming referred to as the water-gas shift (WGS) reaction:

$$2CO + H_2O \longleftrightarrow H_2 + CO_2$$

The gas combination undergoes a reversible equilibrium reaction within a shift converter, changing CO to CO_2 and producing more H_2 in the next reaction. Following the water-gas shift (WGS) reaction, the resulting gas, enriched with H_2 and CO_2, undergoes a cooling process and subsequent treatment for the capture of sulfur compounds and CO_2. This treatment involves the utilization of physical solvents such as methanol-based Rectisol or Selexol solutions [38]. Once the gas has been purified, it predominantly consists of hydrogen, which can be utilized in the processes like chemical synthesis or power generation. The pre-combustion CO_2 capture process is shown in Figure 2.3. Power is produced using a gas and steam system incorporating the leftover hydrogen [39].

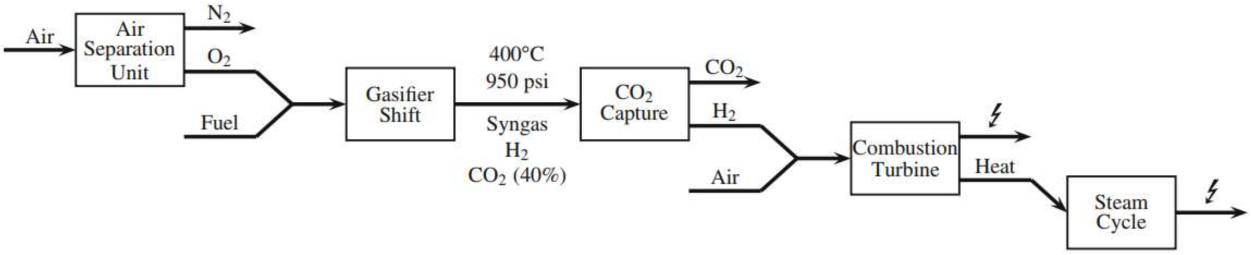

Figure 2.3: Schematic illustration of pre-combustion CO_2 capture strategy [40]

Experts are interested in understanding the characteristics of gasifiers, which are influenced by various factors such as the composition of reactants and products, operating temperature, residence time, operating pressure, and particle size. These gasification-based systems offer feasible possibilities for power production from a technological viewpoint.

In pre-combustion CO_2 capture, separation technologies are categorized: solvents, sorbents, membranes, and water gas shift membranes. Notable examples of such membrane systems include the Porous Membrane Contactor, Composite Polymeric Membrane, and Immobilized Liquid Membrane. These endeavors primarily aim to achieve effective separation of H_2 and CO_2, thereby enabling more efficient processes [38].

Researchers emphasize effectively separating the two gases, H_2 and CO_2, produced by WGS reactors. The technical and economic variables to be considered while putting in place NGCC or IGCC systems are also affected by some technical specifications. These parameters include gas mixture selectivity, permeance, adsorption capacity for H_2 or CO_2, operating temperature, renewability, stability, and energy requirements.

2.3.1 Utilization trends

Coal gasification is a widely adopted method for producing syngas, which serves as a fundamental building block for various industrial applications, including methanol synthesis. However, the application of gasification technology for power generation remains limited, with only a few commercially operated Integrated Gasification Combined Cycle (IGCC) power plants worldwide. The currently attainable efficiencies of IGCC plants are on par with those of traditional coal-fired power plants. There is a rising interest in carbon capture in IGCC power plants because of the significant efficiency possibilities offered by integrated cycle processes using coal and the

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practicality of applying tested CO_2 separation methods. This growing interest stems from the promising prospects it presents for generating cleaner energy while making use of reliable and well-established approaches. For CO_2 capture, the preferred approach is the Rectisol wash method, which enables the simultaneous removal of CO_2, carbonyl sulfide, and H_2S from the syngas. The Rectisol process encompasses several sequential steps, including the absorption of SOx and CO_2, as well as the subsequent desorption of the concentrated solvent. The sulfur-containing compounds must be isolated from the solvent and appropriately treated, often through a Claus unit. The solvent utilized in this process is based on methanol and operates under elevated pressure conditions (30-60 bar) and lower temperatures at -40°C during the absorption stage. CO_2 is effectively separated from the saturated or loaded solvent by using nitrogen and changing the temperature, conditioning, and compression. Notably, the Rectisol process is capable of achieving more than 99% purity for CO_2 [41].

Syngas preparation is well-established in various industrial sectors, indicating experience in this domain. Therefore, the primary technical challenge is the implementation of the fundamental IGCC process. Improvements are required in gasification technology, optimization of raw gas cooling (including efficient utilization of waste heat and partial quenching), and the integration of hydrogen utilization in gas turbines [39]. As with other lines of CCS technology, the development of an optimal thermodynamic design is important for maximizing process efficiency.

2.3.2 Advanced techniques pre-combustion processes

In the long run, membranes in the pre-combustion process present a possible substitute for physical cleaning because of favorable pressure circumstances. Two types of membranes can be utilized: H_2-selective membranes (e.g., sol-gel, microporous zeolite and MPEC membranes) and CO_2-selective polymer membranes [42]. The selection of the membrane type primarily relies on the specific IGCC configuration, which determines the key framework parameters such as temperature, pressure, and syngas composition. Efficiency losses ranged from 8.7 to 10.5 % for CO_2-selective membranes [42]; for H_2-selective membranes, the range was 9.1 to 11.1 %. Compared to scrubbing, which results in 9-12 % efficiency losses, membranes exhibit only marginal efficiency benefits. Nonetheless, the incorporation of catalytic high-temperature H_2 membranes holds great promise, as it seamlessly integrates H_2 separation with the CO shift reaction in one streamlined process. This innovative approach offers substantial potential, combining two vital functionalities within a unified system. An advantage of this approach is the possibility of achieving a stoichiometric ratio for the shift reaction (steam to CO) instead of a super-stoichiometric ratio, which can substantially reduce the steam requirement.

Moreover, unlike the Rectisol wash, there is no need for temperature reduction during conversion reaction, resulting in an efficiency gain of 0.8 to 2.9 % compared to other membrane concepts mentioned earlier [42]. However, it is essential to perform hot gas dedusting prior to the membrane reactor. Notably, the current membrane types under discussion do not exhibit the necessary characteristics (such as permeability,

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selectivity, and stability) for employment in various separation schemes, highlighting the need for fundamental research and development efforts in membrane development and fabrication.

2.3.3 Efficiency

The introduction of physical CO_2 scrubbing in an IGCC power plant leads to efficiency losses ranging from 9 to 12 % compared to a plant without carbon capture [43]. Originally planned for the Hurth site in Germany, the IGCC demonstration power plant aimed for an efficiency of 34% and a gross efficiency of 48.5%. By transitioning to a partial quench, it was projected to achieve an efficiency improvement of approximately 1-1.5%. Harnessing the considerable potential for efficiency, a remarkable gross efficiency target of 44% was achieved, surpassing a capture rate of over 90% [44]. This impressive accomplishment showcases the ability to maximize energy output while achieving a high degree of carbon capture.

2.3.4 Advantages and disadvantages of pre-combustion processes

The pre-combustion process offers a significant advantage by utilizing commercially established physical scrubbing techniques such as Rectisol and Selexol for syngas purification, which directly parallels IGCC power plants. This process also enables high levels of purity, which is a valuable characteristic. Moreover, it is crucial to consider the substantial efficiency potential inherent in the fundamental IGCC process, encompassing gasification, comprehensive thermodynamic optimization, and advancements in gas turbine technology [31]. Another notable benefit of IGCC plants is their remarkable fuel flexibility, allowing for the generation of various products alongside power production. For instance, syngas can produce gaseous or liquid commodities like synthetic gas, synthetic fuels, methanol, etc. However, a major challenge is that these facilities are more complicated than traditional power plants. The substantial investment involved in implementing the fundamental IGCC power plant process is also a factor in the scarcity of IGCC plant worldwide. Recent cases have indicated that these elevated investment costs have hindered the implementation of some planned IGCC power plants with carbon capture [45].

2.4 Oxy-combustion capture

Oxy-combustion capture represents a modified version of the post-combustion capture process, wherein the use of normal air is replaced by oxygen-enriched air or pure oxygen. However, employing nearly pure oxygen during fuel combustion results in extremely high flame temperatures. To circumvent the need for excessively expensive equipment capable of withstanding such heat, a portion of the flue gas is redirected back to the boiler in oxy-combustion capture. This modification controls the flame's temperature and improves heat transmission via convection.

Figure 2.4 provides an overview of the general process flow of oxy-combustion capture. Pulverized coal-fired power plants utilize oxy-combustion capture technology. The primary distinction between pre-combustion and oxy-combustion lies in the composition of the inlet gas entering the boiler for fuel reactions. In oxy-combustion systems, a crucial cryogenic ASU is positioned before to the pulverized coal (PC) boiler to eliminate nitrogen (N_2), resulting in highly concentrated oxygen (O_2). Subsequently, coal is fed into the PC boiler and combusted with oxygen. The following products mainly contains of concentrated CO_2 and substantial level of water vapor (H_2O). While the remaining amount of the gas steam is subjected to particle and sulfur removal operations, more than 20% of it is carried via steam turbines to produce electricity. Following the condensation of water vapor, pure CO_2 can be obtained directly. Simultaneously, the clean flue gas is compressed and returned back into the boiler for reuse.

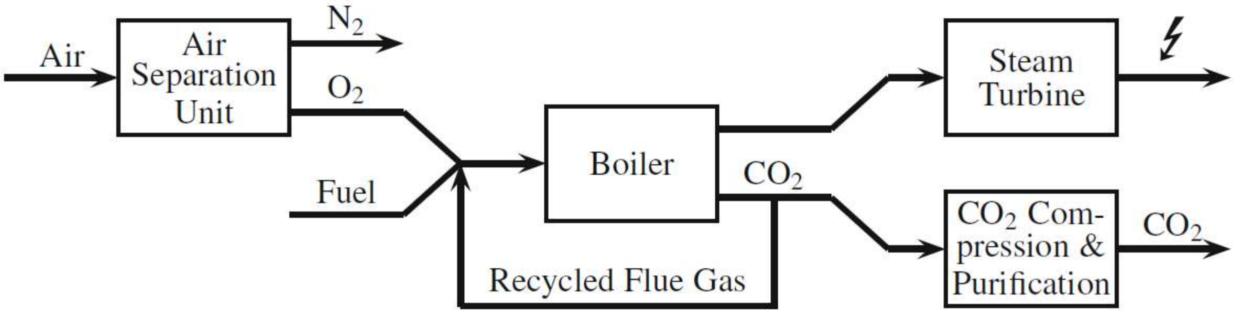

Figure 2.4: Schematic illustration of oxy-combustion CO_2 capture strategy [40]

Oxy-combustion capture processes have reached a level of maturity, primarily due to its use of tried-and-tested processes like O_2 separation and flue gas recycling, which have been successfully utilized in various industries such as chemical, petrochemical, and metal industries, making oxy-combustion capture viable option for retrofitting existing coal-fired power plants.

An air separation or external CO_2 separation equipment is typically required in the general oxy-combustion capture process. However, chemical looping combustion (CLC) technology offers an inherent CO_2 separation capability. CLC uses a fluidized bed containing metal oxide to supply O_2 for the boiler's combustion process. The leftover material can undergo re-oxidized in the air, returning to the boiler for further fuel reactions through a process known as "chemical looping." This looping involves the oxidation of the metal material, expressed as a redox reaction. The primary products obtained are highly concentrated CO_2 and water vapor, with no nitrogen gas dilution. The CLC process offers a significant advantage over traditional oxy-combustion processes, eliminating the need for additional CO_2 or air separation equipment, resulting in lower energy costs.

The final gas mixture resulting from the oxy-combustion process comprises CO_2, H_2O, excess O_2, a small amount of N_2, as well as contaminants like SOx, NOx, and Hg. To separate CO_2 and H_2O, the flue gas undergoes cooling to condense the gaseous H_2O, facilitating its removal. The amount of flue gas requiring downstream processing (after air separation) is greatly decreased since the flue gas is not diluted with nitrogen from the air, resulting in lower energy consumption by avoiding handling large gas volumes.

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Additional treatments are necessary to remove SO_x, NO_x, and Hg to enhance CO_2 purity.

Improvements in capture processes aim to address critical challenges, particularly achieving CO_2 concentrations exceeding 95% in the gas mixture, which is more costly than traditional technologies with lower CO_2 concentrations below 65% [28].

2.4.1 Utilization trends

The energy-intensive air separation process presents a significant challenge in oxyfuel power plants, leading to notable efficiency losses. The focus is on enhancing the energy efficiency of the ASU and effectively incorporate it into the power plant operations. Process engineering improvements such as employing a three-column process can potentially reduce the specific energy demand by 20% [28]. However, achieving the desired oxygen purity of approximately 99.5% (with residual components of Ar and N_2 becomes more challenging as conventional air separation units tend to result in higher residual gas content with lower oxygen purity. This necessitates additional gas purification, which further increases energy consumption and compression efforts [46].

The use of pure oxygen for combustion reduces flue gas volumes and requires modifications to the design of heat exchange firing chamber geometries, surfaces, and flue gas channels to accommodate altered radiant heat transfer. In general, it is believed that the oxygen levels in this context are lower compared to a conventional fire, potentially leading to challenges related to combustion completeness and the possibility of corrosion in the walls of the combustion chamber.

An additional hurdle arises from unwanted air infiltration, which presents a notable portion of the overall flue gas flow and has the potential to escalate as the power plant ages. Managing this issue becomes crucial to maintain optimal performance throughout the lifespan of the power plant. This results in a compromise on the necessary CO_2 purity and necessitates additional energy for compression. Ongoing research and development efforts are currently investigating several of these issues.

2.4.2 Advanced techniques in oxyfuel processes

Oxygen separation can also be achieved through oxygen-conducting membranes, employing ceramics such as perovskites and fluorites. These ceramics possess specific conductivity and permeability to oxygen ions at temperatures exceeding 700°C. This process offers the advantage of attaining relatively high levels of oxygen purity. Therefore successfully incorporating the membrane process into the operation of the power plant continues to be a difficult task, necessitating ongoing development and testing of concepts such as the three-end and four-end processes [47]. According to the literature, efficiency losses range from 6 to 10 %, depending on the selected concept and other influencing parameters [48,49].

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2.4.3 Efficiency

The efficiency reductions in an oxyfuel power plant range from 8 to 11%. The primary cause of this decrease is air separation unit operation, accounting for a loss of 7 %. The other losses are attributed to CO_2 conditioning and compression. Research conducted by Kather and Klostermann [46] suggests that with the utilization of an enhanced air separation unit and improved conditioning technologies, the efficiency losses can be reduced to approximately 10%. By implementing a three-column air separation method it would follow the overall efficiency losses to approximately 8%. It is crucial to underscore the importance of evaluating efficiency in conjunction with carbon capture efficiency alongside the necessary levels of CO_2 and O_2 purities [48].

2.4.4 Advantages and disadvantages of oxyfuel processes

The oxyfuel method exhibits significant efficiency potential and does not necessitate new technological advancements as all the required components are readily available in the market. The O_2 required for power plant operation can be easily obtained since ASU are widespread used and constructed. This simplicity of the oxyfuel process, in comparison to scrubbing methods, is advantageous and eliminates the need for by-product disposal. The current difficulty of this technology is the relatively high investment costs involved. Additionally, the feasibility of retrofitting oxyfuel processes into existing power plants remains uncertain. Furthermore, the operational flexibility of oxyfuel power plants cannot be definitively determined at this stage.

2.5 Direct air capture

Direct air capture (DAC) is becoming more important technology for net zero emissions goals. This innovative technology includes the direct retrieval of carbon dioxide from the atmosphere, which is than stored for long-term use. The captured CO_2 can also serve as a raw material for various CCU products that contain a carbon, thereby enabling the creation of goods that have minimal or smaller environmental impact. By removing CO_2 from the air, DAC is an important method for offsetting unavoidable and hard-to-abate emissions. This proves particularly valuable in mitigating the impact of emissions arising from challenging sectors such as long-distance transportation and heavy industry. Direct air capture offers a promising and one of the solution for dealing with the burden of past emissions. Direct air capture serves as a multifaceted approach with far-reaching implications for achieving sustainable and carbon-neutral practices [19].

DAC technologies use several separation methods to capture CO_2 from the atmosphere. Most common approaches are chemical absorption with amine solutions, adsorption into solid materials, and chemical reactions with sorbents or solvents.

In 2024, 27 DAC plants have been commissioned worldwide, capturing almost 0.01 Mt CO_2/year [22]. To achieve the target of net zero emissions, a significant increase in the deployment of Direct air capture is extremely urgent during this decade. According

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to the IEA's Net Zero Emissions by 2050 Scenario, the scale of DAC deployment will witness a large surge, with an estimated reach of about 85 Mt_{CO2} by 2030. Scaling of DAC will by 2050 reach up to 980 Mt_{CO2}.

On the market are for direct air capture two technological approaches familiar: Low Temperature (LT) DAC and High Temperature (HT) DAC. The LT DAC method involves the utilization of solid sorbent filters. This solid sorbent are creating a chemical bond with the CO_2. Upon subjecting these filters to heat, they release the concentrated CO_2, which can then be effectively captured for further storage or utilization purposes. Contrary to that, HT DAC systems function by passing air through chemical solutions, such as hydroxide solutions, which effectively eliminate the CO_2 from the air, while allowing the remaining components of the air to be released back into the environment.

Aside from the already mentioned approaches, there are also emerging technologies at the prototype stage, such as electro-swing adsorption and membrane-based separation. These innovative approaches offer new potential in CO_2 capture and separation. Electro-swing adsorption uses specialized electrodes that exploit electrical forces for the selective adsorption of CO_2, allowing for its subsequent collection. Membrane-based separation involves the usage of advanced membranes that facilitate the separation of CO_2 from air through a filtration process, therefore enabling its isolation and later use in one utilization process.

Technological approaches previously explained shows important progress in the capturing CO_2 from the atmosphere, because they present different approaches with diverse innovative mechanisms. Also their development at the prototype level demonstrates the continuous efforts in pushing the boundaries of CO_2 capture technology, aiming to address the pressing issue of climate change and reduce the concentration of CO_2 in the atmosphere [19].

2.5.1 Low temperature DAC

Low temperature direct air capture (LT DAC) begins with adsorption of ambient air into the module and during the adsorption phase, ambient air is drawn into the system using fans and passes through a unit where it chemically bonds with a sorbent. This filter, or sorbent, has the ability to capture and retain CO_2 from the air. As the sorbent becomes saturated with CO_2, the system moves into the second phase - regeneration phase.

In the second phase - regeneration phase, the sorbent that is saturated with CO_2 is going to transformation process where the captured CO_2 is released. This release happened at a temperature of approximately 100°C. To begin a new adsorption phase and the process from the start, the unit must be cooled back down to the ambient temperature.

In Figure 2.5 is presented the schematic of the low temperature DAC process. Byproduct of the low temperature DAC is water.

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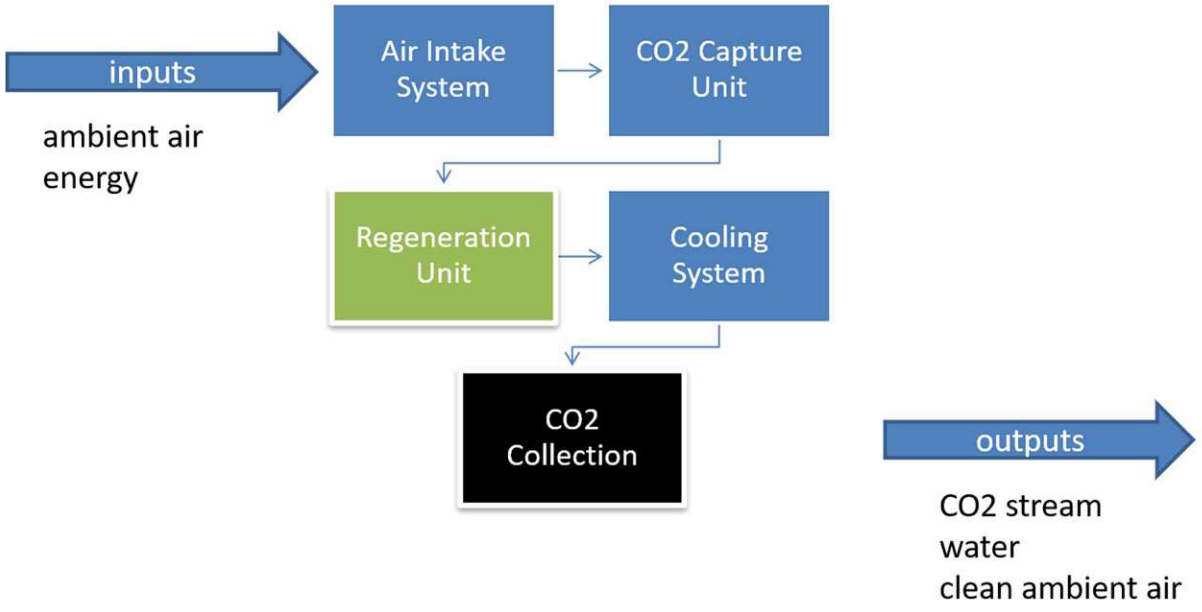

Figure 2.5: Schematic of LT DAC process

It is important to emphasize that the sorbent used in low temperature direct air capture systems has a limited lifespan. Over time, the sorbent becomes less effective at capturing CO_2 and therefore there is a need for replacement. This has an influence on cost.

To achieve a high level of purity in the captured CO_2, heat energy and vacuum are applied during the regeneration phase. This has impact on energy efficiency of the process, but this combination of forces make sure that the released CO_2 is of a high quality, with a purity level of greater than 99%.

Different companies have proposed different sorbents and methods for the adsorption and desorption processes. For example, Climeworks uses a filter made of special cellulose fiber supported by amines, while Global Thermostat uses a proprietary amino-polymer adsorbent. These companies have different energy demands for their systems, with Climeworks requiring 200-300 kWh of electricity and 1500-2000 kWh of heat for regeneration, and Global Thermostat requiring 150-260 kWh of electricity and 1170-1410 kWh of heat. This two approaches is showing clearly in energy demand how completely different they are [23].

Other systems use steam at high temperatures for desorption. Recording one study a temperature swing system using different amino-modified metal organic frameworks (MOF), and found that the one based on magnesium had lower electricity and heat demand. Antecy uses a composite sorbent based on potassium carbonate and has a lower regeneration temperature of 80-100 degrees Celsius.

There are differences in the reported energy demands among these companies, with Climeworks having the lowest energy demand, after that is company Global Thermostat. In terms of CO_2 purity, all of the companies aim for a purity of over 99% [23].

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Climework system it's in a modular format. These modules and standardize, and can be assembled in any configuration to meet specific needs. Each module has a potential of capturing 50 tons of CO_2 per year. A configuration of six standard modules is equivalent to a capacity of 300 tons of CO_2 per year and with a processing unit, can be accommodated within a 40-foot container [23].

2.5.2 High temperature DAC

In the high temperature direct air capture (HT DAC) process, there are two main processes involved: absorption and regeneration. But these processes have separate units dedicated to their functions and the processes can run simultaneously.

In the air contactor unit, the ambient air with a CO_2 concentration of approximately 400ppm comes into contact with sprayed sodium hydroxide (NaOH). So is a solution of sodium carbonate (Na_2CO_3) formed. This chemical reaction takes place at room temperature and ambient pressure, make certain efficient absorption of CO_2 from the air.

In the next process - regeneration process the sodium carbonate (Na_2CO_3) that has been absorbed in the previous step is mixed with calcium hydroxide ($Ca(OH)_2$) and it forms compounds calcium carbonate ($CaCO_3$) and sodium hydroxide. The sodium hydroxide recovered from this process is then reused again in the air contactor for further absorption of CO_2.

To further facilitate the regeneration process, a separate unit, also known as calciner unit, is utilized. In this unit, the calcium carbonate ($CaCO_3$) produced in the regeneration step is heated to temperatures more than 900°C. This high temperature is needed for the CO_2 to be released and extracted. The compound that remains, known as calcium oxide (CaO), is then mixed with water to form calcium hydroxide ($Ca(OH)_2$) once again. This regenerated calcium hydroxide can be used in the regeneration process, and this create a continuous cycle.

By combining these separate units for absorption and regeneration, high temperature direct air capture offers an efficient and sustainable method for capturing CO_2 from the ambient air. This technology has very important role in combat with climate change by reducing GHG emissions and helping to achieve the worldwide climate goals [23].

$$2 \cdot NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$$

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

$$CaO + H_2O \rightarrow Ca(OH)_2$$

This technology operates at a high temperature of over 900°C and it's very energy demanding, both heat and electrical demanding. For the regeneration process is heat demand in range from 1230 to 2250 kWh_{th} per t_{CO2}. For adsorption process, spraying and moving solutions is estimated electrical energy demand from 366 to 764 kWh_{el} per t_{CO2} and that includes the energy demand for CO_2 compression [23].

High temperature DAC requires the use of natural gas for the regeneration process, but the emissions from this combustion are also captured [22]. But this option is not sustainable. Capturing 1 ton of atmospheric CO_2 by using oxy-fuel combustion of natural gas with 90% efficiency to provide 2000 kWh_{th} high-grade heat, would still release 0.44 ton of direct natural gas based CO_2 emissions, not considering the emissions from its life cycle. DAC technology operates entirely on natural gas and would emit 0.5 ton of CO_2 for every ton of atmospheric CO_2 it captures. Although this captured CO_2 can be repurposed, it will eventually reenter the atmosphere after a few utilization cycles. As a result, the cost of net-captured CO_2 would rise significantly due to this effect, since most studies calculate costs based on total captured or atmospheric CO_2. One potential remedy for this issue could involve utilizing carbon-neutral renewable synthetic natural gas (RE-SNG). Implementing this solution would steer to a rise in the energy demand for hydrogen production, in the end raising production costs as SNG production is expensive [23].

2.5.3 Advantages and disadvantages of DAC technology

One of the main benefits of low temperature DAC is the water production. This means that while capturing carbon dioxide from the air, low temperature DAC can also generate usable water. Also low temperature DAC requires less capital cost compared to high temperature DAC, making it a more cost-effective option. The modular nature of low temperature DAC allows for flexibility and scalability, making it adaptable to varying needs. Another advantage is that low temperature DAC can rely only on low-carbon energy sources for operation. This reduces dependence on fossil fuels and aligns with sustainability goals. Therefore being a novel technology, low temperature DAC has the potential to go through further development and cost reduction in the future.

On another side, high temperature DAC, has own set of advantages. High temperature DAC is less energy-intensive compared to the low temperature DAC. Also high temperature DAC can be implemented on a large scale, enabling significant carbon dioxide capture. The operation of high temperature DAC depend on commercially available solvents, which makes the process simpler and allows for easier integration into existing systems. In fact, the technology used in high temperature DAC is adapted from existing commercial units, which adds to its reliability and feasibility.

There are also some disadvantages associated with low temperature DAC. Manual maintenance is needed for the replacement of the adsorbents used in the process. This adds to the operational complexity and labor requirements of low temperature DAC.

One major drawback for high temperature DAC is its higher capital investment costs. Implementing high temperature DAC requires significant initial investment, which may be a challenge for widespread adoption. Using high temperature DAC also relies on

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natural gas combustion for solvent regeneration, which contributes to greenhouse gas emissions and lowers the efficiency of captured CO_2. With a potential for future electrification and the use of renewable energy in the process, there is a possibility to potentially increase the net value of captured CO_2.

Both technologies have their own unique features and considerations, and further research and development will be crucial in advancing carbon capture technology [19].

2.6 Overview of carbon capture technologies

Table 2.1 provides a summary of the carbon capture technologies, highlighting their key features, advantages, and disadvantages. For this study chosen carbon capture technology is DAC. DAC is the newest technology on the market, therefore is currently more expensive but holds the greatest potential for future scalability and cost reduction. As the technology develops and scales, costs are expected to decrease. Another advantage of choosing DAC is the flexibility in selecting the location for the production facility.

While other carbon capture technologies might lower the cost of producing e-methanol due to cheaper CO_2 capture, it is important to take in consideration also if the existing facilities have enough space for the necessary upgrades of carbon capturing system or if the technology even is possible to be used. With DAC technology are transport cost of CO_2 eliminated and e-methanol production facilities to be placed in a single location.

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Table 2.1: Overview of carbon capture technologies

	Post-combustion capture	**Pre-combustion capture**	**Oxy-combustion capture**	**Direct Air Capture**
Description	captures CO_2 after fuel is burned. CO_2 is separated from flue gases.	captures CO_2 before combustion by gasifying fuel.	burns fuel in oxygen instead of air, producing a concentrated CO_2 stream.	captures CO_2 directly from ambient air.
CO_2 Concentration	low (CO_2 partial pressure: 0.1 to 0.13 bar)	high (as part of syngas)	high (due to absence of nitrogen in the combustion process)	very low (~400 ppm in the air)
Energy requirement	120-300 kWh/t for solvent regeneration and CO_2 compression	150-450 kWh/t for gasification and CO_2 separation	energy required for oxygen production ~300 kWh/t and for CO_2 compression ~80–120 kWh/t	LT DAC: 150–300 kWh/t (electricity); HT DAC: 1200–2250 kWh/t (thermal)
Efficiency impact	reduces plant efficiency by 9-14%	reduces efficiency by 9-12%	reduces efficiency by 8-11%	energy-intensive, exact efficiency impact varies by technology
Technological maturity	mature; commonly used in power plants	mature, but less common due to complexity	mature, especially in industries like petrochemicals	emerging, with both low and high-temperature options being explored
Advantages	- high CO_2 purity (>99.99%) - retrofit existing plants possible	- high CO_2 purity - high fuel flexibility (can produce other products)	- high CO_2 concentration simplifies separation - no nitrogen in the flue gas, reducing downstream processing needs	- can capture CO_2 from dispersed sources - important for achieving net zero emissions
Disadvantages	- high energy consumption - significant efficiency losses	- high investment cost - complexity and cost limit deployment	- high oxygen production cost - uncertainty in retrofitting to existing plants	- expensive and energy-intensive - requires further technological development and scaling

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2.7 Transport of CO_2, hydrogen and methanol

Following the carbon dioxide capture and separation process, it is crucial to ensure the CO_2 is transported in the fitting phase state. Although there are several transportation methods, such as using the gaseous phase, this is not economically feasible due to high pressure losses. Regarding to that, it is preferable to transport that substantial amounts of CO_2 as a liquid or supercritical fluid or as dense phase fluid [50].

Transporting CO_2 in its dense phase offers many advantages in terms of energy efficiency. Its viscosity is closer to that of a gas, while its density is similar to that of a liquid. Factors that are impacting the transport cost of CO_2 are density, viscosity, heat capacity and thermal conductivity of CO_2.

The transportation of CO_2 can be categorized into offshore and onshore, each having its own characteristics. Onshore transportation options are tank trunks, railroads tankers, and pipelines, while offshore options encompass pipelines and ships tankers [24].

Among the available transportation methods, onshore and offshore pipelines, as well as transport ships, are the most technologically mature options. Pipelines are used to transport CO_2 in a supercritical state, which requires temperatures above 31 °C and pressures of 73 bar. This unique state enables a high volumetric flow rate, similar to that of the liquid phase. By cooling the CO_2 to approximately minus 50°C and applying 6 bar pressure, it condenses into a liquid state, making it more compact and easier to transport. Ships are commonly used to transport CO_2 in this form [51]. These methods are now in the final stage of development (TRL 9) as they are currently being implemented on a commercial scale. It's also possible to transport CO_2 by road and rail tankers, though this is not usually the method of transportation for large-scale Carbon Capture and Storage (CCS) projects, mostly because of the cost.

Each transportation method have own advantages and disadvantages when it comes to transportation of CO_2. Rail tankers have the advantage of being unaffected by weather conditions or traffic congestion, therefore is reliable and timely transportation. They also do not require the construction of specialized railroad infrastructure, making them a cost-effective option. Road tankers offer flexibility in transportation as they are not limited by CO_2 source or destination. They also do not require significant investments in new transportation infrastructure, making them a convenient option. Pipelines have a high volume transportation capacity, allowing for efficient transportation of large quantities of materials. They are known for their cost-effectiveness, making them a preferred choice for many industries. Ships are efficient in terms of economy as they can transport large quantities of goods across long distances. They benefit from well-established and advanced transportation technology, ensuring smooth and reliable transportation [24].

On another side, each method of transportation also has its disadvantages. Rail tankers require strict adherence to CO_2 standards and close proximity to the rail for both the source and destination, which can be limiting in some situations. Road tankers come with significant expenses associated with transportation, are influenced

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to weather and traffic factors, and the high costs of labor and fuel can make them an expensive option. Pipelines require a substantial financial commitment for infrastructure development and they have high volume transportation capacity and are cost-effective once they are build and in use. Ships have regulations on shipping equipment related to temperature and pressure control, which can add additional costs and complexities to the transportation process [24].

Despite the fact that there are various transportation methods available, the appropriate method choice depends on factors such as distance and project scale – the quantity of CO_2 that is needed to be transported. Regardless of the high level of development and advances in transport technologies, further research and development are required to optimize the efficiency and cost-effectiveness of CO_2 transportation [24].

Transportation of hydrogen is similar to transportation of CO_2. It's deviated into long distance and local distribution.

The commonly used long distance transportation are pipelines and shipping. Pipelines are normally used for transporting big quantities and over long distances with low operational costs. Around the world there is around 5000 km of pipelines for hydrogen transportation. Transport of pure hydrogen by ship would be possible only in liquid state, what would add additional cost for liquidation of hydrogen [52].

Local distribution of hydrogen are done with trucks and pipelines. Transport by trucks is commonly used for distances of 300 km as compressed gas. For longer distances for around 4000 km are used insulated cryogenic tankers [26].

Selection of suitable transportation method for hydrogen depends on several factors, mainly of quantity to be transported, distance it needs to travel, and pre-existing infrastructure available. Each method offers advantages and challenges, therefore is important to tailor the choice to specific requirement. Given hydrogen's low energy density, transportation costs may tend to be slightly higher [53].

Transportation of methanol is done in similar ways: by pipelines, ships, rails and trucks. Important factors to consider when choosing the appropriate method for methanol transportation are safety and cost-effectiveness [53].

The most cost-effective method transportation of methanol is by ship, particularly for large quantities and over long distances. Using large tankers is well-suited for international and overseas shipping, offering economies of scale and efficient transport logistics. Transportation of methanol by pipelines requires big capital investment and is typically reserved for large-scale quantities. Transportation by rail uses already existing infrastructure, with strict regulations focusing on the tankers used to transport hazardous liquids. The most expensive method to transport methanol is by truck. Typically is used to for smaller distances and that from distribution centers to the end user for consumption [54].

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2.8 Carbon utilization

The process of CO_2 utilization means utilizing CO_2 through chemical reactions in products that have economic value. This process is not only helping in reducing emissions but also creates valuable products and so giving the companies a financial incentive to invest in this technologies. The potential of CO_2 is extensive and it can be used directly without any chemical alteration, known also as non-conversion, and with the conversion into valuable products. This can result in the production of materials, fuels chemicals, building materials and even used directly in processes like enhanced oil recovery. The graphic presentation of CO_2 use is presented in Figure 2.6. CO_2 is currently used in different industrial processes, with significant amounts being used in urea manufacturing – with conversion of CO_2 and enhanced oil recovery (EOR) – with direct use of CO_2. Around 130 Mt of CO_2 are annually used for production of urea, a key component in fertilizers. Additionally, around 80 Mt of CO_2 are annually used in enhanced oil recovery (EOR), where the CO_2 is injected into oil fields to help extract more oil [50].

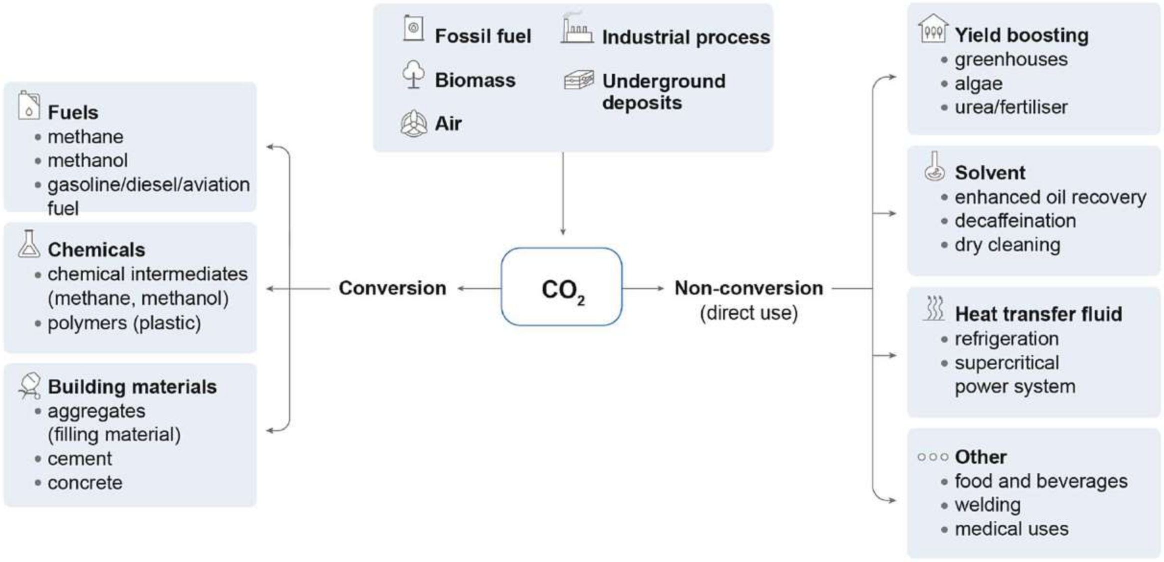

Figure 2.6: Simple classification of pathways for CO_2 use [50]

CO_2-derived synthetic fuels are created by converting CO_2 into usable energy carriers. By reducing greenhouse gas emissions they are seen as a greener alternative to traditional fossil fuels. Using a process called electrochemical reduction, CO_2-derived synthetic fuels are created such as methane, ethanol or methanol. These fuels have a big potential and it's around 1 to 4.2 Gt of CO_2 by year 2050, with costs up to 610 EUR per ton of CO_2 [50, 55].

CO_2-derived chemicals like methanol or polymers are created employing catalysts and chemical reactions. The potential benefits of CO_2 chemicals are vast and promising. Demand of CO_2 for CO_2 chemicals is estimated between 0.3 and 0.6 Gt of CO_2 by year 2050 with costs ranging from -70 EUR to 270 EUR per ton of CO_2 [50, 55].

Concrete is one of the most widely used building material in the world and it is responsible for 5% of global CO_2 emissions. Researchers estimate that the potential for using CO_2 in concrete production could reach 0.1 to 1.4 Gt of CO_2 by year 2050 with cost ranging from -25 EUR to 60 EUR per ton of CO_2 [50, 55].

For production of oil the CO_2 is pumped in oil walls, therefore the impact on environment is questionable, that this way is more CO_2 is produced. EOR has a big potential and it’s estimated that 0.1 to 1.8 Gt of CO_2 utilized by year 2050 at costs ranging from -55 EUR to -35 EUR per ton of CO_2 [50, 55].

The reduction in emissions and positive outcome for the climate is not guaranteed when the CO_2 is used. There are a lot of factors that can influence that and the most important ones are:

- source of CO_2 – regarding the source of CO_2, the price of CCU product is going to change
- energy source – CCU processes are high energy demanding and therefore is using a low-carbon energy important
- scale of the market – product that have more potential, is going to take more CO_2 from the atmosphere and have bigger impact on the environment
- how long CO_2 is stored in this particular product – products that can store CO_2 longer, are going to have more importance [50].

To develop future market for CCU product, market scalability and competitiveness are more than enough, but according IEA [50] the climate benefit is the most important factor. The most important factors for developing future market potential are presented in Figure 2.7.

The CCU projects are characterized with significant costs and extended payback periods, therefore are traditional investment decision making methods not applicable. Given that the real option method accounts for uncertainty and management flexibility, it is particularly well-suited for analyzing investment decisions related to CCU projects. Under the real option approach, the value of energy project can change over time, which gives investors the flexibility to delay investments until conditions are better. A critical factor affecting the economics of CCU is the accurate prediction of future costs, especially when considering the learning effect [56]. Learning effect presents the improvement in performance of a specific technology as its production volume increases. It’s typically showed in a reduction in cost per unit, but also in other metrics such as energy consumption and emissions per unit. It's important to understand that cost reductions are achieved through learning [57]. By incorporating the learning curve approach into the real options investment decision model, the accuracy of these decisions can be significantly improved [56].

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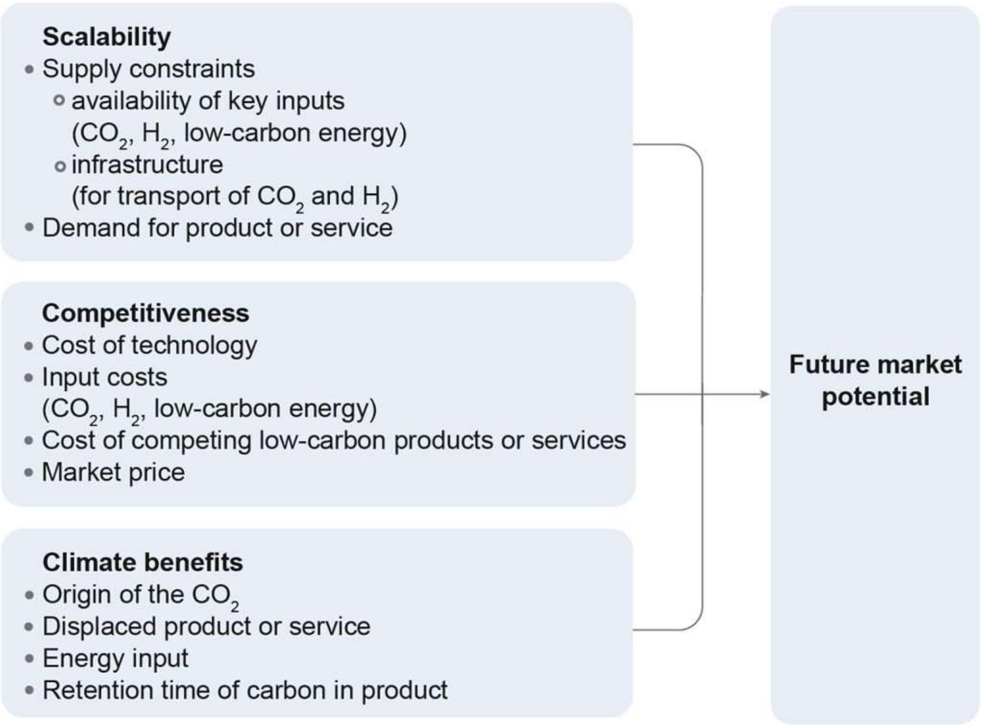

Figure 2.7: Factors affecting future market [50]

The future for CO_2 utilization technologies looks promising. Advancements in the field are driving down costs and increasing efficiency, making it a compelling choice for industries aiming to reduce their carbon emissions. The integration of CO_2 utilization technologies with renewable energy sources and the growing interest in circular economy principles further enhance their potential. Despite difficulties such as scalability and regulatory support there is a need to be addressed for widespread adoption to become a reality. With continued research, innovation, and collaboration, CO_2 utilization technologies have the potential to make a substantial impact on mitigating climate change and creating a more sustainable future.

2.9 Methanol

Renewable methanol has the same chemical structure as methanol produced from fossil fuels - CH_3OH and can potentially replace it in all of its current uses. This means, it can be used as a raw material for a production of chemicals (as olefins, formaldehyde, acetic acid and esters), materials, plastics, fuels (mix with gasoline or used in methanol fuel cells) and various other products [53, 58]. It can be used as a fuel for different purposes such as transport, shipping, cooking, heating and electricity generation. Methanol is a fuel that can be used in marine vessel, in adapted diesel trucks and in hybrid and fuel cell-powered vehicles. Dimethyl ether (DME), a derivative of methanol that is easily obtainable, is particularly effective as a fuel for compression ignition engines. As there are more options for light vehicles as cars, such as hydrogen and batteries, heavy trucks and shipping, that belong to hard-to-electrify sector, are more suitable for renewable methanol. Renewable methanol has a potential to replace a big portion of fossil fuel-based hydrocarbons and petrochemicals [53].

To produce e-methanol sustainable sources of H_2 and CO_2 are necessary. The similar established technologies, that are used to produce methanol from fossil fuel-based syngas can also be applied for production of e-methanol. Fossil fuel-based technology is high developed, proven and fully commercial and already TRL 9. Additionally, electrolysis of water and CO_2 capture technologies have reached a sufficient level of development [53]. Methanol is typically produced by converting syngas through catalytic processes, with syngas most commonly sourced from natural gas using steam methane reforming (SMR) [59].

According to report from IRENA and Methanol Institute [53] is type of the hydrogen and CO_2 used in the production of methanol important and taking that in consideration there are more types of methanol. Production routes are presented in Figure 2.8. For production of e-methanol are renewable CO_2 and green hydrogen needed. Renewable CO_2 is through DAC captured and from bio-origin and the non-renewable CO_2 has fossil origin from industry.

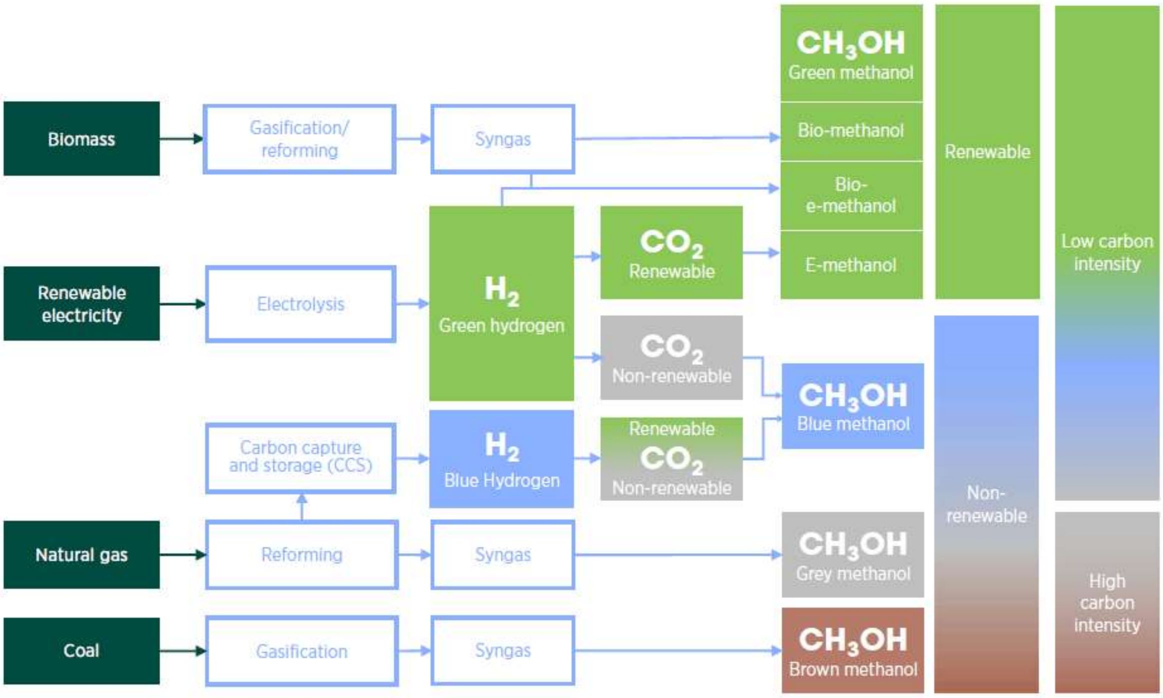

Figure 2.8: Principal methanol production routes [53]

To make hard-to-electrify sector carbon neutral, measures has to be implemented as carbon taxes, mandates and incentives. This is going to impact the demand of renewable methanol.

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2.9.1 Production of hydrogen

Currently, hydrogen is produced on a large scale, with a majority (approx. 65%) of it being pure hydrogen and remaining being mixed with other gases. This mixed hydrogen is utilized in industries like methanol and iron/steel manufacturing. Pure hydrogen plays a crucial role in multiple industrial operations, but the majority of it is derived from fossil fuels. Only a small portion, around 4%, is produced through electrolysis, whether powered by grid electricity or renewable sources (also known as green hydrogen). In Figure 2.9 is presented the production of hydrogen regarding of method of production [53].

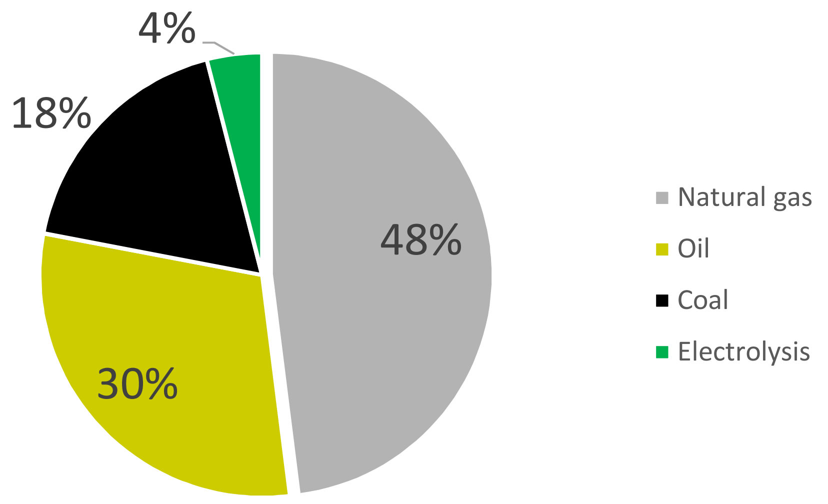

Figure 2.9: Hydrogen production by way of source [53]

Hydrogen is mostly produced through method known as: steam methane reforming (SMR) – that is using natural gas as the most common feedstock. Other methods of production, known also as coal gasification or biomass gasification are less commonly used on a large scale because of higher costs and environmental concerns [53]. The most environmental friendly way to produce hydrogen is with electrolysis. This method requires a lot of electricity, which should be from renewable energy source. By using electrolysis method of production, hydrogen that is produced is pure without any impurities and by-product is pure oxygen, that can be used in other process [60]. Figure 2.10 shows types of hydrogen regarding the production process.

The current primary technologies available for electrolysis are:

- Alkaline electrolysis
- PEM electrolyse
- Solid Oxide electrolysis.

An overview of the technologies is given in Table 2.2.

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Table 2.2: Electrolysis production technologies [60]

Parameter	**Alkaline**	**PEM**	**Solid Oxide**	**Unit**
Temperature	60 - 90	50 - 80	600 - 1000	$°C$
Pressure	1.05-30	10-200	1 - 25	bar
Energy consumption	4.5 - 6.6	4.2 - 6.6	3.7 - 3.9	$\frac{kWh}{m^3{}_{H2}}$
Max. capacity	5.3	1.1	n.a	MW
Capital cost	800 - 1500	900 - 2200	>2000	$\frac{EUR}{kW}$
TRL	9	5 - 7	3 - 5	

Each of these electrolysis technologies has its advantages and disadvantages, and their suitability depends on the specific application and requirements. Alkaline electrolysis is well-suited for large-scale applications due to its long history and cost-effective operation at high capacities. PEM electrolysis operates at lower temperatures and compact design of the process, is more suitable for decentralized and portable applications. Solid Oxide electrolysis, which operates at high-temperature, is a promising technology for industrial-scale hydrogen production, especially when combined with renewable energy sources like concentrated solar power [60].

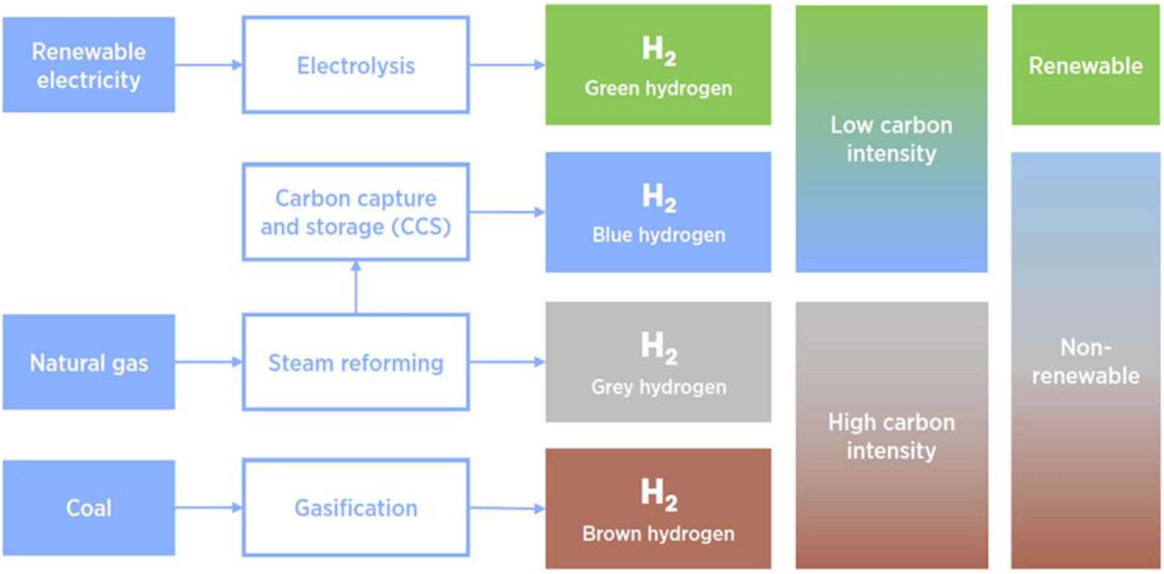

Figure 2.10: Types of hydrogen according to production process [53]

In recent years, there has been significant progress in electrolysis technology, driven by the increasing demand for hydrogen as a clean energy carrier. Researchers and engineers continue to explore novel materials, designs, and manufacturing techniques to improve the efficiency, cost-effectiveness, and scalability of water electrolysis. This

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ongoing development is crucial for realizing a sustainable hydrogen economy and reducing dependence on fossil fuels. With advancements in electrolysis technology, water electrolysers are becoming increasingly important as key components in energy storage, grid balancing, transportation, and various industrial processes [53].

2.9.2 Cost of e-methanol

Cost of e-methanol is mostly influenced by the cost of production of hydrogen and the cost of captured CO_2. To produce renewable and low carbon intensity methanol CO_2 should come from DAC and hydrogen should be produce with renewable electricity. DAC and electrolysis of water requires a lot of energy, therefore the price of e-methanol depends on price of renewable electricity. Other renewable sources are also viable options, but solar and wind energy have the greatest potential for expansion to meet the demand for e-methanol.

The production cost of methanol on market is fluctuating between 185 EUR/t and 370 EUR/t[1]. With production cost of natural gas-based methanol from 90 – 180 EUR/t they are slightly better than production cost of coal-based methanol with 140 – 230 EUR/t. Compared to that production costs of renewable methanol are generally anticipated to be higher and are in range 740 – 2200 EUR/t. It is important to point out that fossil-based methanol in advantage based on their energy content compared with petroleum-based fuels as gasoline, diesel, jet fuel and heating oil. Methanol is priced at 9 – 18.5 EUR per GJ, while petroleum-based fuels are prices around 15.7 EUR per GJ [53].

With the expectation of lowering renewable energy costs, the potential for reduced operative expenses of producing green hydrogen and captured CO_2 are big and the projected production costs of e-methanol are approximately 230 – 580 EUR/t excluding CO_2 taxes and even lower with the inclusion of CO_2 taxes. Apart from the cost of electricity, it is also important for electrolyser costs to continue to decrease, while having stable supplies of reasonably priced renewable CO_2 [53].

2.9.3 Potential of methanol and impact on electrical grid

According to IRENA [53] more than 60% of methanol produced was used for synthesizing chemicals like formaldehyde, acetic acid, methyl methacrylate, ethylene and propylene. Additionally to that, more than 31% of methanol is used for production of various methanol-based fuels or fuel mix with methanol.

By projections from IRENA [53] the global production of methanol will increase from approximately 100 Mt at the moment, to more than 120 Mt by 2025 and 500 Mt by 2050. Currently, there are over 90 methanol production plants globally, with production capacity of around 120 Mt [61], which is more than enough to cover the current demand.

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[1] Exchange rate 1 USD = 0.93 EUR

The report by Triton [62] predicts a 3.72% annual growth rate for the European methanol market during the period from 2019 to 2027. Meanwhile, the Methanol Market Report [63] forecast a 5% compound annual growth rate (CAGR) for the global methanol market through 2030.

The process of converting CO_2 to methanol requires significant energy, and mostly in the production of renewable hydrogen and DAC. This makes the process costly and energy-intensive [23, 64]. For example, the conventional production of olefins, such as ethylene and propylene, which accounts for 25% of methanol consumption [53], requires 3.3 to 4.6 MWh/t of energy. In contrast, the directly production of olefins from CO_2 and hydrogen also known as Methanol-to-Olefins (MTO) process demands approximately 27 MWh/t [65].

By 2050 in expected to be produced 500 Mt of methanol, where are about 250 Mt of e-methanol [53]. To achieve this production of e-methanol approximately 350 Mt of CO_2 and 48 Mt of hydrogen will be necessary. Production of this quantity of hydrogen, assuming an energy demand of 60.7 MWh/t_{H2} [64], requires around 3 120 000 GWh of electricity – only for producing the hydrogen needed for the process. To meet this electricity demand through solar power, an installed capacity of about 1 120 GW would be needed, or with wind power approximately 607 GW of installed capacity. Additionally, DAC requires approximately 360 GWh of electricity. This shows how big the impact of production of e-methanol on energy infrastructure is going to have.

2.10 Environmental implication of CCU

The use of CCU has the potential to assist the environment – reducing the CO_2 emissions and the economy – creating new products and jobs. During the course of a product's or service's full life cycle, the LCA technique takes into consideration a wide range of environmental impacts [66, 67]. When doing a life cycle assessment (LCA) on a technology that uses carbon capture and utilization (CCU), there are several unique methodological challenges to consider. To deal with these problems, approximately 40 specialists worked together to draft a detailed guideline for LCA of CCU technology. By providing explicit methodological advice and established assumptions on feedstock and utilities, the guideline should increase the comparability of LCA studies [66].

When comparing CCU production to more traditional methods of making the same conventional products, the environmental implications, especially those related to global warming/climate change, are reduced. Clean energy processes, such as the electrolysis of water for hydrogen production, are essential to bringing about these changes in environmental impact. Results from LCA studies are not directly comparable due to methodological differences. It is crucial to establish standardize LCA approaches for analysing CCU systems, and to ensure that these approaches are documented and justified in the LCA report [67].

In 1990s was the LCA methodology standardized with ISO 14040 and 14044 Standards and it undergoes regular updates and extensions, with the most recent revision occurring in May 2018 [66]. Before 2014, life cycle assessment (LCA) was not

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a commonly adopted practice for environmental studies related to carbon capture and utilization (CCU) [67].

In adherence to the ISO standard, a Life Cycle Assessment (LCA) study is divided into four phases:

1. goal and scope definition
2. life cycle inventory analysis
3. life cycle impact assessment
4. interpretation.

In the initial phase, goal and scope definition, of LCA it’s important to establish clear objectives and boundaries for the study. Assessing CCU technologies the crucial steps are defining the overarching goal of the study and determining the functional units and system boundaries. In the life cycle inventory analysis it is crucial to meticulously select inventory data sets and reference processes. Additionally, methods to address any data gaps within the inventory must be considered to ensure the accuracy and completeness of the assessment. In the third phase it is important to select the appropriate impact assessment methods, by considering regional differences and accounting for factors such as temporary storage of CO_2. This can influence greatly the overall findings of the LCA study. In the final phase of LCA, the interpretation, it is necessary to conduct uncertainty and sensitivity analyses to understand the reliability of the results. Guidance on interpreting neutral and negative environmental impacts is also provided to ensure a comprehensive understanding of the potential consequences of the studied processes [66, 68].

The primary objective of many Life Cycle Assessment (LCA) studies on Carbon Capture and Utilization (CCU) is to quantify the potential reductions in environmental impact that CCU processes or products may offer when compared to existing processes.

Life Cycle Assessment (LCA) studies conducted on lab-scale processes face a dual challenge, potentially resulting in either underestimation or overestimation of environmental impacts. The inherent uncertainty arises from the unpredictable nature of these early-stage technologies and their evolving characteristics.

Moreover, predicting future developments introduces an additional layer of uncertainty into LCA studies. Attempting to forecast advancements in technology, process optimization, or integration may introduce variability and make it challenging to accurately assess the long-term environmental implications of CCU processes. These uncertainties highlight the complex and dynamic nature of evaluating environmental impacts in the context of emerging and evolving technologies [66].

Life cycle assessment often involve analyzing cradle-to-gate systems, determining functional units based on mass output (such as "producing 1 kg of methanol") and incorporating system expansion into their evaluations. The majority of research on technological revolves around capturing CO_2 from combustion processes, producing

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hydrogen through water splitting, and using the national grid mix as a source of electricity [67].

CarbonNext provided the following recommendations for applying life cycle assessment to study carbon capture and utilization (CCU) systems:

- when comparing CO_2-derived products with conventional produced ones, it is important to ensure that the stages of combustion, use, and end-of-life stages are consistent in both scenarios. Therefore, a cradle-to-gate analysis is recommended.
- location-specific study should be conducted whenever possible.
- system expansion should be utilized to address multifunctional processes, and the functional unit should be extended accordingly to account for additional products.
- include CO_2 capture in the study if feasible [67].

After life cycle assessment also important factor for CCU technology is technology readiness level (TRL). TRL system is a nine level rating system and it helps to monitor and assess the current state of technological advancements in that technology field [24]. The overview of the TRL system is shown in Table 2.3.

The TRL is a subjective measure of technological maturity, which may can vary. It considers the technical readiness of a technology and does not include economical evaluation or environmental impact. Low TRL shows that this technology wasn’t tested in practical settings, which leads to unrealistic data for real world scenarios.

In the case of Carbon Capture and Utilization (CCU) technologies in early stages of development, characterized by a low technology readiness level, comparisons in studies can be challenging due to inherent disparities. These studies may inadvertently lead to bad comparisons as reference technologies are typically well-established and have undergone years of optimization. Processes with low TRL may exhibit higher energy demand or solvent consumption due to the absence of established heat integration and/or process optimization [66].

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Table 2.3: Technology readiness level definitions [24,69]

Technology readiness level	***Description***
TRL 0	unproven concept
TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in lab
TRL 5	technology validated in relevant environment
TRL 6	technology demonstrated in relevant environment
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment

The overview of TRL of carbon capture technologies is presented in Figure 2.11.

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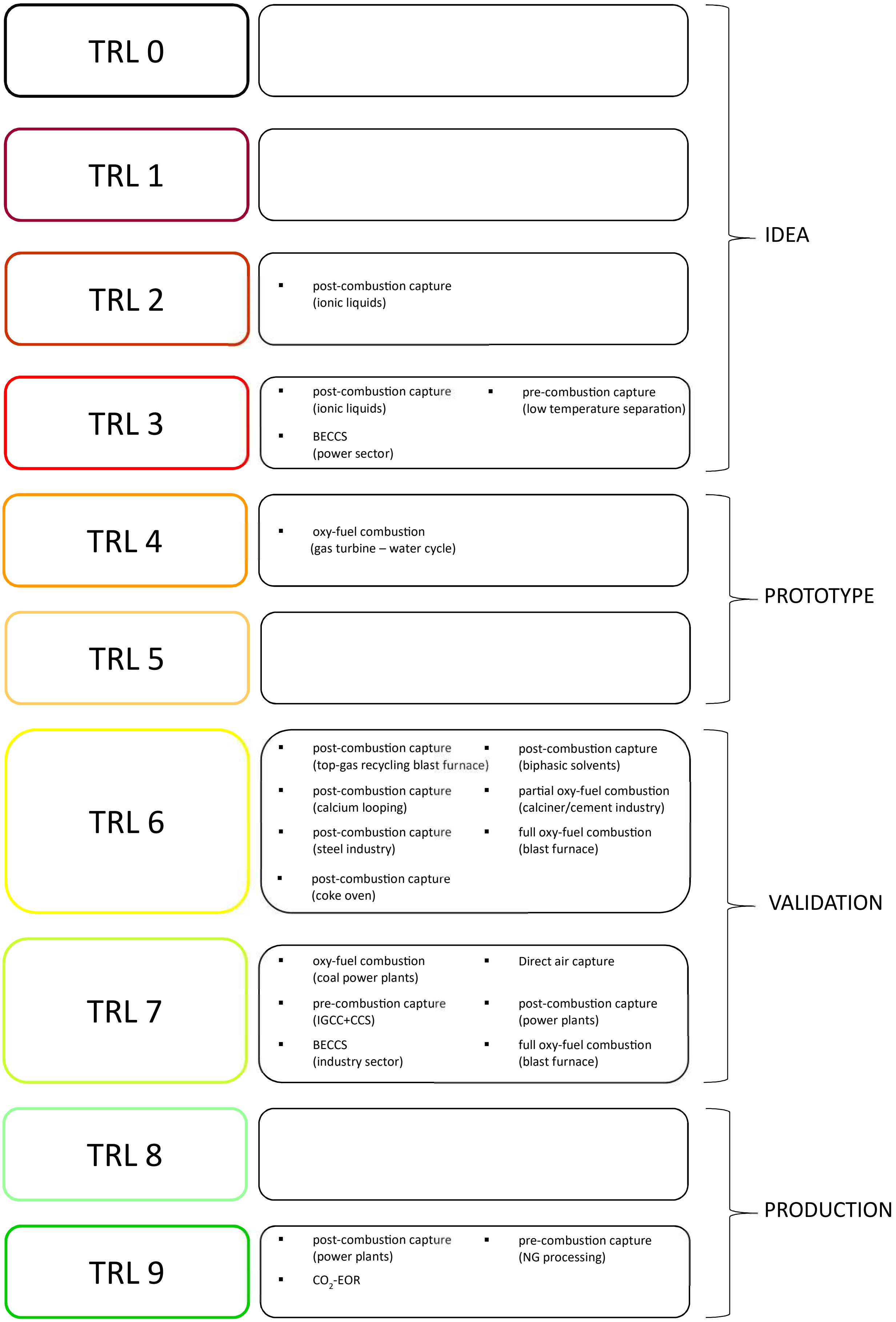

TRL 0		IDEA
TRL 1		
TRL 2	post-combustion capture (ionic liquids)	
TRL 3	post-combustion capture (ionic liquids) pre-combustion capture (low temperature separation) BECCS (power sector)	
TRL 4	oxy-fuel combustion (gas turbine – water cycle)	PROTOTYPE
TRL 5		
TRL 6	post-combustion capture (top-gas recycling blast furnace) post-combustion capture (biphasic solvents) post-combustion capture (calcium looping) partial oxy-fuel combustion (calciner/cement industry) post-combustion capture (steel industry) full oxy-fuel combustion (blast furnace) post-combustion capture (coke oven)	VALIDATION
TRL 7	oxy-fuel combustion (coal power plants) Direct air capture pre-combustion capture (IGCC+CCS) post-combustion capture (power plants) BECCS (industry sector) full oxy-fuel combustion (blast furnace)	
TRL 8		PRODUCTION
TRL 9	post-combustion capture (power plants) pre-combustion capture (NG processing) CO_2-EOR	

Figure 2.11: Capture technology regarding TRL [24,69]

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2.11 Economics of direct air capture

The costs regarding with CO_2 capture plants can be categorized into two main groups - capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX, which covers the initial investment, encompasses various expenses such as acquiring land, purchasing materials and equipment, conducting planning and engineering activities, obtaining permits, and constructing the plant. On the other hand, OPEX can be further divided into fixed and variable costs. Variable OPEX involves expenses related to energy consumption (electricity, heat, fuels), procurement of consumables like chemicals, catalysts, and streams for CO_2 capture, and the management and treatment of waste and wastewater. A fixed operational expenditure is frequently calculated as a percentage of the variable OPEX when broader information is not available.

The staff of a CO_2 capture facility can be overseen by current staff members of power plant without incurring substantial expenses related to personnel. Nevertheless, there is not so much data on large-scale CO_2 capture plants, which means that cost estimates often rely on actual expenses in the chemical and process industry [70].

The economics of DAC are currently challenging, primarily because of high costs, energy requirements, and the absence of an established market value for captured CO_2. As technology improves, renewable energy becomes more widespread, and carbon pricing mechanisms are implemented, the economics of DAC could improve, making it a more viable solution for addressing climate change [23].

Table 2.4: Economic parameters of DAC [23]

Technical parameter	***Low temperature***	***High temperature***	***Unit***
capacity	*360000*	*1000000*	$\frac{t_{CO_2}}{a}$
CAPEX	*730*	*625*	$\frac{EUR}{t_{CO_2} \cdot a}$
OPEX (% of CAPEX)	*n.a.*	*3.7*	$\frac{EUR}{t_{CO_2} \cdot a}$
lifetime	*25*	*25*	*years*
el. demand	*694*	*366*	$\frac{kWh_{el}}{t_{CO_2}}$
heat/fuel demand	*2083*	*1460*	$\frac{kWh_{eh}}{t_{CO_2}}$
costs	*177*	*139*	$\frac{EUR}{t_{CO_2}}$

In Table 2.4 are the economic parameters for two types of direct air capture (DAC) technologies listed: low temperature DAC utilizing solid sorbent, and high temperature DAC utilizing aqueous solution as the separation technology.

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3. Methodology and data used

This study was based on the idea of converting all of Austria's methanol production into e-methanol by using renewable energy sources. This approach aims to reduce environmental impact of production of methanol and enhance sustainability within the production process.

The following steps were conducted in this study:

- Based on literature research suitability of following technologies was assessed with focus on their energy demand: existing CO_2 capture technologies, hydrogen production methods, and methanol synthesis processes.
- The environmental impact of various energy sources was evaluated, and the most environmentally favorable option was selected for further calculations.
- Assessment of e-methanol production costs was performed by levelised-cost method. As energy costs have a significant impact on the levelised cost analysis, sensitivity analysis was conducted in order to assess their effect on the overall price. Regarding to the results scenarios were created for better analysis of results:
    - first scenario : e-methanol is produced in a non-EU country
    - second scenario : carbon capture and hydrogen production are conducted abroad, while e-methanol synthesis takes place in Austria
    - third scenario : e-methanol is produced entirely in another country and transported to Austria as a ready-to-use product
- The analysis of e-methanol production costs in the future was calculated by taking into consideration learning curve of the processes and lower energy cost.

To produce e-methanol there are three separate units required:

- CO_2 capture plant
- hydrogen production
- methanol synthesis.

The ideal location for the e-methanol production facility was determined on several factors, such as the source of CO_2 emissions, the availability of infrastructure, economic considerations, and regulatory requirements. The key factors for determining an ideal location for are:

- accessibility to renewable energy and availability of renewable energy: because of the big energy demand to reduce the carbon footprint of e-methanol, it's important to have access to renewable energy sources like wind, solar, or hydroelectric power
- local workforce: availability of skilled labor and a workforce experienced in the relevant industries
- relatively proximity to emission sources: the ideal location for a production facility in Austria should be close to significant sources of CO_2 emissions, such as industrial facilities, power plants, or transportation hubs. This is important

because it minimizes the cost and energy required for transporting CO_2 to the production site.

- transportation Infrastructure: efficient transportation infrastructure, including road and rail networks, is essential for moving captured CO_2, hydrogen and e-methanol to and from the production facility.
- market demand: consider the availability of a market for e-methanol or materials. Potential customers in the neighborhood can be a significant advantage, as it reduces transportation costs.
- regulatory environment: ensure that the location complies with Austrian regulations regarding carbon capture, emissions, and waste management.
- environmental considerations: evaluate the environmental impact of the e-methanol on the surrounding area and ecosystems. Choose a location that minimizes negative environmental consequences.
- financial and incentive programs: research if government provides or plans incentives or subsidies that could support CCU products at the chosen location .
- community acceptance: confirm that the local community is supportive of the production facilities and in-site CO_2-storing, as public acceptance and cooperation are important for its further success.

The ideal location for a production facility should be a balance between the proximity to emission sources, access to clean energy, infrastructure, availability of skilled local workforce and other practical considerations. A thorough study that considers all these factors is important when choosing the site for a specific project.

In this case study the proximity to CO_2 source was evaluated as irrelevant, as the carbon capture technology chosen was DAC. One of the case study assumptions was that the DAC unit, hydrogen production unit and MeOH production are placed on one location, therefore the cost of transport of captured CO_2 and hydrogen are not included.

Foremost, the environmental impact of different potential renewable energy sources for e-methanol production was evaluated. The energy sources compared were wind power, Photovoltaic (PV) and energy from grid, known also as Grid Electricity Mix (Table 3.1).

The 10.6 $g_{CO2\text{-}eq.}$/kWh for the wind energy is for the onshore wind parks with weak wind in Germany power network and the 40 $g_{CO2\text{-}eg.}$/kWh for PV is the median of mono c-Si systems. Although Austria does not have offshore wind parks, they are included here for comparison of environmental impact. Energy generated from offshore wind parks emits significantly less CO_2 into the atmosphere [71].

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Table 3.1: CO_2 emissions by potential energy source

Type of energy	***Value***	***Unit***	***Reference***
Wind energy (onshore)	*10.6*	$g_{CO2\text{-}eq.}/kWh$	*[71]*
Wind energy (offshore)	*7.3*	$g_{CO2\text{-}eq.}/kWh$	*[71]*
PV	*40*	$g_{CO2\text{-}eq.}/kWh$	*[71]*
Grid Electricity Mix (year 2021)	*226*	$g_{CO2\text{-}eq.}/kWh$	*[72]*

According to Perez-Fortes et al. [26] equations (1) and (2) optimal energy source for e-methanol production with lower environmental impact was determined.

$$(CO_2)_{not-produced} = (CO_2)_{conv} - (CO_2)_{CCU} \tag{1}$$

$$(CO_2)_{avoided} = (CO_2)_{not-produce} + (CO_2)_{in-CCU} \tag{2}$$

$(\mathrm{CO_2})_{\mathrm{not-produced}}$ [t_{CO2}] present difference between CO_2 released by conventionally produced methanol($(CO_2)_{conv}$) and e-methanol ($(CO_2)_{CCU}$).

$(\mathrm{CO_2})_{\mathrm{avoided}}$ [t_{CO2}] present sum of CO_2 that is not released in the atmosphere ($(CO_2)_{not-produced}$) and CO_2 that is needed to produce e-methanol ($(CO_2)_{in-CCU}$).

In the Figure 3.1 and Figure 3.2 are production processes graphics presented and they are created according to the Table 3.2. The black arrows show the flow of CO_2 in the process and the blue ones show the electricity required for the process. Figure 3.1 graphically presents the conventional method of methanol production, also known as Business as Usual (BAU) and Figure 3.2 illustrates the production of e-methanol.

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Table 3.2: *Technical parameters for production of methanol and e-methanol*

Technical parameter	***Value***	***Unit***	***Reference***
Carbon needed for production of methanol	*0.56*	$\frac{t_C}{t_{MeOH}}$	*[73]*
Electricity needed for production of methanol	*0.147*	$\frac{MWh}{t_{MeOH}}$	*[73]*
CO_2 released to atmosphere by production of methanol	*0.7*	$\frac{t_{CO_2}}{t_{MeOH}}$	*[73]*
CO_2 released to atmosphere from methanol combustion	*1.37*	$\frac{t_{CO_2}}{t_{MeOH}}$	*[73]*
Hydrogen needed for production of e-methanol	*0.199*	$\frac{t_{H2}}{t_{MeOH}}$	*[25]*
Electricity needed for production of hydrogen	*12.08*	$\frac{MWh}{t_{MeOH}}$	*[73]*
Electricity needed for capturing CO_2	*1.022*	$\frac{MWh}{t_{MeOH}}$	*[73]*
CO_2 released to atmosphere by producing e-methanol	*0.09*	$\frac{t_{CO_2}}{t_{MeOH}}$	*[73]*
Electricity needed for production of e-methanol	*0.169*	$\frac{MWh}{t_{MeOH}}$	*[73]*

Heat energy required for DAC is assumed that is used from other processes as waste energy, taking into consideration that methanol synthesis and hydrogen production via PEM electrolysis - PEMEL are exothermic reaction. Therefore, in cost analysis are costs for heat energy not included.

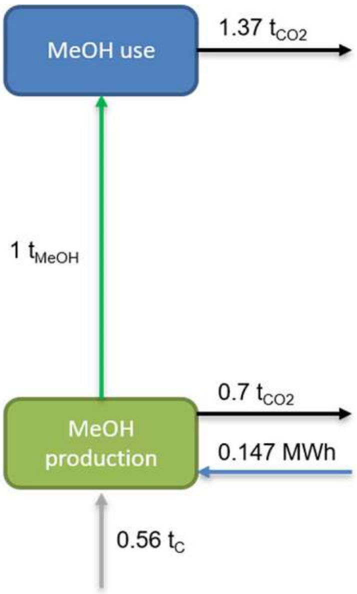

Figure 3.1: Schematic overview of conventional methanol production (BAU)

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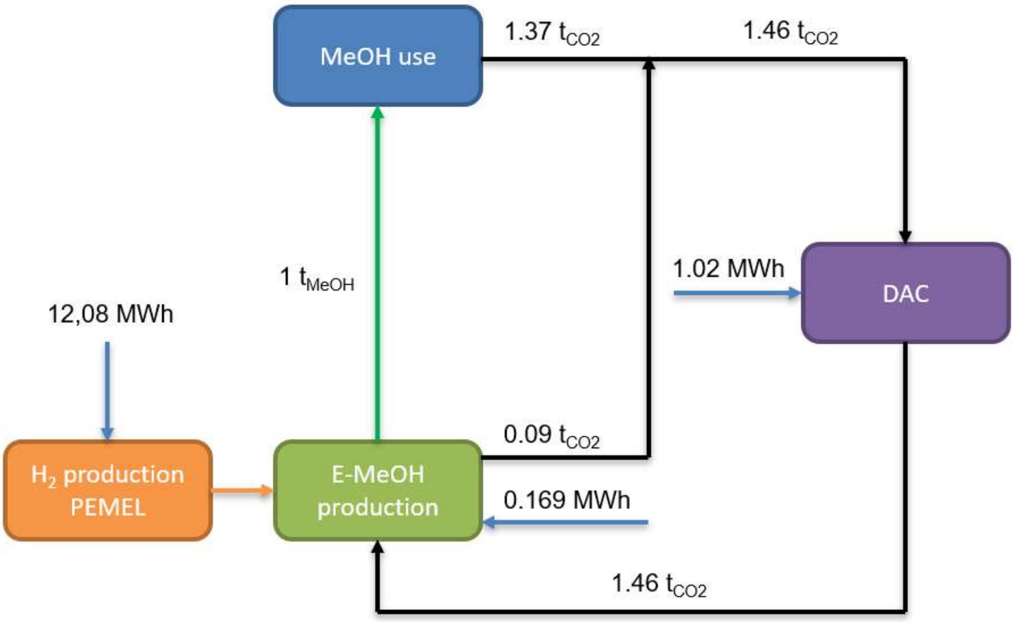

Figure 3.2: Schematic overview of e-methanol production process

3.1 Cost analysis

In order to calculate the levelised cost of e-methanol production, levelised costs of both captured CO_2 and hydrogen must be determined. In this case study, low temperature DAC and PEMEL for production of hydrogen were chosen and investigated. The parameters needed for calculation of DAC levelised cost are included in Table 3.3.

Table 3.3: Technical and economic parameters for DAC

Parameter	***Value***	***Unit***	***Reference***
CAPEX (in 2020)	*730*	$\frac{EUR}{t_{CO_2} \cdot a}$	*[23]*
lifetime	*12*	*year*	*own assumption*
WACC	*8*	*%*	*own assumption*
Heat needed	*3.305*	$\frac{MWh}{t_{CO_2}}$	*[23]*
LCOE	*76.35*	$\frac{EUR}{MWh}$	*[74]*
Levelised cost of heat	*35*	$\frac{EUR}{MWh}$	*[23]*

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The cost of captured CO_2 was calculated with equations 3 and based on study from Fasihi et al. [23]:

$$LCOD = \frac{CAPEX_{DAC} \cdot CRF + OPEX_{fix}}{Output_{CO_2}} + DAC_{el.input} \cdot LCOE + DAC_{th.input} \cdot LCOHeat \tag{3}$$

with:

LCOD – Levelised Cost of DAC [EUR/t_{CO2}]

$CAPEX_{DAC}$ – Capital expenditures of DAC plant [EUR]

CRF – capital recovery factor

$Output_{CO2}$ – quantity of captured CO_2 [t]

$OPEX_{fix}$ – fix operative expenditures [EUR]

$DAC_{el.input}$ – electrical power required for the process [MWh/t_{CO2}]

LCOE – Levelised Cost of Electricity [EUR/MWh]

$DAC_{th.input}$ – heat energy needed for the process [MWh/t_{CO2}]

LCOHeat – Levelised Cost of Heat [EUR/MWh]

The fix operative expenditures are assumed to be 4% of capital expenditures.

The capital expenditure of DAC plant is determined in year 2020 and therefore needed to be recalculated for year 2023. The following equation is used:

$$CAPEX_y = CAPEX_x \left(\frac{I_y}{I_x}\right) \tag{4}$$

with:
$CAPEX_x$ - capital expenditures determined in year x [EUR]

$CAPEX_y$ - capital expenditures recalculated for year y [EUR]

I_x – Chemical Engineering Plant Cost Index in year x

I_y – Chemical Engineering Plant Cost Index in year y.

For updating the capital costs of process engineering projects, the Chemical Engineering Plant Cost Index (CEPCI) is frequently used.

Capital recovery factor is calculated with equation:

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{5}$$

with:

i – interest rate

n – annuity for a given lifetime.

The Levelised Cost of Hydrogen (LCOH) was calculated similarly to the levelised cost of DAC in equation 3 and it is mostly dependant on the LCOE. There are two primary capital expenditures: one for the electrolyzer and another for the compressor [64]. These both expenditures are strongly dependant on the system size. The economic and technical parameters needed for calculation of LCOH are shown in the Table 3.4.

Table 3.4: Economic and technical parameters for hydrogen production

Parameter	**Value**	**Unit**	**Reference**
Electrolyzer system cost	*1400*	EUR/kW_{ely}	*[75]*
Compressor cost	*3800*	EUR/kW_{comp}	*[64]*
Installed electrolyzer system capacity	*10000*	*kW*	*[64]*
Installed compressor capacity	*800*	*kW*	*[64]*
Production rate	*4044*	kg_{H2}/day	*[64]*
Total energy demand	*60.7*	kWh/kg_{H2}	*[64]*
Utilization rate	*90*	*%*	*[64]*
Lifetime PEMEL	*7*	*year*	*[64]*
Lifetime compressor	*10*	*year*	*[64]*
Lifetime plant	*30*	*year*	*[64]*
Discount rate	*4*	*%*	*[64]*
Site preparation costs (of CAPEX)	*5*	*%*	*[64]*
Engineering costs (of CAPEX)	*10*	*%*	*[64]*
Installation costs (of CAPEX)	*10*	*%*	*[64]*
Contingency (of CAPEX)	*5*	*%*	*[64]*
O&M costs (of CAPEX)	*3*	*%*	*[64]*

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As shown in Figure 3.2, it is evident that for the synthesis of 1 t of e-methanol 0.199 t of hydrogen and 1.46 t of CO_2 is required. From an energy perspective, the synthesis process necessitates 0.169 MWh to produce 1 t of e-methanol [73].

The Levelised Cost of E-Methanol (LCOMeOH) is the sum of capital expenditures, fix operational expenditures, cost of energy needed for synthesis of e-methanol and "Fuel cost". The fuel costs consist of the cost of hydrogen and CO_2 needed for the synthesis of e-methanol. The LCOMeOH is calculated on similar way as LCOD and showed in equation 6:

$$LCOMeOH = \frac{CAPEX \cdot CRF + OPEX_{fix}}{Output_{MeOH}} + OPEX_{var} \qquad (6)$$

with:

LCOMeoH - Levelised Cost of E-Methanol [EUR/t_{MeOH}]

CAPEX - Capital expenditures of methanol plant [EUR]

$OPEX_{fix}$ - operative expenditures [EUR]

$Output_{MeOH}$ - quantity of produced methanol [t]

$MeOH_{el.input}$ - electrical power needed for the process [MWh/t_{MeoH}]

$OPEX_{var}$ - costs of hydrogen and CO_2 needed for the synthesis of methanol.

The economic parameters for methanol plant are presented in Table 3.5. The purchase equipment cost (PEC) for methanol plant is 60.5 mil EUR and they are determined in year 2018, therefore using similar method as in equation 4 and based on study from Nyari et al. [25]. They have to be recalculated for year 2023 with equation 7:

$$PEC_{2023} = PEC_{2018}\left(\frac{I_{2023}}{I_{2018}}\right) \qquad (7)$$

with:

PEC_{2023} – purchase equipment cost in year 2023 [EUR]

PEC_{2018} – purchase equipment cost in year 2018 [EUR]

I_{2023} – Chemical Engineering Plant Cost Index in year 2023

I_{2018} – Chemical Engineering Plant Cost Index in year 2018.

The PEC primarily covers the expenses incurred solely for the purchase of equipment, whereas CAPEX encompasses a broader range of costs [25]. In addition to equipment costs, CAPEX incorporates expenses related to the installation of the equipment and covers all construction-related activities such as piping, land development, civil engineering, and architectural work. Furthermore, CAPEX also accounts for costs associated with start-up activities, working capital, and research and development efforts. The estimation of CAPEX was derived using a simplified equation 8 that relates PEC and CAPEX and is taken from study done by Nyari et al. [25]:

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$$CAPEX = 6.32 \cdot PEC \tag{8}$$

The PEC is determined for the specifications needed to build a methanol plant that can produce 5 kt of methanol per day. For this study case, the PEC needs to be scaled to a plant that can produce 105 t of methanol per day in order to accurately estimate the CAPEX.

Table 3.5: Economic parameters for methanol plant

Parameter	Value	Unit	Reference
PEC (2018)	*60.5*	mil EUR	*[25]*
CEPCI (2018)	*603.1*		*[76]*
Lifetime plant	*25*	year	*[25]*
WACC	*8*	%	*own assumption*
OPEX fix	*4% of CAPEX*	mil EUR	*[25]*
α	*0.6*		*own assumption*
η	*0.9*		*own assumption*
Production rate	*34492.5*	t	*calculated*

The production time of the methanol plant is presented as η in Table 3.5 and represents the operational efficiency of the facility. Every production facility has downtime, due to repairs and maintenance. It is therefore assumed that the methanol plant operates at 90% capacity over the course of a year.

Using equation 9, CAPEX for this study case is recalculated:

$$CAPEX_{model} = CAPEX_{lit} \left(\frac{X_{model}}{X_{lit}}\right)^{\alpha} \tag{9}$$

with $CAPEX_{model}$ is capital expenditures for this case study (105 t/day of methanol), $CAPEX_{lit}$ is capital expenditures calculated from original PEC, X_{model} is the production capacity of plant used in this case study, X_{lit} is the production capacity of plant from literature and α is the scaling exponent. The assumption for scaling exponent is based on paper from Tribe et al. [77].

Equation 9 is based on study done by Fasihi et al. [23].

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3.2 Sensitivity analysis of e-methanol pricing

Production of e-methanol is an energy intensive process and consequently a significant part of levelised cost of e-methanol is depended from levelised cost of electricity. One of the solutions would be to capture CO_2 and produce hydrogen on another location and to synthesize it in Austria. In this case, additional CO_2 and hydrogen transportation costs should be taken into consideration.

Shipping of CO_2 is not considered due to the production location, and pipelines are not a viable option due to quantity constraints. The only feasible transportation methods are by trucks and rail. In Table 3.6 are the transport costs of cryogenic CO_2 presented. Transport of CO_2 by rail is less common, however for this study it proved to be the most suitable option taking into consideration the required transport volume and associated costs. There are additional costs for transportation by rail for staging and loading operation of 1.86 EUR/t_{CO2} [78].

Table 3.6: Transport costs of CO_2 regarding the type of transportation [78]

Type of transport	***Value***	***Unit***
Truck	*0.1*	$\frac{EUR}{t \cdot km}$
Rail	*0.041*	$\frac{EUR}{t \cdot km}$

The quantity of hydrogen needed to produce 34450 t of methanol a year is 6855.55 t. This quantity is too small to be transported via pipeline, and the shipping is not an option due to the chosen location. Therefore, for this study transport by truck was chosen. The transport cost for hydrogen by truck is 1.49 EUR/(t·km) [52].

Other possible solution was to produce e-methanol on completely different location, where LCOE is lower than in Austria, and then to transport it to Austria, as ready to use product. In this case the only additional cost would be the cost of methanol transport and it depend from the type of the transportation. For the smaller quantity it is cheaper to use already existing infrastructure and to use trucks or rails as type of transportation.

The transport costs of methanol are detailed in Table 3.7 and shipping emerges as the most economical mode, followed by rail. Due to the selected location, shipping isn't a viable option. As there is an existing infrastructure for further calculation is transportation by rail chosen.

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Table 3.7: Transport costs of methanol regarding the type of transportation [54]

Type of transport	Value	Unit
Truck	0.26598	$\frac{EUR}{t \cdot km}$
Rail	0.02325	$\frac{EUR}{t \cdot km}$
Pipeline	0.026156	$\frac{EUR}{t \cdot km}$
Ship	0.001412	$\frac{EUR}{t \cdot km}$

The impact of transportation on overall emissions was also evaluated in this study. CO_2 emissions from rail freight are different by country and largely depend on the energy grid mix. According to the Annual report by the Community of European Railway and Infrastructure Companies [79] are rail freight emissions 15.6 g_{CO2}/tkm. CO_2 emissions from ship transport vary depending on the size of the vessel and other operational factors. On average, emissions range from 10 to 20 g_{CO2}/tkm. Table 3.8 represents emissions data categorized by transportation type, providing an overview of the environmental impact associated with different modes of transport.

Table 3.8: CO_2 emissions with respect to the type of transportation type

Type of transport	Value	Unit	Reference
Truck	51.95	$\frac{g_{CO2}}{t \cdot km}$	[80]
Rail	15.6	$\frac{g_{CO2}}{t \cdot km}$	[79]
Ship	10 - 20	$\frac{g_{CO2}}{t \cdot km}$	[81]

3.3 Analysis of e-methanol cost in the future

Important factors in calculating the cost of e-methanol in the future are the technological learning curve, the forecasted cost of renewable electricity and the technological scalability. All of these factors have to be taken into consideration.

The costs of e-methanol were analysed for years 2030 and 2050.

Total capital expenditures were divided into two components - new and conventional part of capital expenditures. They were calculated using eq. 10:

$$CAPEX_{total} = CAPEX_{new} + CAPEX_{conv} \quad (10)$$

A learning curve shows improvement of performance or efficiency through repetition and experience. A learning curve has an impact only on new components and they were calculated with eq. 11 and 12:

$$CAPEX_{new}(t_1) = CAPEX_{new}(t_0) \cdot \left(\frac{Y_{t_1}}{Y_{t_0}}\right)^{-b} \quad (11)$$

with:

$\mathrm{CAPEX_{new}}(\mathrm{t_1})$ – capital expenditures at time t_1

$\mathrm{CAPEX_{new}}(\mathrm{t_0})$ – capital expenditures at time t_0

$\mathrm{Y_{t_1}}$ – installed capacity at time t_1

$\mathrm{Y_{t_0}}$ – installed capacity at time t_0

b – index of learning and is in direct correlation with learning rate:

$$LR = 1 - 2^{-b} \quad (12)$$

with:

LR – learning rate.

The learning rate is in correlation with TRL of novel technology. As a new technology progresses towards its full industrial application it is assigned to different TRL stages and consequently the learning rate of this technology changes.

Also important factor is scalability, given the expected rise of methanol demand in the future. According to the Methanol Market report [61] it is assumed CAGR for methanol demand of 5% until 2050. The capital costs for new production facilities are recalculated using equation 9 to account for this growth.

The equations (10), (11) and (12) were used to calculate cost of e-methanol in future and are based on Radosits et al. [27].

In Table 3.9 are technical parameters presented that are used for calculation of DAC costs. DAC technology is still not fully developed, therefore the learning rate was assumed to be 20% [23]. The residual costs are an approximation of the raw materials and energy consumed during the manufacturing and operation of DAC system.

The Climaworks has a plan to reduce energy demand to 0.5 MW/t_{CO2} by year 2025, therefore for further calculation was this energy demand taken [23].

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Table 3.9: Technical parameters for calculating DAC costs in future

Technical parameter	***Value***	***Unit***	***Reference***
Learning rate	*20*	*%*	*[23]*
Residual cost	*27.9*	$\frac{EUR}{t_{CO2}}$	*[82]*
Installed capacity	*0.01*	Mt_{CO2}	*[19]*
Installed capacity in 2030	*85*	Mt_{CO2}	*[19]*
Installed capacity in 2050	*980*	Mt_{CO2}	*[19]*

According to Kirsten Vidal de Oliveira et al. [83] the learning rate for PEM electrolyzers is in range 3 – 10% and the conventional share is 40% [27]. On conventional share technological learning is not applied.

At the moment 2/3 of all installed electrolyzers are alkaline, 1/3 are PEMEL and less than 1% are high-temperature solid oxide electolyzers. In future, this ratio should transition to 40% for alkaline, 40% for PEM, and 20% for SOE, respectively [27]. Installed capacity for years 2030 and 2050 are recalculated according to than ratio and listed in Table 3.10.

Table 3.10: Technical parameters for calculating PEMEL costs in future

Technical parameter	***Value***	***Unit***	***Reference***
Learning rate	*3 - 10*	*%*	*[83]*
Conventional share	*40*	*%*	*[27]*
Installed capacity	*227.7*	*MW*	*[27]*
Installed capacity in 2030	*70*	*GW*	*[27]*
Installed capacity in 2050	*1468*	*GW*	*[27]*

The learning rate for synthesizing methanol is according to literature in range of 20 – 30% [53], where conventional share is only 20% [27]. Radosits et al. [27] calculated the capacities needed in the year 2030 and 2050. The technical parameters are presented in Table 3.11.

.

Table 3.11: Technical parameters for calculating costs of methanol plant in future

Technical parameter	**Value**	**Unit**	**Reference**
Learning rate	*20 - 30*	*%*	*[53]*
Conventional share	*20*	*%*	*[27]*
Installed capacity	*76*	*GW*	*[27]*
Installed capacity in 2030	*118*	*GW*	*[27]*
Installed capacity in 2050	*345*	*GW*	*[27]*

For determining the LCOMeoH in the future the LCOE has also a significant impact. As reference, wind energy was used due to its minimal CO_2 emissions. According to the report of IRENE [84] is the LCOE assumed for future and presented in Table 3.12. The provided costs of electricity are within the average range and are progressing well towards meeting targets.

Table 3.12: Levelised Cost of Electricity in future [84]

Year	**Value**	**Unit**
2030	*27.87 – 46.45*	$\frac{EUR}{MWh}$
2050	*18.57 – 27.87*	$\frac{EUR}{MWh}$

For further calculations in this study, an LCOE of 30 $\frac{EUR}{MWh}$ for year 2030 and 20 $\frac{EUR}{MWh}$ for year 2050 was assumed.

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4. Results and discussion

In this chapter are findings presented from an environmental and economic analysis of e-methanol production. Foremost, it evaluates the environmental impact of CO_2 emissions that can be avoided by using different renewable energy sources to produce e-methanol. In addition to a discussion of cost results.

This chapter also provides a sensitivity analysis to examine how changes in electricity costs affect overall production costs and assess future cost scenarios based on projected technological advances and cost reductions.

4.1 Environmental impact

For the production of 1 ton of e-methanol, as shown in Figure 3.2, total energy of 13.27 MWh is required. The environmental impact of e-methanol production is calculated with the eq. 1 and 2, where $(\mathrm{CO_2})_{\mathrm{avoided}}$ present sum of CO_2 that is not released in the environment and CO_2 that is captured from air and used in the production of e-methanol. In this case study, that value was 1.46 t_{CO2} [73].

The results of environmental impact are illustrated in Figure 4.1 and they clearly show that the best energy source for producing e-methanol would be the offshore wind power (offshore WP). CO_2 that is avoided producing e-methanol with offshore wind energy is 1.97 t_{CO2}/t_{MeOH}. Austria does not have any offshore wind parks, therefore for the further calculation was wind energy from onshore wind park consider as energy source. Producing e-methanol with onshore wind energy results in 1.93 t_{CO2}/t_{MeOH} of CO_2 that is avoided. Furthermore, the results reveal that using the grid energy mix for production of e-methanol have negative impact on environmental, what would mean that the producing methanol in conventional way is releasing less CO_2 in environment than producing it like e-methanol.

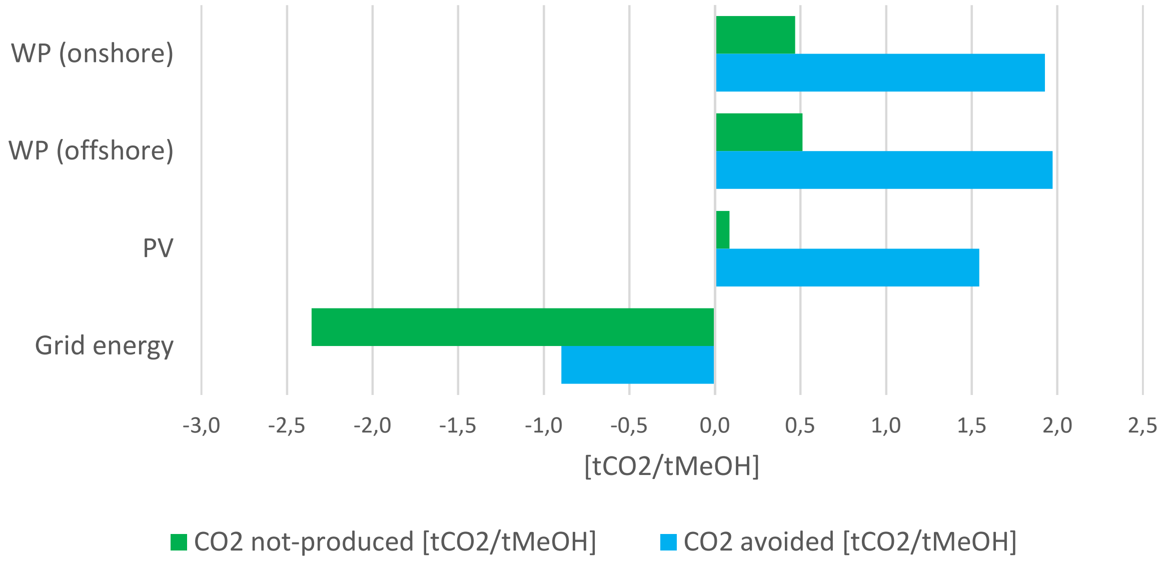

Figure 4.1: Environmental impact originating from energy source

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In 2018, Austria produced 28.7 kt of methanol, according to Andreas Windsperger [65]. Based on this and a report from Triton [62], the production quantity for this case study is calculated at 34.45 kt of methanol, all of which is assumed to be produced as e-methanol for this study.

Using offshore wind energy could significantly reduce CO_2 emissions in the production of e-methanol. Since Austria relies only on onshore wind parks, producing 34.45 kt of e-methanol would result in 16.17 kt of CO_2 not being produced and with 66.46 kt of CO_2 avoided. This may seem insignificant, but every small reduction in CO_2 emissions counts when working toward the goals set by the Paris Agreement in 2016 [7].

4.2 Cost results

Assuming an annual production of 34.45 kt of e-methanol, the size of the e-methanol and hydrogen production facilities would be adjusted to accommodate this production volume. The costs of DAC capture unit are not going to be scaled, because Climeworks system is modular system and the only cost reduction could come from economy of scale.

Using eq. 4 the capital expenditures are recalculated for year 2023, knowing that in 2020 the CEPCI was 596.2 and in 2023 was 803.2 [76]. The capital recovery factor is calculated with the eq. 5 and the results are presented in Table 4.1.

Table 4.1: Calculated economic parameters for DAC

Economic parameter	***Value***	***Unit***	***Reference***
CAPEX (in 2023)	*983.46*	$\frac{EUR}{t_{CO_2} \cdot a}$	*calculated*
CRF	*0.1327*		*calculated*
OPEX fix	*39.34*	$\frac{EUR}{t_{CO_2} \cdot a}$	*calculated*

Although the process of capturing CO_2 from air requires a lot of heat, in this study, heat cost will be disregarded. The calculated value for LCOD where the heat needed for the process is used as waste energy from another process is calculated with the eq. 3 and it results in 223.28 EUR/t_{CO2}. Calculated levelised cost of captured CO_2 is in within the framework mention in other literature. Only to compare this two values to see how big impact is heat energy needed for the process, the calculated LCOD in that case is 338.96 EUR/t_{CO2}, increase of almost 52%.

Pressure of hydrogen needed for synthesis of methanol is 80 bar. PEMEL system produces hydrogen at 30 bar and then is compressed to 80 bar. Size of PEMEL system is 10 MW and size of compressor 800 kW, needed to compress hydrogen to 80 bar.

Additional costs will be incurred due to PEMEL stack deterioration, as well as the full compressor overhauling after 5000h of operation. Cost of stack replacement are 35% of electrolyzer system CAPEX and service costs of compressor are assumed to be 20% of compressor CAPEX [64]. Cost of electrolyzer system are assumed at 1400 EUR/kW$_{ely}$ [75].

Using economic parameters listed in Levelised Cost of Hydrogen (LCOH) is calculating similar to the LCOD in equation 3 and mostly depends from LCOE. There are two primary capital expenditures: one for the electrolyzer and another for the compressor, both of which are correlated with the size of the system. The economic parameters needed for calculation of LCOH are in Table 3.4.

The LCOH is calculated and results in 8.27 EUR/kg$_{H2}$. The largest factors influencing the price of hydrogen are the energy cost (approximately 56% of LCOH) and the capital expenditure of the electrolyzer system (21% of LCOH). The graphical distribution of cost of producing hydrogen is shown in Figure 4.2.

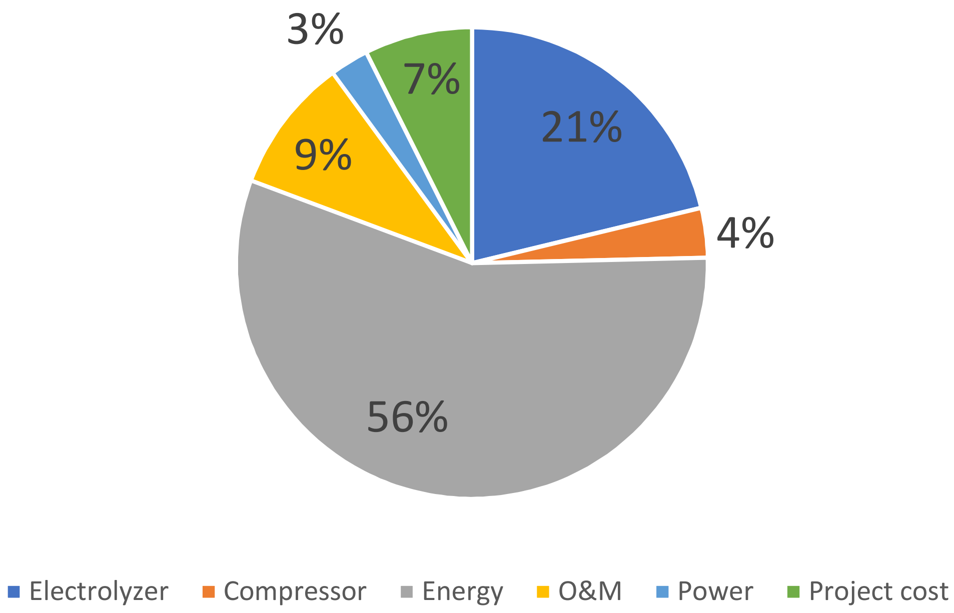

Figure 4.2: Breakdown of productions cost of hydrogen

Because of the different PEMEL and compressor lifetime, the CRF is calculated separately for each and used to determine their respective annual CAPEX. Energy costs are based on the total energy demand for production and the price of electricity. Operation and maintenance costs consist of the percentage of the CAPEX, the costs of replacing the electrolyzer stack, and the expenses associated with compressor overhauls. The total project cost encompass cost for site preparation, engineering, installation, and contingency.

Purchasing equipment cost for e-methanol plant had to be recalculated with CEPCI for 2018 and 2023 using eq. 7. After determining purchasing equipment cost for 2023

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year, the CAPEX for year 2023 is calculated using eq. 8. The calculated CAPEX are for a plant that produce 5 kt of methanol a day and using eq. 9, they are recalculated for a plant that produce 105 t of methanol a day. The results are presented in Table 4.2.

Table 4.2: Economic parameters for methanol plant

Economic parameter	***Value***	***Unit***	***Reference***
PEC (in 2023)	*80.57*	$mil\ EUR$	*calculated*
CAPEX (2023)	*509.22*	$mil\ EUR$	*calculated*
CAPEX in (2023) scaled	*50.15*	$mil\ EUR$	*calculated*
CRF	*0.0937*		*calculated*
Production rate	*34.49*	kt	*calculated*

Under assumption that this plant has 90% of full load time ($\eta = 0.9$), this plant produces 34492.5 t of e-methanol per year, which is about 20% more than produced in 2018 in Austria.

Using equation 6 the calculated Levelised Cost of E-Methanol is 2178.67 EUR/t_{MeOH}, which is more than 5 time higher that the cost of fossil fuel based produced methanol.

The Figure 4.3 displays the breakdown of costs among these three processes needed to produce e-methanol. The production cost of hydrogen accounts for the majority of the total cost of e-methanol, constituting a significant 73%, where 56% of that costs are energy cost.

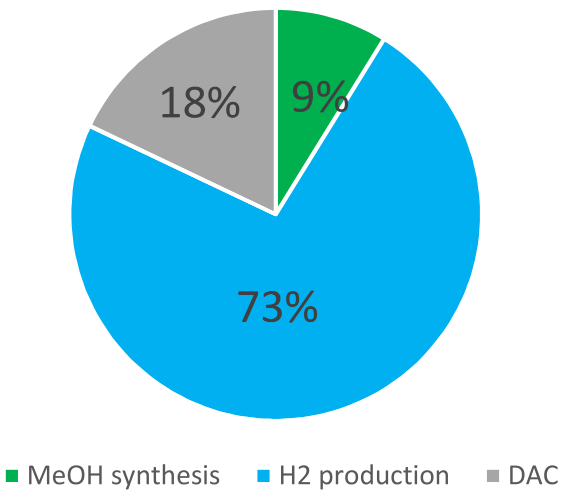

Figure 4.3: Distribution of e-methanol production cost

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The total energy demand for producing 1 t of e-methanol is 13.27 MWh. The hydrogen production constitutes the largest share of this demand, requiring 12.08 MWh, or 91% of the total energy. CO_2 capture is responsible for 1.02 MWh, or 9% of the total, while e-methanol synthesis requires an additional 0.169 MWh per ton of e-methanol [73]. The breakdown of energy demand between processes is presented in Figure 4.4.

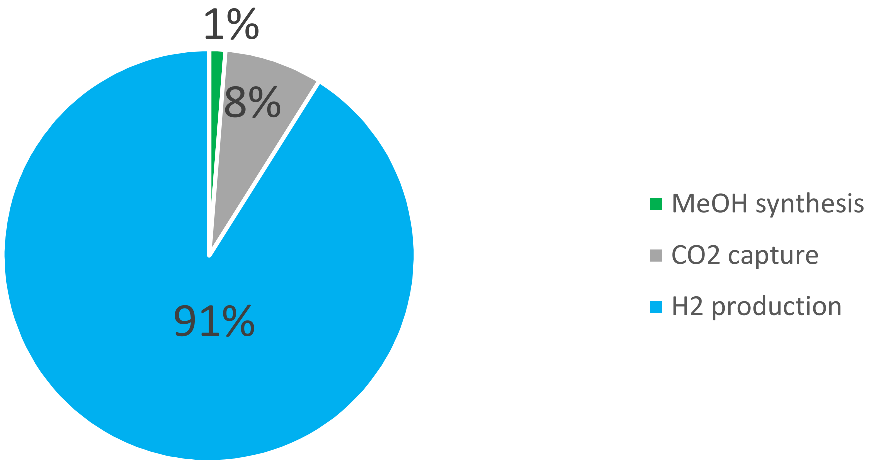

Figure 4.4: Breakdown of energy demand for e-methanol production

The energy cost is accountable for a cost of 1013.19 EUR/t_{MeOH}, constituting almost 47% of the total price of e-methanol (LCOMeOH of 2178.67 EUR/t_{MeOH}). The remaining expenses are attributed to capital and operating costs.

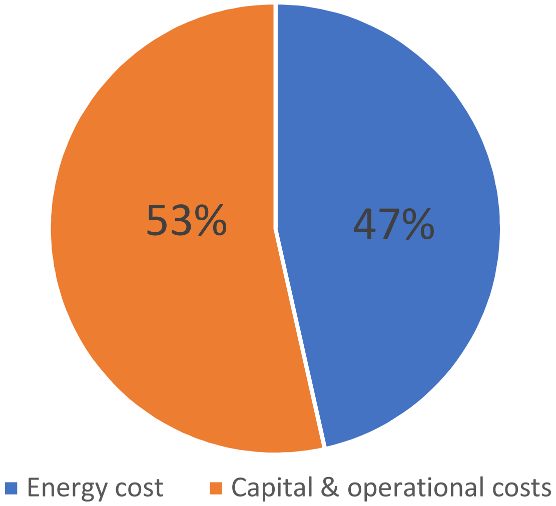

Figure 4.5: Impact of energy cost in levelised cost of e-methanol

The energy system would be significantly affected by the production of e-methanol. In order to produce an annual amount of 34.45 kt of e-methanol, a total of 457151.5 MWh or 457.15 GWh of energy is required. This amount accounts for 6.21% of the wind energy produced in 2022, as reported by the Federal Ministry for Climate Action,

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Environment, Energy, Mobility, Innovation, and Technology in Austria (BMK) in 2024 [85].

Due to high energy demand, it becomes imperative to understand and analyse how the cost of electricity influences the price of e-methanol. In order to gain valuable insights into this relationship, a sensitivity analysis was conducted to assess the impact of electricity costs on e-methanol pricing.

4.3 Sensitivity analysis of e-methanol pricing with respect to environmental impact

Taking into consideration that energy costs are responsible for almost 47% of the e-methanol price and relatively high electricity prices in Austria at the moment, the only potential to reduce price of e-methanol is by producing it in another country, that has lower electricity prices.

One viable scenario would be to place e-methanol production outside of Europe and transport it to Austria by ship. Ships specifically designed for methanol transport offer lower transportation costs though the distances are significantly longer compare to transportation methods by truck or rail. Currently, China is the largest producer of e-methanol, accounting for 58% of global production [10], but according to the Jülich Research Center [86], Saudi Arabia is more feasible option for Austria's needs. E-methanol could be shipped from major ports like Jeddah or Dammam, which are commonly used for large-scale chemical shipments to the port of Genoa in Italy. From there, rail transport would be recommended due to its lower CO_2 emissions compared to road transport. Currently, nearly 100% of electricity production in Saudi Arabia is derived from petroleum liquids and natural gas, with minimal contributions from renewable energy sources [87]. Assuming that all energy required for e-methanol production would originate from fossil fuels, this would result in CO_2 emission of 614.2 g_{CO2}/kWh [88]. Furthermore, transportation distance between Saudi Arabia and Austria of approximately 8,000 km by ship and 900 km by rail [89], needed to be evaluated as it also contributes to CO_2 emissions. Resulting total emission of e-methanol production and transport would be 8.33 t_{CO2}/t_{MeOH}. Thus, environmental impacts of e-methanol import from Saudi Arabia were over 10 times higher than those of local production in Austria using grid electricity mix.

The most energy intensive processes in the production of e-methanol are CO_2 capture and hydrogen production using a PEM electrolyzer. Therefore, the second scenario considered that CO_2 capturing and hydrogen production are done in country with lower electricity price than Austria. Captured CO_2 and produced hydrogen would be then transported to Austria, where e-methanol would be synthesized. According to the transport prices of CO_2, hydrogen and electricity prices, favourable country was determined.

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According to Levelised Cost of Electricity Calculator [74], Italy and Denmark are two countries with relatively lower LCOE, making them potentially viable options for e-methanol production. Additionally for the third scenario, the transportation costs could be minimized by using train as transportation because the infrastructure already exist, to move produced e-methanol to Austria. This could further enhance the economic viability of this alternative production and transportation strategy.

The distance from Italy to Austria and Denmark to Austria was estimated with Google Maps [89]. As a suitable location for e-methanol synthesis plant area around city of Liezen, placed in the middle of Austria was chosen, due to its developed industrial zone. Data based on which cost of CO_2 and hydrogen transportation were calculated are presented in Table 4.3. The LCOE taken for calculations are for wind energy, as in the main study. The LCOE of wind energy it's noticeable lower in Denmark, but therefore the transport distance is longer. According to that the transportation costs were also higher and the clear example to show the impact of transport cost on the total price of e-methanol. Only as comparison is LCOE for offshore wind park also included.

Table 4.3: Parameters for calculations

Parameter	***Italy***	***Denmark*** *onshore*	***Denmark*** *offshore*	***Unit***	***Reference***
LCOE	*52.87*	*29.18*	*45.05*	$\frac{W}{MWh}$	*[74]*
Distance	*937*	*1355*		km	*[89]*

The levelised cost of DAC and hydrogen were calculated in the same way, as in previous calculation done for Austria market, only with the levelised cost of electricity for that country accordingly. In Table 4.4 are costs of captured CO_2 and produced hydrogen in Italy and Denmark showed and only as comparation the cost of methanol in Austria previously calculated. Even if the transport distance is more than 40% longer from Denmark than Italy, the total costs of e-methanol production with transport cost are lower than in Italy. This is only due to the low cost of transportation method.

At the last column of Table 4.4 are the costs of e-methanol produced in Austria taken from the own calculation. In comparison to Italy and Denmark, production of e-methanol in Austria is 50% and 65% more expensive, respectively. This results clearly show the significance of transport costs. The production costs are smaller, because of the lower electricity price, but the transport cost of hydrogen have huge impact on total cost of e-methanol production.

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Table 4.4: Calculated costs of e-methanol with transport of CO_2 and hydrogen

Parameter	***Italy***	***Denmark*** *onshore*	***Denmark*** *offshore*	***Austria***	***Unit***
LCOD	*206.85*	*190.06*	*208.35*	*223.28*	$\frac{EUR}{t_{CO_2}}$
LCOH	*6843.26*	*5405.27*	*6368.58*	*8268.49*	$\frac{EUR}{t_{H_2}}$
Transport cost of CO_2	*40.28*	*57.41*		*0*	$\frac{EUR}{t_{CO_2}}$
Transport cost of H_2	*1396.13*	*2018.95*		0	$\frac{EUR}{t_{H_2}}$
Synthesis of E-MeOH	*207.25*	*207.25*	*207.25*	*207.25*	$\frac{EUR}{t_{MeOH}}$
LCOMeOH	*2207.70*	*2045.98*	*2264.38*	*2178.67*	$\frac{EUR}{t_{MeOH}}$

Transportation costs affect the overall levelised cost of e-methanol. As results indicate Figure 4.6, the only economically viable solution would be Denmark, but only when using onshore wind energy. Even if Denmark has lower energy prices than Italy, offshore wind energy is less competitive due to the greater transportation distance, placing it last in terms of cost-effectiveness.

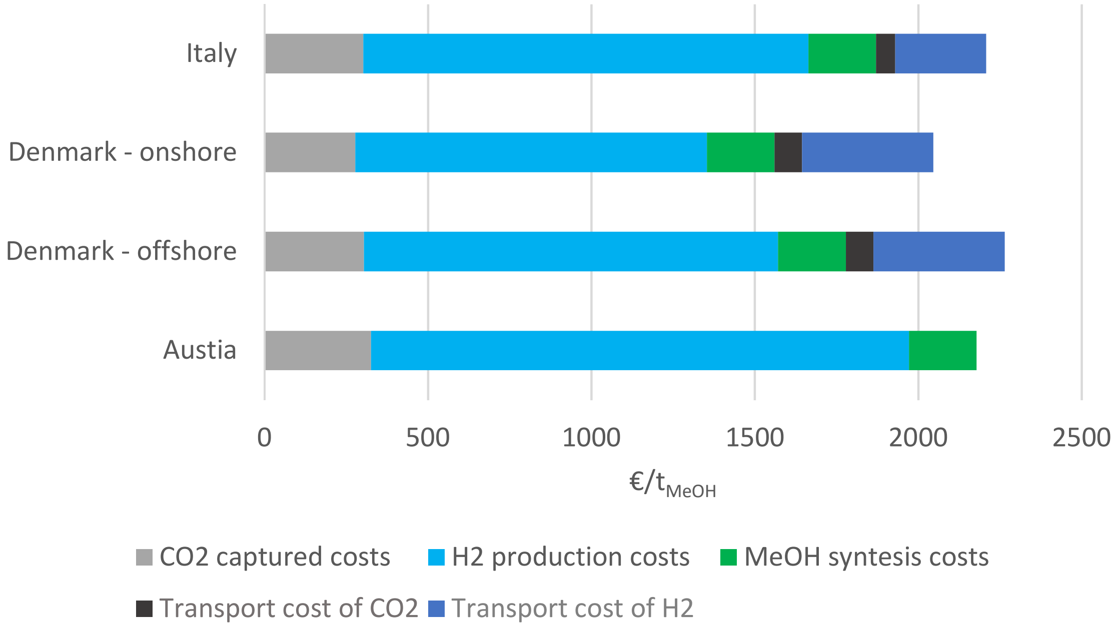

Figure 4.6: E-methanol production costs (with transport of CO_2 and hydrogen) in Italy, Denmark and Austria

Transport of the captured CO_2 and hydrogen required for e-methanol synthesis also generates CO_2 emissions. Since CO_2 and hydrogen would be transported by different

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transportation methods, their emissions are presented separately. In Table 4.5 are presented the results of environmental impact of transportation.

Table 4.5: Environmental impact including transport of CO_2 and hydrogen

Parameter	***Italy***	***Denmark*** *onshore*	***Denmark*** *offshore*	***Austria***	***Unit***
Transport of CO_2	*21.34*	*30.86*	*30.86*	*0*	$\frac{kg_{CO2}}{t_{MeOH}}$
Transport of hydrogen	*9.69*	*14.00*	*14.00*	*0*	$\frac{kg_{CO2}}{t_{MeOH}}$
Actual CO_2 not-produced	*438.27*	*424.44*	*468.24*	*469.30*	$\frac{kg_{CO2}}{t_{MeOH}}$
Actual CO_2 avoided	*1898.27*	*1884.44*	*1928.24*	*1929.30*	$\frac{kg_{CO2}}{t_{MeOH}}$

The transport of CO_2 and hydrogen generates 31.03 kg_{CO2}/t_{MeOH} and 44.86 kg_{CO2}/t_{MeOH}, from Italy and Denmark, respectively. On account of greater distance, the transport from Denmark would also generate more CO_2 compare to transport from Italy. The transport doesn't have significant impact on overall environmental impact of e-methanol, yet it remains a factor worth considering. Figure 4.7 illustrates the results from the Table 4.5.

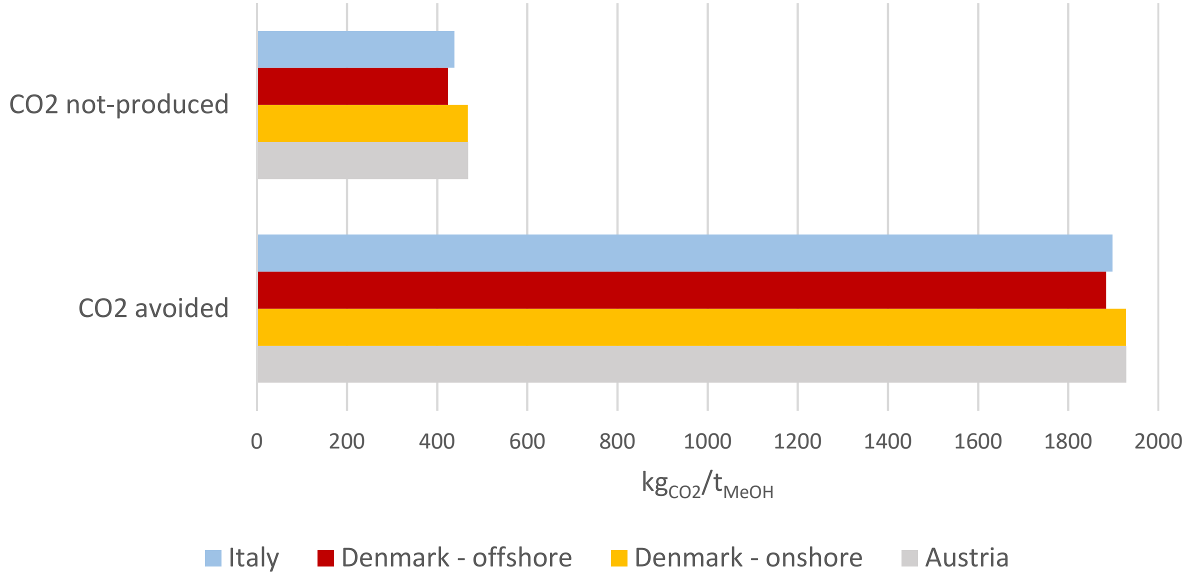

Figure 4.7: Environmental impact including transport of CO_2 and hydrogen

Interesting is that using offshore wind energy almost compensates the transport emissions from Denmark to Austria, but the higher transport costs outweigh the benefits of Denmark's lower electricity prices. The most cost-effective solution would be to capture CO_2 and produce hydrogen in Denmark using onshore wind energy, and then transport it to Austria for e-methanol synthesis. This approach does come with some minor environmental drawbacks.

Another potential scenario involves the full production of e-methanol in another country and subsequently transporting it to Austria as a finished product. This means capturing CO_2, producing hydrogen, and synthesizing e-methanol in a country with a lower levelised price of electricity, and then transporting it to Austria.

The chosen countries for production of e-methanol in third scenario are the same as in the second scenario, Italy and Denmark.

Table 4.6: Calculated costs of e-methanol with transport

Parameter	***Italy***	***Denmark*** *onshore*	***Denmark*** *offshore*	***Austria***	***Unit***
LCOD	*206.85*	*190.06*	*208.35*	*223.28*	$\frac{EUR}{t_{CO_2}}$
LCOH	*6843.26*	*5405.27*	*6368.58*	*8268.49*	$\frac{EUR}{t_{H_2}}$
Transport cost of E-MeOH	*21.79*	*31.50*	*31.50*	0	$\frac{EUR}{t_{MeOH}}$
Synthesis of E-MeOH	*203.28*	*199.28*	*201.96*	*207.25*	$\frac{EUR}{t_{MeOH}}$
LCOMeOH	*1888.88*	*1583.92*	*1805.00*	*2178.67*	$\frac{EUR}{t_{MeOH}}$

According to Table 4.6 is Figure 4.8 created and it represents the levelised cost of e-methanol including transport of e-methanol to Austria. The transport cost of e-methanol is only 1,15% and 1.99% responsible of the levelised cost of e-methanol produced in Italy and Denmark, respectively.

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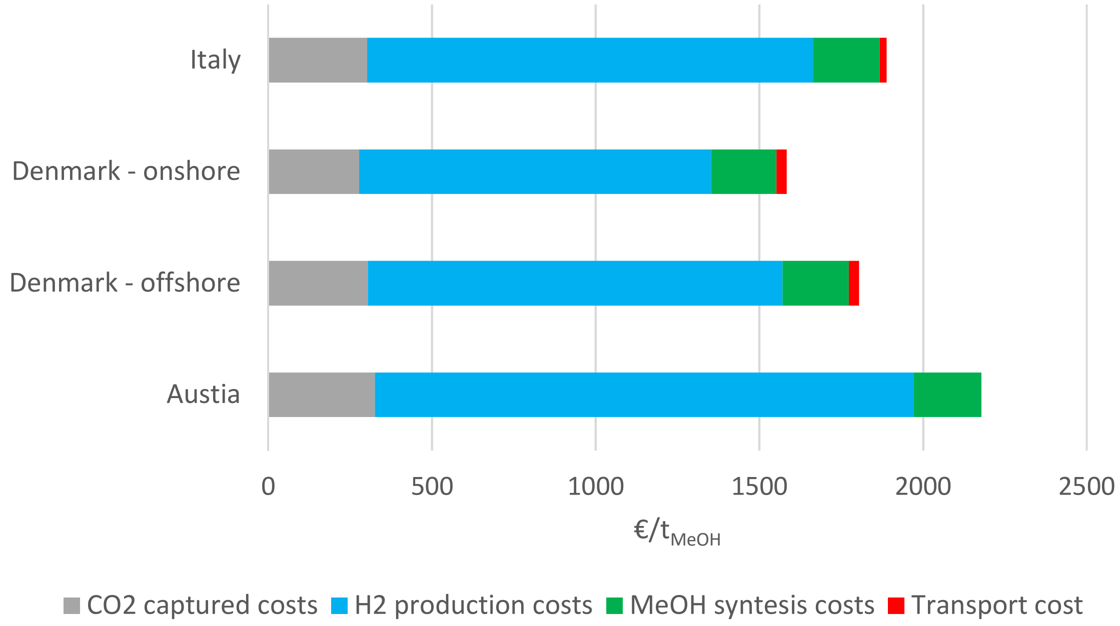

Figure 4.8: E-methanol production costs (with transport of e-methanol) in Italy, Denmark and Austria

This scenario demonstrates that e-methanol production in a country with lower electricity prices may offer a more cost-effective solutions than Austria in this moment. The significant impact of electricity prices is evident and production of e-methanol in Italy and Denmark is around 13% and 28% cheaper than production in Austria, respectively.

The transportation of e-methanol also has an impacts on environment, and this should not be overlooked. Since e-methanol is transported by train, the associated CO_2 emissions are relatively low, accounting to only 14.62 kg_{CO2}/t_{MeOH} from Italy and 21.14 kg_{CO2}/t_{MeOH} from Denmark. The results are detailed in Table 4.7.

Table 4.7: Environmental impact including transport of e-methanol

Parameter	***Italy***	***Denmark*** *onshore*	***Denmark*** *offshore*	***Austria***	***Unit***
Transport of e-methanol	*14.62*	*21.14*	*21.14*	*0*	$\frac{kg_{CO2}}{t_{MeOH}}$
Actual $CO_{2\ \text{not-produced}}$	*454.68*	*448.16*	*491.96*	*469.30*	$\frac{kg_{CO2}}{t_{MeOH}}$
Actual $CO_{2\ \text{avoided}}$	*1914.68*	*1908.16*	*1951.96*	*1929.30*	$\frac{kg_{CO2}}{t_{MeOH}}$

Producing e-methanol outside Austria is more viable option from both economic and environmental perspective. It is cheaper to produce in countries with lower electricity prices and using offshore wind energy, resulting in lower CO_2 emissions. Although lower production costs also mean increased CO_2 emissions, comparing onshore wind energy in Italy and Denmark with Austria. The overall environmental disadvantages are smaller in comparison with economic advantages.

Producing and transporting e-methanol from Italy or Denmark would generate annually additional 531.14 t_{CO2} or 768.02 t_{CO2}, respectively.

The results from Table 4.7 are graphical presented in Figure 4.9.

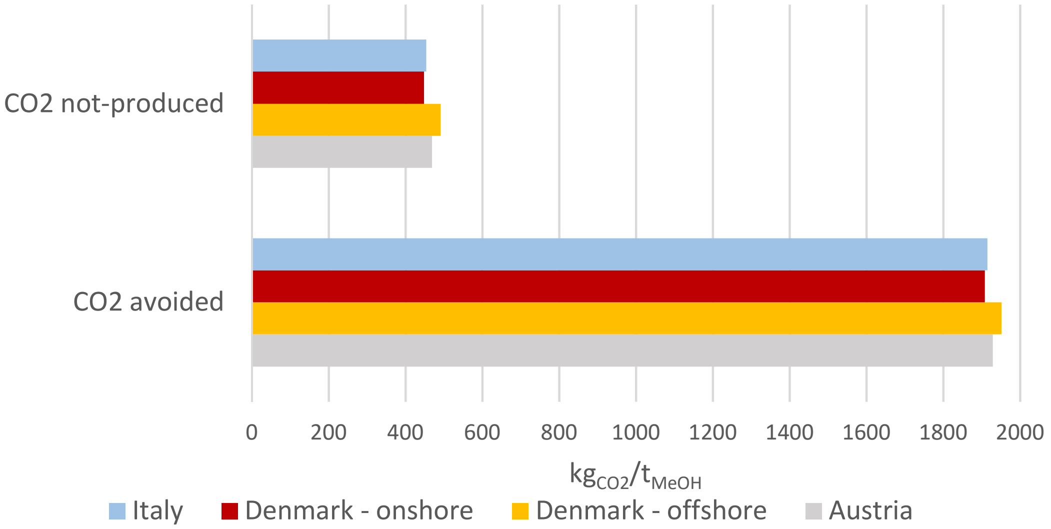

Figure 4.9: Environmental impact including transport of e-methanol

4.4 Analysis of e-methanol cost in the future

The calculated size of e-methanol production facilities according to Methanol Market Report [63] for the years 2030 and 2050 are 48.48 kt and 128.62 kt, respectively. Using eq. 9 the capital cost was recalculated.

The levelised cost of DAC is calculated with eq. 10, where cost of conventional share is replaced with residual cost. Because of big plans according to NZE [19], the learning curve has a big impact on capital expenditures. The operational expenditures are assumed to stay the same, 4% of capital expenditures in the year 2023.

In Figure 4.10 are calculated LCOD presented and compared with LCOD for year 2023. For year 2030 is LCOD 87.24 EUR/t_{CO2} and for year 2050 79.52 EUR/t_{CO2}. Both of the calculated LCOD are under 100 EUR/t_{CO2}, which corresponds to the costs reported in the literature [19].

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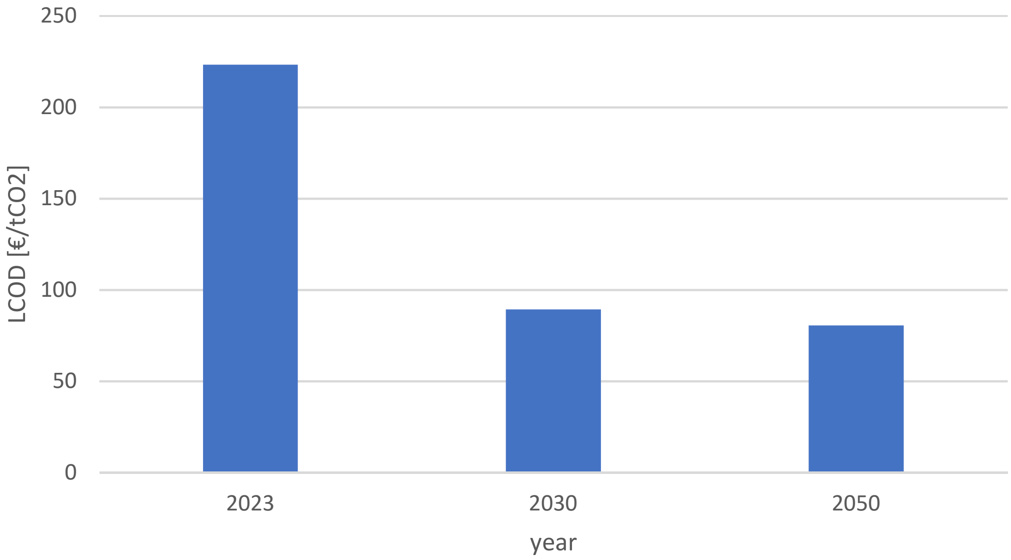

Figure 4.10: Levelised Cost of DAC for 2030 and 2050

The LCOH for the years 2030 and 2050 was calculated with eq. 10 and it depends from cost of electrolyzers. The cost of electrolyzer from Table 3.10 is adjusted with a learning rate adapted to learning rate of 10% for year 2030 and 2050 its amount 683 EUR/kW$_{ely}$ and 637.45EUR/kW$_{ely}$, respectively. High impact of the LCOH has also the LCOE, due to high energy demand of the process. Therefore, is LCOH for year 2030 and 2050 only 3944.43 EUR/t$_{H2}$ and 3241.82 EUR/t$_{H2}$, respectively. The results of LCOH for year 2030 and 2050 are presented in Figure 4.11, with result for year 2023 for comparison.

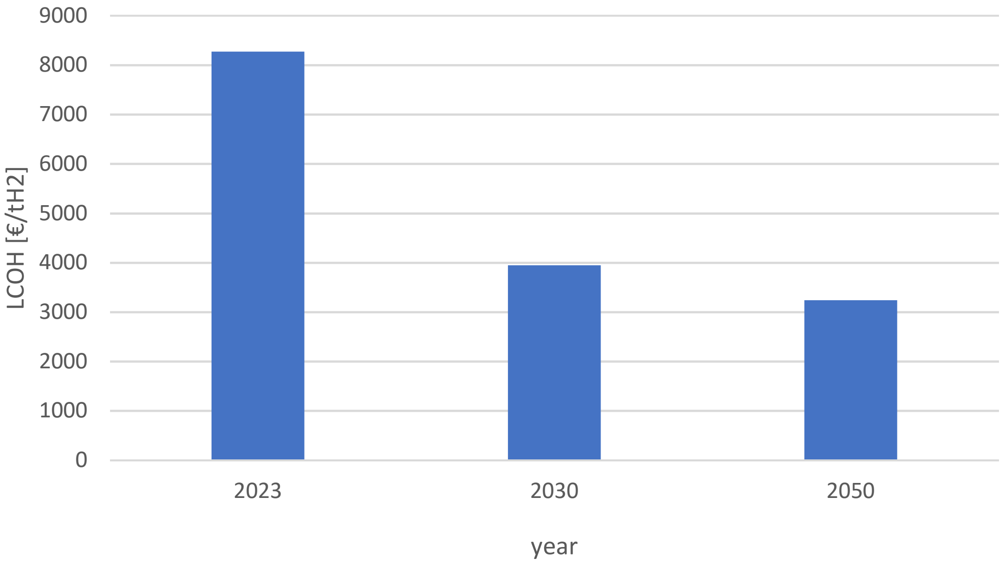

Figure 4.11: Levelised Cost of Hydrogen for 2030 and 2050

The learning effect is also applied on process of e-methanol synthesis and cost is calculated in same manner, as for the cost of CO_2 capturing and hydrogen production. At this process of e-methanol synthesis the strongest impact on price in future has the

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high learning rate of 20%. In the year 2030 are costs of e-methanol synthesis determent of 131.95 EUR/t_{MeOH} and in year 2050 of 43.80 EUR/t_{MeOH}. The results are presented in Figure 4.12 and compared with the costs determent for year 2023.

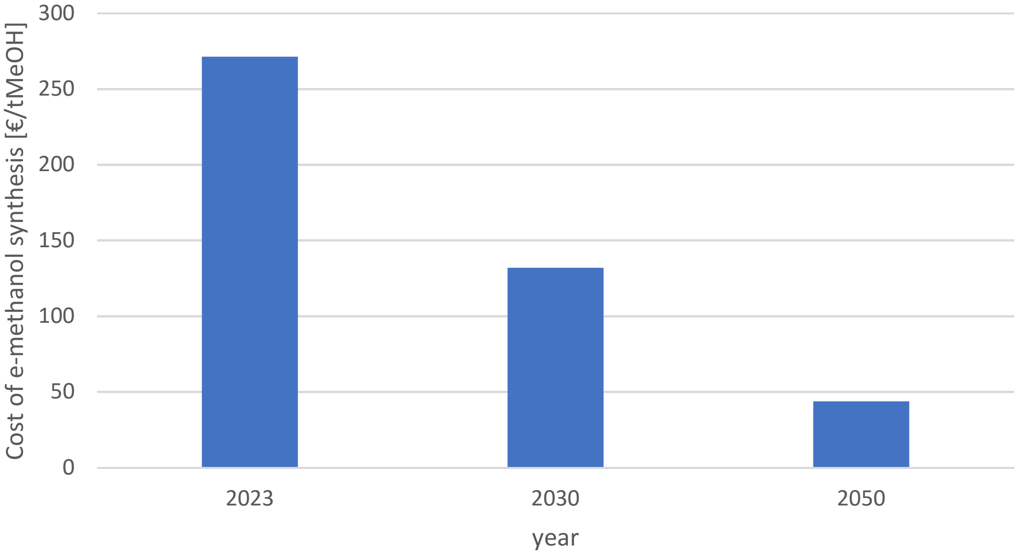

Figure 4.12: Cost for e-methanol synthesis for 2030 and 2050

The levelised cost of e-methanol was calculated as sum of calculated cost for captured CO_2, production of hydrogen and methanol synthesis. For year 2030 and 2050 are determined levelised cost of e-methanol 1047.31 EUR/t_{MeOH} and 806.41 EUR/t_{MeOH}, respectively. The results are graphically presented in Figure 4.13.

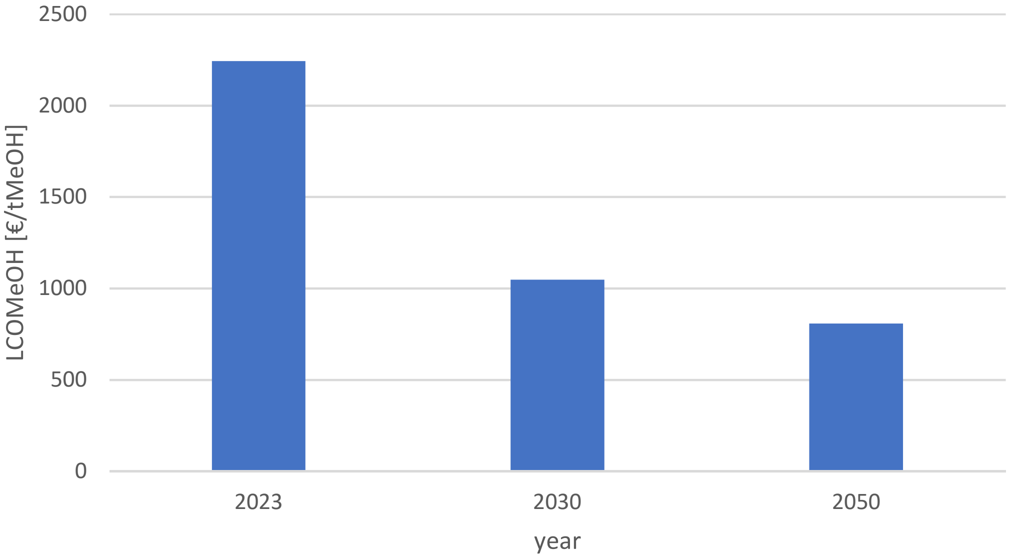

Figure 4.13: Levelised Cost of E-Methanol for 2030 and 2050

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The results clearly show that future e-methanol production costs will depend on technology advancements and significantly lower energy prices. Current costs are largely driven by energy-intensive processes such as CO_2 capture and hydrogen production, and they are still higher than the cost of conventionally produced methanol. With an expected technological learning curve and rising demand, by 2050 production costs could drop significantly. This makes e-methanol a potential alternative to fossil methanol. The results also highlight the importance of further investment in renewable energy infrastructure and process optimization. To increase the economic competitiveness of e-methanol production.

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5. Conclusion

In this study, a combined methodology was applied to explore ecologically and economically viable scenarios for e-methanol production for the Austrian market. The obtained results were in accordance with literature findings with similar research aim.

The studied e-methanol production consisted of following processing steps: DAC technology for capture of CO_2, PEMEL technology for hydrogen production and methanol synthesis process that is the same as conventional. This study finds that complete production of e-methanol in Austria is not economically feasible due to the high energy demand of DAC and PEMEL, compared to conventionally produced methanol. On ground of this finding, other scenarios for more sustainable and cost-effective e-methanol production were explored.

In the first scenario, e-methanol production placed in none-EU country was considered. Chosen country was Saudi Arabia, as it is already significant producer of methanol. The results indicated that from sustainability perspective e-methanol production in Saudi Arabia would be highly disadvantageous compared to e-methanol production in Austria. The reasons could be found in the fact, that almost all electricity needed for production of e-methanol would originates from fossil fuels, which have high carbon footprint.

Other two scenarios explored possibility of outsourcing the whole e-methanol production or PEMEL and DAC as energy intensive to selected EU-countries. Finally, the complete production of e-methanol was evaluated in selected EU countries. The second scenario revealed that if DAC and PEMEL technology were placed in Italy and Denmark, obtained e-methanol would have higher environmental impact compared to e-methanol produced completely in Austria. The third scenario revealed that although the prices of e-methanol produced in Italy and Denmark were lower compared to e-methanol produced in Austria, their environmental impact was higher. The only exception was in case of e-methanol produced in Denmark with offshore wind power. This e-methanol was more environmentally friendly and cost-effective compared to e-methanol produced in Austria.

This study finds that e-methanol represents a promising pathway towards sustainable fuel and help to reach the goals set by Paris Agreement. A favourable outcome requires further investments in renewable energy, DAC technology and PEMEL technology to reduce production costs and improve scalability.

While this study offers valuable insights, there are several issues that deserve further research. Foremost, the high costs associated with DAC technology and renewable hydrogen production remain a major issue. Future study should also explore technological and policy changes, that can reduce these costs. Furthermore, the environmental impact of transporting CO_2, hydrogen and methanol, especially over long distances, needs further analysis to make sure that e-methanol's carbon footprint is minimized.

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