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Faculty of Infrastructure and Environment

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Doctoral School

Doctoral thesis

# Application of LCA analysis for evaluation of carbon capture and utilization supply chain

# Zastosowanie analizy LCA do oceny łańcucha wychwytu i utylizacji $CO_2$


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# List of manuscripts

This thesis is based on the following papers:

1. **Publication no 1 (P1)** - Popielak, P., Majchrzak-Kucęba, I., Wawrzyńczak, D., 2024. Climate change mitigation with CCUS - A case study with benchmarking for selected countries in adapting the European Union's Green Deal. International Journal of Greenhouse Gas Control 132, 104057. https://doi.org/10.1016/j.ijggc.2023.104057 (Popielak et al. 2024)
2. **Publication no 2 (P2)** - Popielak, P., Majchrzak-Kucęba, I., Wawrzyńczak, D., The environmental impacts of circulating fluidized bed unit in coal-fired power plant with DR-VPSA carbon capture and $CO_2$-ECBM storage technology in Poland (unpublished)
3. **Publication no 3 (P3)** - Falco MD, Natrella G, Popielak P, Capocelli M (2022) Methodologies for CCU technologies environmental analysis. In: The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies. CRC Press https://doi.org/10.1201/9781003336587 (Falco et al. 2022)
4. **Publication no 4 (P4)** - Facchino, M., Popielak, P., Panowski, M., Wawrzyńczak, D., Majchrzak-Kucęba, I., De Falco, M., 2022. The Environmental Impacts of Carbon Capture Utilization and Storage on the Electricity Sector: A Life Cycle Assessment Comparison between Italy and Poland. Energies 15, 6809. https://doi.org/10.3390/en15186809 (Facchino et al. 2022)

Appendix papers

The manuscript below have been published as supportive papers to mainstream topics.

1. De Falco, M., Natrella, G., Capocelli, M., Popielak, P., Sołtysik, M., Wawrzyńczak, D., Majchrzak-Kucęba, I., 2022. Exergetic Analysis of DME Synthesis from $CO_2$ and Renewable Hydrogen. Energies 15, 3516. https://doi.org/10.3390/en15103516 (De Falco et al. 2022)

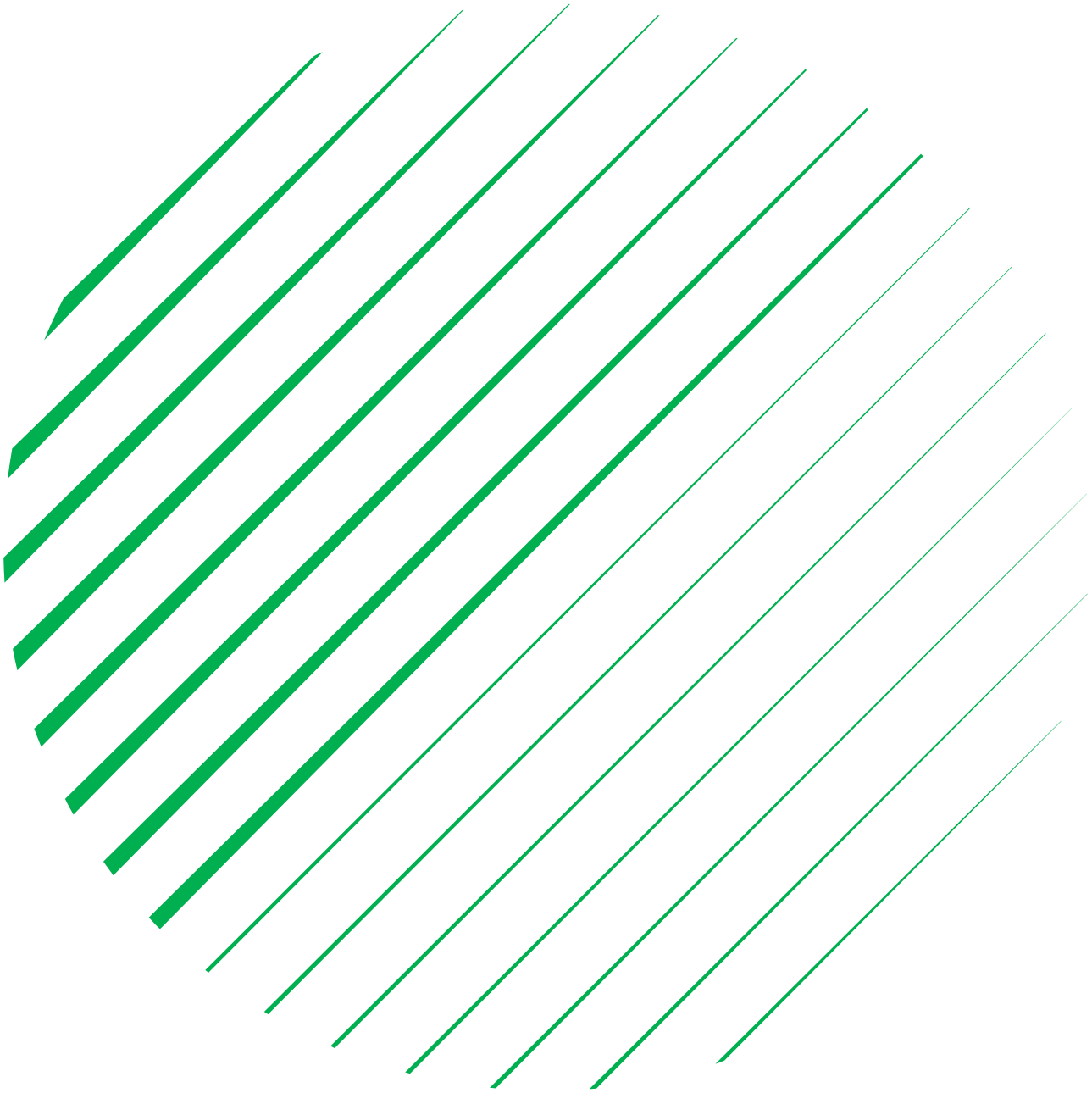
Abstract

Poland is the 6th largest economy and the second largest emitter of greenhouse gases (GHG) in the European Union (EU). In 2019 Poland's energy sector is responsible for 46.9% of domestic GHG emissions, followed by transport (20.04%) and energy-intensive industry sectors such as iron&steel or cement production, which accounted for 9.7% share of total GHG emissions. Moreover, a share of fossil fuels in domestic Gross Electricity Production was about 84.02%. Furthermore, fuel combustion accounts for about 92.1% of $CO_2$ emissions in total net emissions (excluding LUC). The country's dependence on fossil fuels with the energy sector's major impact on domestic GHG emissions makes it an interesting case study country for the implementation of decarbonizing technologies such as Carbon Capture Utilisation and Storage (CCUS). CCUS technology is intended to capture $CO_2$ from industrial processes (such as power generation in power plants) and transport it to its final storage destination or to utilize it in manufacturing processes. CCUS is one of the key technologies in climate change mitigation, as it can significantly reduce $CO_2$ emissions and support the transition to a decarbonized economy. Life Cycle Assessment (LCA) analysis is a methodology characterized by a holistic, comprehensive approach to assessing the environmental impact of a product or service at all stages or throughout its life cycle. LCA provides an in-depth understanding of how environmental impacts are linked to and can change outcomes with the implementation of the CCUS supply chain. The purpose of this dissertation is to investigate, through the use of LCA analysis, the environmental benefits of a CCUS supply chain in the energy and cement industries, with a particular focus on the potential for utilization through the production of dimethyl ether (DME), methanol (MeOH) and carbonated concrete. Three case studies were selected: (1) a comparative analysis of power plants with and without CCS located in Poland, (2) a comparative analysis of power plants and cement plants with CCUS, (3) a comparative analysis of natural gas power plants in Italy and Poland, with and without CCUS. As proven in the study, there is potential to reduce the environmental impact of the studied facilities, although $CO_2$ storage technology offers greater environmental benefits than the selected $CO_2$ utilization technologies.

Streszczenie

Polska jest szóstą co do wielkości gospodarką i drugim największym emitentem gazów cieplarnianych (GHG) w Unii Europejskiej (UE). W 2019 r. polski sektor energetyczny odpowiadał za 46,9% krajowych emisji gazów cieplarnianych, a następnie transport (20,04%) i energochłonne sektory przemysłu, takie jak hutnictwo żelaza i stali czy produkcja cementu, które odpowiadały za 9,7% całkowitej emisji GHG. Ponadto udział paliw kopalnych w krajowej produkcji energii elektrycznej brutto wyniósł około 84,02%. Co więcej, spalanie paliw odpowiada za około 92,1% emisji $CO_2$ w całkowitej emisji netto (z wyłączeniem LUC). Zależność kraju od paliw kopalnych i duży wpływ sektora energetycznego na krajowe emisje GHG sprawiają, że jest to interesujący kraj do studium przypadku dla wdrażania technologii dekarbonizacyjnych, takich jak technologie wychwytywania, utylizacji i składowania $CO_2$ (CCUS) z energetyki i innych gałęzi przemysłu. Technologia CCUS ma na celu wychwytywanie $CO_2$ z procesów przemysłowych (takich jak wytwarzanie energii w elektrowniach) i transportowanie go do miejsca docelowego składowania lub jego utylizację w procesach produkcyjnych. CCUS jest jedną z kluczowych technologii w łagodzeniu zmian klimatycznych, ponieważ może znacznie zmniejszyć emisję $CO_2$ i wspierać przejście na gospodarkę niskoemisyjną. Analiza cyklu życia (Life Cycle Assessment) to metodologia charakteryzująca się holistycznym, kompleksowym podejściem do oceny wpływu produktu lub usługi na środowisko na wszystkich etapach lub w całym cyklu życia. LCA pozwala na dogłębne zrozumienie, w jaki sposób wpływ na środowisko jest powiązany i może zmienić jego wyniki wraz z wdrożeniem łańcucha dostaw CCUS. Celem rozprawy doktorskiej jest zbadanie poprzez zastosowanie analizy LCA, korzyści środowiskowych z zastosowania łańcucha dostaw CCUS w energetyce i przemyśle cementowym, ze szczególnym uwzględnieniem możliwości utylizacji poprzez produkcję dimetyloeteru (DME), metanolu (MeOH) oraz karbonatyzowanego betonu. Wybrano trzy studia przypadku: (1) analizę porównawczą elektrowni z i bez CCS zlokalizowaną w Polsce, (2) analizę porównawczą elektrowni i cementowni z CCUS, (3) analizę porównawczą elektrowni na gaz ziemny we Włoszech i Polsce, z i bez CCUS. Jak udowodniono w badaniach, istnieje możliwość zmniejszenia wpływu na środowisko przebadanych obiektów, chociaż technologia składowania $CO_2$ oferuje większe korzyści środowiskowe od wybranych technologii utylizacji $CO_2$.

# Chapter 1 Global energy and environment



## 1.1 Climate change mitigation with CCUS – A case study with benchmarking for selected countries in adapting the European Union's Green Deal

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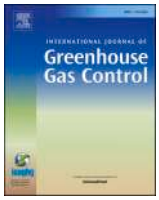

# Climate change mitigation with CCUS - A case study with benchmarking for selected countries in adapting the European Union's Green Deal

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ABSTRACT

Carbon Capture Utilization and Storage (CCUS) is a technology highlighted as one of the tools in climate change mitigation and one of the ways to reach the goal of 1.5℃ set by the Paris Agreement. The European Commission (EC) developed this goal by creating and implementing the European Green Deal (EGD) – the European Union's (EU) environmental policy. This paper provides an analysis of environmental policies and an overview of crucial CCUS projects of selected member states based on a benchmarking analysis of 27+ UK member states. An overall review of a total of 28 countries was undertaken based on economic and environmental factors. Afterward, a benchmarking analysis was performed ranking the countries according to the TOP10 for the selected five categories: total net emissions with international transport, percentage share of the energy sector, percentage share of fossil fuels, percentage share of fossil fuels in the Gross Electricity Production (GEP), and numbers of CCUS projects. Subsequently, a detailed and comprehensive overview of four selected member states was done, with a special focus on the national energy policy towards net-zero emission goals, the role of CCUS in domestic environmental policy, with current projects and facilities development. Finally, this paper outlines how the EGD has reformed the national energy policies of selected member states, and what is the part of CCUS technology in the national efforts towards climate neutrality.

## 1. Introduction

Since the early 1970s, the EU has played a leading role on the global political stage in environment protection, setting various pathways to protect the environment over the decades in an abundance of legislative actions (Bourguignon et al., 2019; Siddi, 2020).

Since the industrial era, the global electricity demand has risen significantly, which is directly related to greenhouse gas (GHG) emissions which can be expected to increase up to 2030 by 25–90 % in comparison to 1990, depending on the scenario of the global economy (IPCC 2000).

In counterpoint, over the period 2000–2020, the EU's total GHG emissions were reduced as shown in Fig. 1. Nonetheless, the percentage share of each member state's economic community emissions remained at similar levels compared to previous years as shown in Fig. 2. Although, as a result of legislative action, each member state is reducing

*Abbreviation:* AFC, Available for Final Consumption; BECCS, Bioenergy Carbon Capture and Storage; BWMi, Federal Ministry of Economic Affairs and Energy; CB6, Carbon Budget 6; CCC, Committee on Climate Change; CCGT, Combined Cycle Gas Turbine; CCOS, Carbon Capture and Offshore Storage; CCS, Carbon Capture and Storage; CCU, Carbon Capture and Utilization; CCUS, Carbon Capture Utilization and Storage; CD, Crown Dependencies; DAC, Direct Air Capture; DME, dimethyl ether; EBN, Energie Beheer Nederland; EC, European Commission; EEC, European Economy Community; EEA, European Environment Agency; EGD, European Green Deal; EGS, Enhanced Geothermal Storage; EOR, Enhanced Oil Recovery; ETS, Emission Trading System; EU, European Union; FEC, Final Energy Consumption; FID, Final Investment Decision; GAE, Gross Available Energy; GDP, Gross Domestic Product; GEP, Gross Electricity Production; GIC, Gross Inland Consumption; HDI, Human Development Index; IEA, International Energy Agency; IPCC, International Panel on Climate Change; KOBiZE, National Centre for Emission Management; LULUCF, Land Use, Land-Use Change and Forestry; MEA, monoethanolamine; MIEK, Multi-year Energy and Climate Infrastructure Programme; NECP, National Energy Climate Plan; NEP, Northern Endurance Partnership; NZT, Net Zero Teesside; OECD, Organisation of Economic Cooperation and Development; OGE, Open Grid Europe; OT, Overseas Territories; RES, Renewable Energy Sources; ROAD, Rotterdam Storage and Capture Demonstration Project; SSE, Scottish & Southern Energy; TES, Total Energy Supply; TCA, Trade and Cooperation Agreement; UK, United Kingdom; UKSAP, United Kingdom Storage Appraisal Project; USCR, Upper Silesia Coal Region; ZCH, Zero Carbon Humber.

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its national GHG emissions from year to year, the overall share remains at a similar level. It is essential to make progress, set climate goals, and progressively work towards accomplishing them.

On July 14th, 2021 the European Commission (EC) released a bundle of legislative proposals aimed at adjusting the EU's climate, energy, transport, and tax policies to the new guidelines known as the European Green Deal - the new climate agreement (European Commission 2019). The main principles of the new agreement are to transform the EU into a state-of-the-art, globally competitive economic union that: will achieve zero net greenhouse gas emissions by 2050, separate economic growth from resource consumption, and no individual or region will be left behind (a fair transition) (Siddi, 2020). This ambitious goal is intended to make the EU the world's first climate-neutral economic community. Thus, several technologies, pathways, and fields of action have been set up as solutions to support efforts in climate change mitigation. Among them, the CCUS's main assignments in the EGD are industrial decarbonization and sharing in the reduction of GHG emissions in European efforts to reach climate neutrality (Baleva et al., 2021).

Although, the EGD is certainly the most publicly recognized piece of legislation, it is not the only basis in the EU for the development of CCUS. Thus, the other acts and proposals that affect the implementation of this technology are summarised and presented in Table 1.

### 1.1. CCUS technology overview

CCUS is a set of technologies that can be categorized into three main aspects. The first is carbon capture, whose technologies depending on the stage of capture can be divided into pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture (DAC) technologies (Rahman et al., 2017; Akimoto et al., 2021; Herold et al., 2011). The second way to categorize carbon capture technologies is the capture method, which is divided into: adsorption, absorption, membrane, and cryogenic (Rahman et al., 2017; Leung et al., 2014).

Further path for captured carbon dioxide can be divided into: utilization and/or storage. In the first case, $CO_2$ is treated as a feedstock (with or without conversion) for other industrial processes for example: the production of fuels (Bonura et al., 2021; De Falco et al., 2022; Okoye-Chine et al., 2022), chemicals (Alper and Yuksel Orhan, 2017; Koytsoumpa et al., 2018; Cordero-Lanzac et al., 2021; Chehrazi and Moghadas, 2022), polymers (Bachmann et al., 2021), or building components (Monteiro and Roussanaly, 2022; Batuecas et al., 2021). Each carbon dioxide utilization technology not only has its requirements in terms of the quality and parameters of the $CO_2$ stream but also the potential and efficiency (Fig. 3) with which the captured $CO_2$ can be converted into a new product.

On the other hand, carbon dioxide storage is a way of $CO_2$ utilization meaning permanent close-in for example underground sites. Thus, to that happen there are specific requirements in the geological characteristic of the chosen site that need to be fulfilled (Wall et al., 2005; Harding et al., 2018; Hendriks and Blok, 1993).

Nonetheless, it is still remarkable that, as in the 1980s CCUS units were able to capture only 0.5 Mt of $CO_2$ per year, by 2020 this level has reached 40 Mt of $CO_2$ per year (IEA, 2021a).

Ultimately, CCS and CCU solutions are complementary, as both require access to a $CO_2$ source with capture facilities, as well as infrastructure and transport services. Thus, both technologies are valuable assets in the climate agenda and, eventually, Europe's climate neutrality by 2050.

Noteworthy is the fact, that Europe has strong possibilities for underground storage of $CO_2$ (Vangkilde-Pedersen et al., 2009a; 2009b; Neele et al. 2006) as well as to transport it via vast network of oil and natural gas pipelines (DNV, 2021).

With regard to the above, there is a keen demand for an in-depth study and comprehensive approach to understanding the contribution of CCUS technology in efforts towards net-zero goals. Since the idea of CCUS technology overlaps a very broad area of knowledge, it is important to make the overview and comparison to take a holistic approach to determining the capabilities, potential, and performance of a particular method with each case study's facility specifications.

The main scope of this paper is to identify what is the role of CCUS in

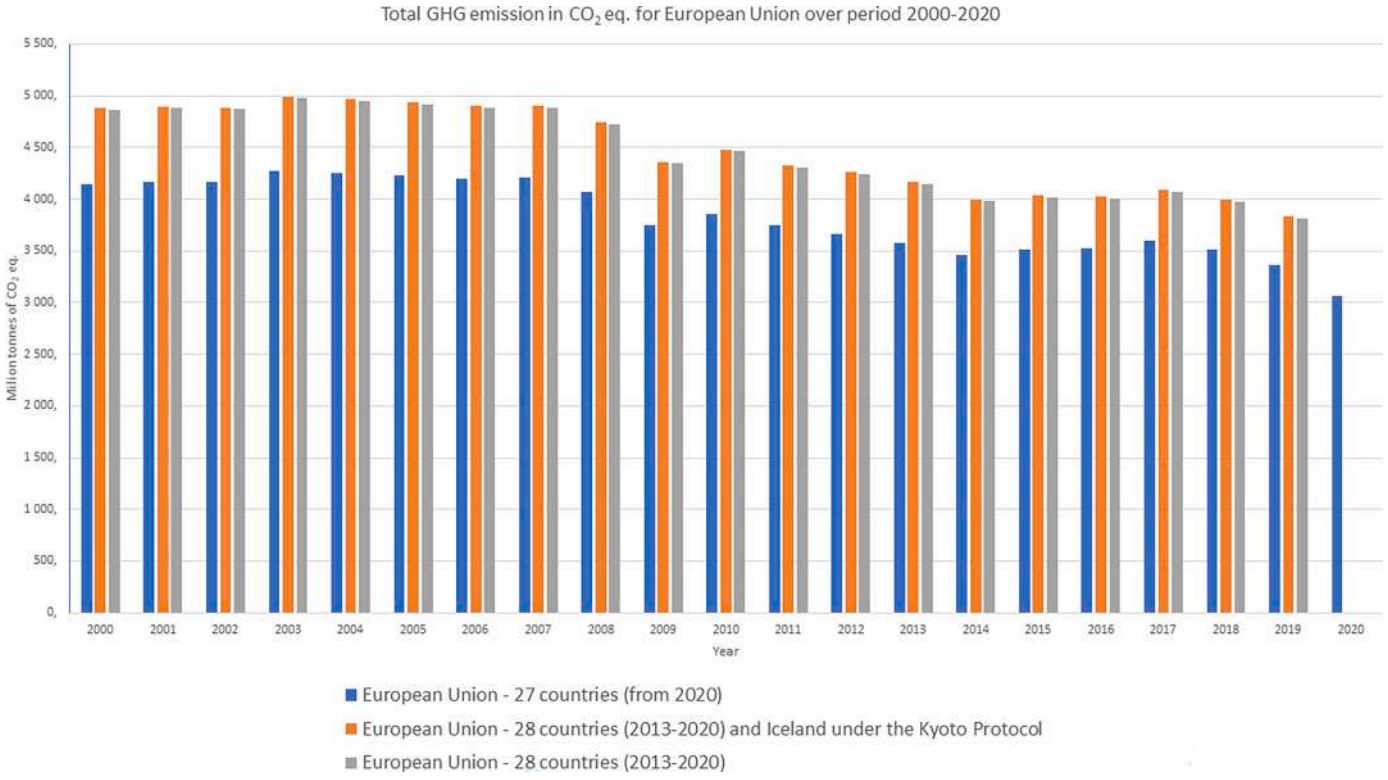


**Fig. 1.** Total GHG emissions of the European Union over the period 2000–2020 (author's compilation based on the Eurostat data).

achieving net-zero emission by 2050 in the selected EU member states, and how selected member states adapted its environmental policies according to the EGD targets. Additionally, following knowledge gaps were also considered: application of the benchmarking method to analyse the environmental aspects of the EU member states, CCUS development issues in the selected EU member states, the EU CCUS policy.

The paper is organized into four sections described as follows: Section 1 is a general introduction to European environmental policy with a brief CCUS technology overview, Section 2 considers methodology, and Section 3 presents the chosen EU's member states environmental and energy profiles, with in-depth country's environmental policy review with description of approach to the EGD and CCUS technology. The last sections includes a summary and conclusions.

## 2. Methodology

The methodology applied in the following investigation of the EU member states profiles in terms of energy and environment is benchmarking.

As mentioned by Kozak (2001) benchmarking is "the continuous measurement and improvement of an organization's performance against the best to obtain information about new working methods or practices in other organisations" (Kozak and Nield, 2001). According to Zuiderwijk (2021), Zanella (2012), Kyrö (2004), and the European Commission Guidelines, the benchmarking method can be adapted to perform a detailed overview for comparison of the EU member states environmental profiles (Zuiderwijk et al., 2021; Zanella et al., 2012; Kyrö, 2004; European Commission, 2016).

### 2.1. Background data

In order to perform the benchmarking analysis, several suppositions were established.

First of all, the Eurostat as well as the European Environment Agency (EEA) databases, as a public tool of the European Commission - available and open to the public - with the International Energy Agency and the United Nations Development Programme databases were chosen as the databases for the benchmarks.

Additionally, a publicly accessible database available on the Zero Emission Platform (ZEP) project was used to obtain data on the number of national CCUS projects (Zero-Emission Platform, 2023a). ZEP is a European techno-innovation platform established and maintained under the European SET Plan (Zero-Emission Platform 2023b).

Furthermore, the year 2019 was chosen as a "zero year" for the study because on February 1st, 2020, an agreement on the withdrawal of the United Kingdom of Great Britain and Northern Ireland from the European Union entered into force and the UK has a major contribution in continental greenhouse gas emissions besides, the ratified European and international climate agreements are still in force (Agreement on the withdrawal of the United Kingdom of Great Britain and Northern Ireland from the European Union and the European Atomic Energy Community 2019). Finally, there was a significant fulcrum of global greenhouse gas emissions in 2020 due to the worldwide Covid-19 pandemic.

### 2.2. Benchmarking factors

In order to perform a comprehensive analysis of member states, it was essential to provide a full overview of indicators including: basic economy, GHG emissions, and energy profile. Data for this purpose were selected and compiled from mentioned in section 2.1 databases (Eurostat Data browser, 2022a; United Nations, 2022; Eurostat Data browser, 2022b; European Environment Agency 2021; Eurostat Data browser 2023), and presented in the supplementary materials. Subsequently, part of these indicators were used for detailed benchmarking analysis presented in Tables 3 and 4, with results presented in Table 5.

The selected indicators that were used for the comprehensive overview can be divided into two categories:

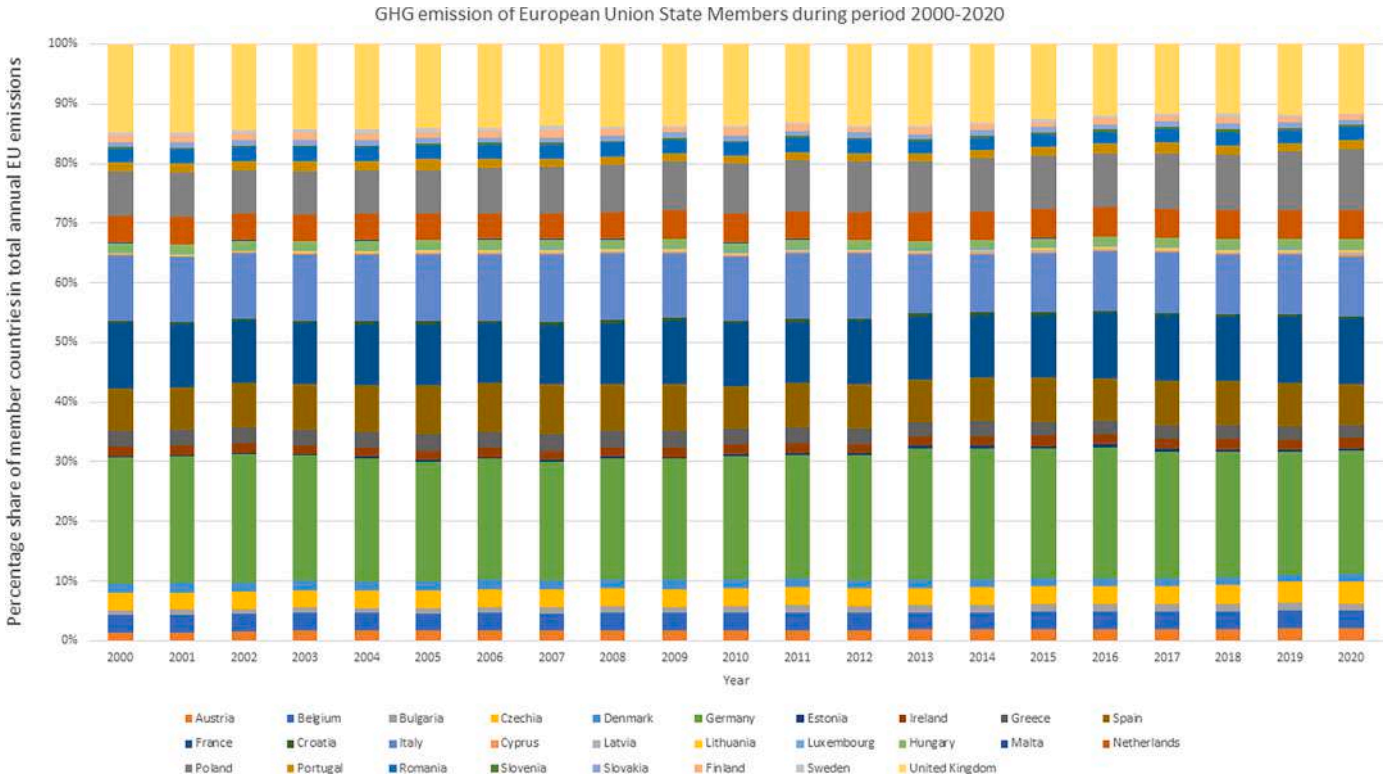


**Fig. 2.** Percentage share of GHG emissions of the European Union member states over the period 2000–2020 (author's compilation based on the Eurostat data).

**Table 1**
Review of the EU legislation relating to or addressing CCUS technology.

| Name of legislation | Data of implementation | Brief description | Ref. |
|---|---|---|---|
| The European Strategic Energy Technology Plan (the SET-Plan) | 13.12.2007 | Advancements of knowledge development and technology transfer, among which was CCUS technology (the SET-Plan was additionally updated after the EGD). | (European Commission 2007) |
| European Green Deal | 14.07.2021 | New European climate agreement to make the EU net-zero economy until 2050. | (European Commission 2019) |
| Directive 2009/31/EC | 23.04.2009 | Regulatory framework for the safe transport and storage of $CO_2$. | (European Commission 2009) |
| Directive 2018/2001/EU | 11.12.2018 | Promotion of the use of energy from renewable sources, as well as fuels produced from captured $CO_2$. | (European Commission, 2018) |
| Communication on Sustainable Carbon Cycles (COM/2021/800) | 15.12.2021 | Aims to establish sustainable and climate-resilient carbon cycles with usage of CCUS. | (European Commission, 2023b) |
| Proposal for a Regulation of the European Parliament and of the Council COM/2022/672 | 30.11.2022 | Framework for carbon removals by utilizing technologies such as BECCS and direct air capture with storage DACCS. | (European Commission 2022) |

a) Economic: population, Human Development Index (HDI), Gross Domestic Product (GDP);
b) Environmental: $CO_2$ emission per capita, $CO_2$ emission per GDP, percentage contribution of source sectors to GHG emissions, total energy supply (TES), gross electricity production (GEP), primary production, recovered and recycled products, imports, exports, change in stock, gross available energy (GAE), gross inland consumption (GIC), energy available for final consumption, total net emissions with international transport is cumulative total GHG emissions (in $CO_2$ equivalent) including Land Use, Land-Use Change and Forestry (LULUCF) with international aviation and shipments.

Percentage contribution of GHG emissions by source sectors are dataset extracted and processed from the EEA data viewer and it's based on merged data from the Eurostat database. In accordance with the IPCCA 2006 guidelines for reporting GHG emissions, it has been divided into sectors following the Common Reporting Format (CRF) classification as shown in Table 2.

### 2.3. Member states selection criteria

According to the main objective of this paper, the benchmarking criteria must reflect the energy profile of the European countries in order to be capable of selecting countries for further detailed analysis on this foundation.

To enable the preselection of countries, benchmarking categories that reflect the problem of GHG emissions, and the impact of the contribution of the energy sector (interlinked with CCUS development which is heavily related to the energy sector), needed to be developed.

The selected criteria includes: (1) total net GHG emissions with international transport, (2) percentage share of energy sector in total net GHG emissions with international transport, (3) percentage share of fossil fuels in national TES, (4) percentage share of fossil fuels in national

**Table 2**
CRF classifications used for GHG emissions reporting in the EEA and the Eurostat databases (Herold et al., 2010).

| Name of category | CRF categories |
|---|---|
| Energy supply | CRF 1A1 (energy industries) 1B (fugitives) |
| Industry | CRF 1A2 (manufacturing industries and construction)<br>CRF 2 (industrial processes and product use) |
| Domestic transport | CRF 1.A.3 |
| Residential and commercial | CRF 1A4a (commercial)<br>CRF 1A4b (residential) |
| Agriculture | CRF 1A4c (agriculture, forestry and fishing)<br>CRF 3 (agriculture) |
| Waste | CRF 5 (waste) |
| Land Use, Land-Use Change and Forestry | CRF 4 (LULUCF) |
| International aviation | CRF 1D1a |
| International shipping | CRF 1D1b |

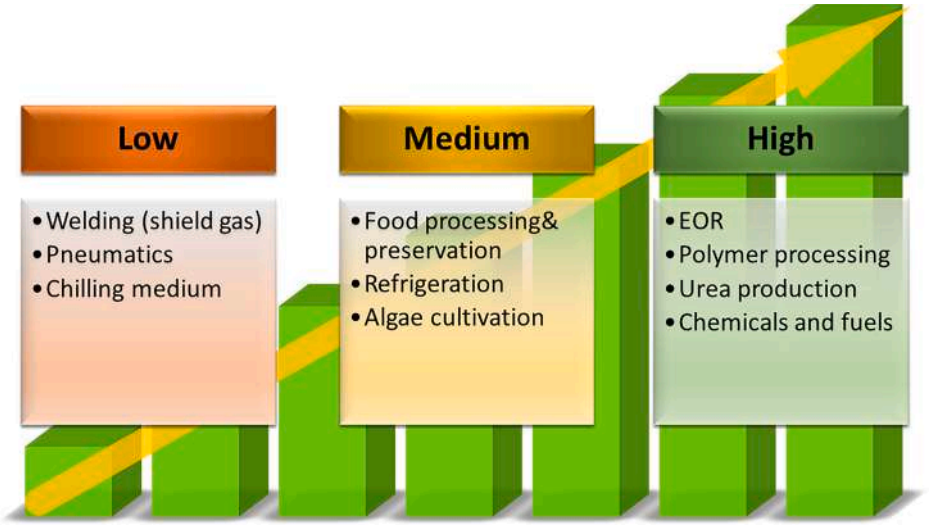


**Fig. 3.** Potential and pathways for captured $CO_2$ utilization (author's compilation based on (Koytsoumpa et al., 2018)).

GEP, and (5) numbers of CCUS projects operational or under development. All criteria are consider as equal.

Additionally, the supplementary materials include a summary of the most important indicators for all 27+UK member states from which certain indicators were selected for benchmarking.

## 3. Selected member states' profiles

The summary of the top 10 countries in the benchmarking criteria, with descending sorting in each benchmarking category has been done in Tables 3 and 4.

Countries were selected based on the following formula. Countries were ranked in Table 3 in descending order in categories (1)-(4) listed in section 2.3. Additionally, Table 4 summarises the top 10 countries in descending order according to category (5). The tables have been split into two for readability reasons.

Subsequently, in both tables member states were assigned with points from 10 to 1 in each category, in descending order. The highest value of $n = 10$ was allocated to the country in first place in the category. Points were then allocated to subsequent countries in a descending manner until $n = 1$, which was the number of points allocated to the country ranked last (i.e. 10th) in a given benchmarking category. The allocation of points was repeated in the same way for each of the five categories.

The points thus obtained were then added up for each country individually and a new point ranking was created for the top 10 countries. The Table 5 presents a summary of the top 10 countries overall, with bolded top 4 countries selected for further detailed analysis.

Additionally, the four countries selected on the performed benchmarking analysis were characterized by the following features: Germany is the 1st GHG emitter in the EU, the Netherlands has the highest% share of fossil fuels in TES, Poland is a country ranking in every category but always higher in relation to other recurring countries, and finally, the UK has the highest contribution in CCUS implementation.

### 3.1. Poland

#### 3.1.1. Introduction

Poland joined the European Union in May 2004 according to the signed in Athens Treaty of Accession (European Commission 2003). According to the Eurostat database, Poland is the 6th European economy by GDP at market prices since 2020 (International Energy Agency 2022).

Poland has been a single EU member state to have had economic growth in years of economic stagnation (2008–2012). In addition, Poland's GDP is still lower than the average Domestic Product of the other EU member states (International Energy Agency 2022).

Since Poland has ratified the Kyoto Protocol and is a signatory to the UN Framework Convention on Climate Change (UNFCCC), it's the base year for the implementation of commitments is 1988 (Olecka et al., 2021).

The next significant step was on January 23rd, 2008, when Poland approved the 3 × 20 Energy and Climate Package, according to which the implementation of three basic goals was undertaken: 20 % share of RES in the primary energy balance, 20 % reduction of greenhouse gas emissions compared to 1990 emission levels, 20 % reduction of global primary energy consumption (Jeszke, 2019).

As part of advancing efforts to address climate change on March 2nd, 2021 the Minister of Climate and Environment established the Energy Policy of Poland 2040, the so-called EPP2040, the country's energy policy until 2040, the implementation of the EGD and its connection with the Paris Agreement. Noteworthy is the fact that Poland was the country that opposed the introduction of the European Green Deal for the longest time, justifying this with the complicated situation of the domestic energy and industrial sector (Hafner and Raimondi, 2020; Tomaszewski, 2020). Three fundamental goals were set, and expanded with eight Strategic Objectives, which included: a fair transition, a

**Table 3**
Summary of top 10 member states by the chosen benchmarking categories – part 1.

| Category no. 1 | | Category no. 2 | | Category no. 3 | | Category no. 4 | |
|---|---|---|---|---|---|---|---|
| *Member state* | *total net emission with international transport [t $CO_2$ eq.]* | *Member state* | *% share of the energy sector in total net emissions with international transport* | *Member state* | *% share of fossil fuels in TES* | *Member state* | *% share of fossil fuels in Gross Electricity Production* |
| Germany | 818 403 556 | Estonia | 54,54 | Netherlands | 90,79 | Malta | 90,20 |
| United Kingdom* | 494 923 731 | Bulgaria | 48,36 | Cyprus | 89,36 | Cyprus | 89,99 |
| France | 447 043 061 | Poland | 46,03 | Ireland | 87,83 | Poland | 84,02 |
| Italy | 396 814 666 | Czechia | 39,16 | Poland | 87,01 | Netherlands | 77,89 |
| Poland | 374 312 481 | Slovenia | 38,5 | Malta | 85,94 | Estonia | 71,87 |
| Spain | 319 017 792 | Finland | 38,14 | Greece | 82,04 | Greece | 66,79 |
| Netherlands | 232 661 448 | Sweden | 36,76 | Germany | 79,28 | Ireland | 61,10 |
| Belgium | 148 151 320 | Romania | 36,43 | Luxembourg | 79,04 | Italy | 59,86 |
| Czechia | 133 081 931 | Greece | 34,42 | Italy | 78,35 | Czechia | 52,29 |
| Greece | 95 022 771 | Germany | 31,42 | United Kingdom* | 78,27 | Latvia | 50,42 |

* No longer member since February 1st, 2020.

**Table 4**
Summary of top 10 member states by the chosen benchmarking categories – part 2.

| Category no. 5<br>*Member state* | *Number of CCUS projects* |
|---|---|
| United Kingdom* | 14 |
| The Netherlands | 8 |
| Belgium | 7 |
| Germany | 5 |
| Sweden | 5 |
| France | 3 |
| Denmark | 2 |
| Italy | 2 |
| Austria | 1 |
| Poland | 1 |

* No longer member since February 1st, 2020.

**Table 5**
Benchmarking summary.

| No. | Member state | Number of points (total) |
|---|---|---|
| 1. | **Netherlands** | 30 |
| 2. | **Poland** | 29 |
| 3. | **Germany** | 22 |
| 4. | **United Kingdom*** | 20 |
| 5. | Cyprus | 18 |
| 6. | Estonia | 16 |
| 7. | Malta | 16 |
| 8. | Italy | 15 |
| 9. | Greece | 13 |
| 10. | Ireland | 12 |

* No longer member since February 1st, 2020.

zero-carbon energy system, and good air quality (EPP2040, 2021; Ministerstwo Klimatu i Środowiska, 2023; European Union Parliment, 2023). Nowadays, the proclamation is the most important document in power, determining the modernization of the energy system and the direction of the forthcoming developments aimed at protecting the climate and the country's energy transformation.

Additionally, in November 2021, Polish government establishes Polish Hydrogen Strategy until 2030 (supported previously by Objective 4 in EPP2040), which defines six key objectives with framework for detail plans, funding, and regulatory changes to support the production, storage, transport and use of low-carbon hydrogen with a focus on hard-to-decarbonise sectors and end-uses (Ministry of Climate and Environment 2021).

### 3.1.2. Poland GHG emission

The case study for Poland is both challenging and demanding due to the country's socio-economic situation and its heavily fossil fuel-dependent energy sector (as shown in Fig. 4). In the European Union Poland is on the 5th place in total net emissions with international transport, the 3rd place in percentage share of the energy sector in total net emissions, the 4th place in percentage share of fossil fuels in TES, and the 3rd place in share of fossil fuels in GEP (Table 3; additional information in supplementary materials: Tables 2-4).

According to the National Centre for Emission Management (KOBiZE), $CO_2$ is the main GHG in Poland (81.8 % of emissions in 2019), followed by methane (11.8 %), and nitrous oxide (5.4 %) (Olecka et al., 2021).

Fuel combustion accounts for about 92.1 % of $CO_2$ emissions in total net emissions (excluding LULUCF) (Olecka et al., 2021), where the largest contributors are the energy sector (46.9 %) (Olecka et al., 2021), transportation (20.4 %) (Olecka et al., 2021), and industrial processes (9.7 %) (Olecka et al., 2021). In contrast, the main source of methane emissions in Poland is fugitive emissions from fuels (39 %) (Olecka et al., 2021), followed by agriculture (30 %) (Olecka et al., 2021) and waste (23 %) (Olecka et al., 2021). In the case of fuel combustion, liquid and gaseous fuels account for the least share; solid fuels account for over 90 % of emissions (Olecka et al., 2021).

Despite this, Poland counted a decrease in GHG emissions in each of the categories defined by the IPCC, compared to the base year: 32.95 % drop in total with LULUCF (Olecka et al., 2021), 32.4 % in the energy sector (Olecka et al., 2021), 22.83 % in the industrial processes (Olecka et al., 2021), 34.77 % in agriculture (Olecka et al., 2021), 22.46 % in LULUCF (Olecka et al., 2021) and 45.09 % in waste category (Olecka et al., 2021).

### 3.1.3. Energy-intensive industries overview

According to the National Centre for Emission Management (KOBiZE), in 2019 in the Industrial Processes and Product Use emission category (CRF2), the mineral industry was responsible for 6.84 % of total domestic GHG emissions (Olecka et al., 2021), with the following sectoral breakdown: mineral industry 46.26 % (with cement production account for 64.92 % of it) (Olecka et al., 2021), chemical industry 19.7 % (Olecka et al., 2021) and metal industry 9.33 % (Olecka et al., 2021).

### 3.1.4. CCUS possibilities and development in Poland

Due to the fact, that the Polish economy is based on a large extent on fossil fuels thus it will have a much more difficult road ahead in the implementation of the undertaken provisions. Although ambitious goals set by the EU seems to be feasible in the era of today's state of the art technology. Within the second fundamental of the EPP2040, one of the specific guidelines is the zero-carbon energy system, which considers system transformation to include the implementation of new methods of carbon capture and utilization along with the development of clean coal technologies.

During the period 2008–2012, the research on the possibility of $CO_2$ storage was coordinated by the Polish Geological Institute and conducted by the Central Mining Institute within the framework of the National Program "Assessment of formations and structures suitable for safe $CO_2$ geological storage along with their monitoring program" (Wójcicki, 2013). Estimated storage potential capacities are shown on Fig. 5 (refer to static, effective capacity).

However, as Dubiński et al. (2010), Mika-Brysk and Wróblewska (2015), and Przybojweska (2018) noted, there is a need to prioritize and update regulations in Poland in order to increase opportunities and investor interest in $CO_2$ sequestration in geological formations (Dubiński et al., 2010; Mika-Brysk and Wróblewska, 2015; Przybojewska, 2018). According to the Polish Geological and Mining Law, until very recently, there were no allowance for geological storage of $CO_2$ on a large scale; $CO_2$ storage was allowed only for demonstration projects. However, on June 16th, 2023 the Polish Geological and Mining Law was updated, allowing a CCS projects on a full-scale (Sejm Rzeczypospolitej, 2023).

On the other hand, through a case study of the Bełchatow CCS project (Breukers et al., 2011), Kaiser et al. (2014) emphasize the importance of dialogue with the Polish public on the issue of implementing $CO_2$ sequestration technology (Kaiser et al., 2014).

Subsequently, CCS in the EPP2040 is a technology repeatedly mentioned as a tool for energy transition although a statement limiting its viability appears in the act that "coal technologies equipped with CCS facilities can be competitive, but under conditions of high $CO_2$ allowance prices exceeding EUR 50/t." (EPP2040, 2021).

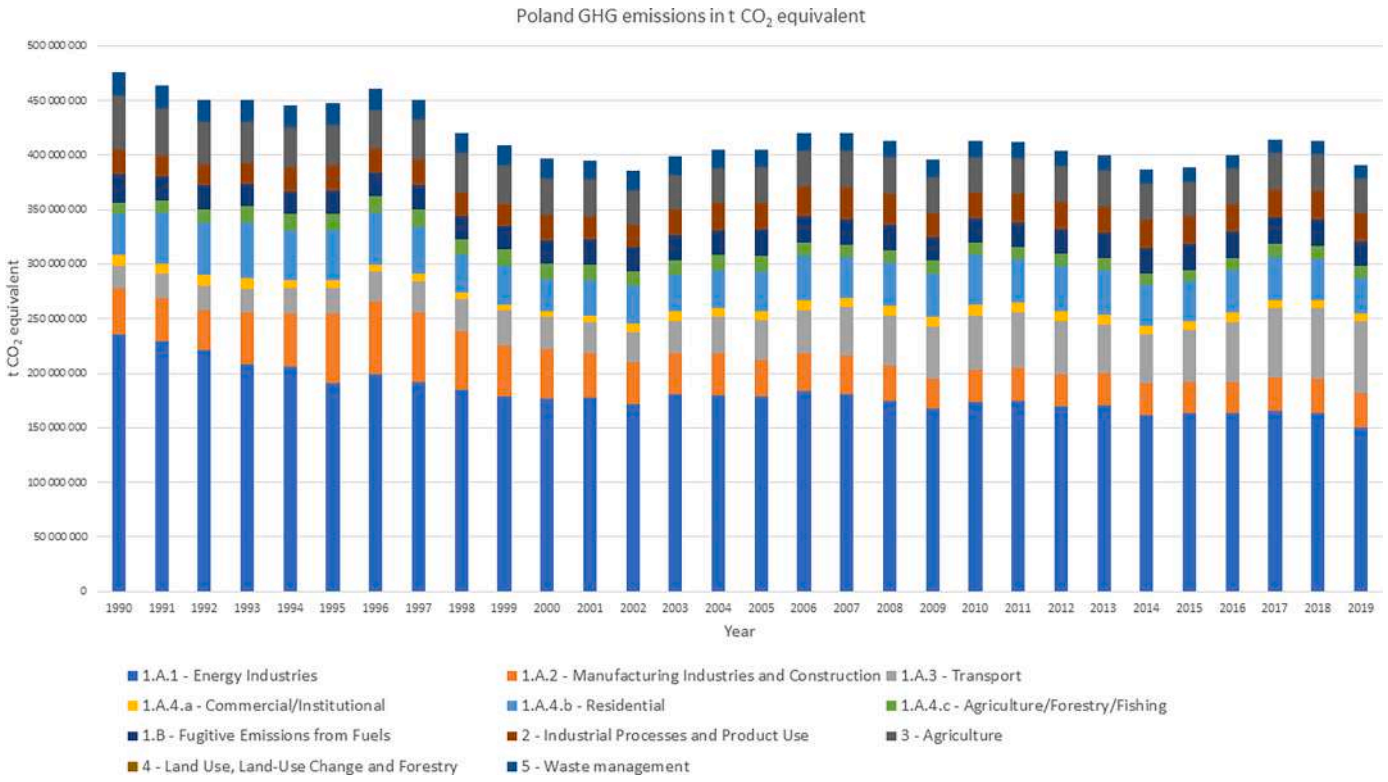


**Fig. 4.** Poland GHG emissions over the period 1990–2019 (based on the Eurostat data).

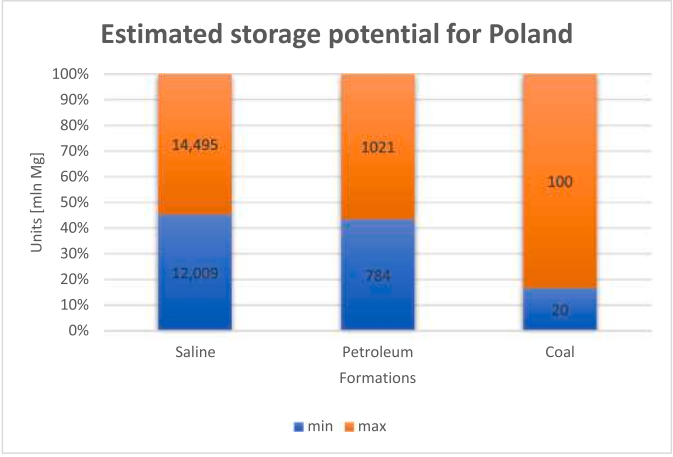


**Fig. 5.** Estimated storage potential for Poland (based on the Polish Geological Institute (Wójcicki, 2013)).

Nowadays in Poland, there is one carbon capture pilot-scale plant in the Łagisza Power Plant in Będzin, Poland, owned by the TAURON Wytwarzanie S.A. (Wawrzyńczak et al., 2018; Majchrzak-Kucęba et al., 2021; Wawrzyńczak et al., 2014). Another one is commenced in September 2020 project FLEXIS – a pilot-scale testing plant with $CO_2$ sequestration in unmineable coal beds in Mikołów (Flexis 2020; Kali et al., 2022).

Moreover, in one of the most recent research available, Śliwińska et al. (2022) conducted an extensive study devoted to the possible implementation of CCUS in the territory of the Upper Silesia - the most heavily industrialized region of Poland responsible for 8.82 % of the country's annual GHG emissions, whose capacity for $CO_2$ storage is very scarce (Śliwińska et al., 2022).

Additionally, Tarkowski et al. (2019), Gładysz et al. (2020), and Sowiżdżał (2022a, 2022b) made research on the feasibility of using a combination of carbon capture technologies to enhance geothermal energy performance ($CO_2$ – EGS - Enhanced Geothermal Systems) in Poland (Tarkowski and Uliasz-Misiak, 2019; Gładysz et al., 2020; Sowiżdżał et al., 2022a; 2022b).

#### 3.1.5. *Overview summary*

Poland, compared to the other European members, has a large potential for carbon utilization and can be potent with possibilities of potential $CO_2$ sites for storage. With the form its coal-dependent economy and necessity for transition period of shifting away from coal-dependent policy, along with its high-energy industry, it could be a valuable source of the carbon element in European-wide CCUS development.

Furthermore, Poland is third blue hydrogen producer in the EU, which also opening possibilities for applying CCUS, to make it low-carbon hydrogen (International Energy Agency 2022).

### 3.2. *The United Kingdom*

#### 3.2.1. *Introduction*

The Trade and Cooperation Agreement (TCA) is mandatory legislation, signed on December 30th, 2020 and entered into force on May 1st, 2021, which describes relations between the United Kingdom and the European Union (Fella et al., 2020). Despite the February 1st, 2020 Brexit, it should not be ignored that the United Kingdom still has strong cooperation with the EU concerning climate change mitigation (Wachowiak, 2021). According to the terms of the EU Withdrawal Agreement, the UK still stands committed to a common climate target with the EU under the Kyoto Protocol. Furthermore, the Kyoto target covers not only the UK but also the Crown Dependencies (CDs) and the Overseas Territories (OTs) for whom ratification has been extended.

However, after Kyoto, before the TCA and Brexit happened, the Climate Change Act 2008 came into force on November 26th, 2008 (The UK Government 2008). This ambitious act in force is still updated with

new regulations, deciding on a course of actions to tackle climate change in the United Kingdom.

In 2008, it introduced an ambitious goal for the UK to reduce GHG emissions by 80 % below year zero by 2050, with five-year mandatory carbon budgets. In addition, it established the independent Committee on Climate Change (CCC) to advise the UK government on setting and implementing the UK emissions budgets, as well as monitoring progress on them.

Subsequent in October 2017 was established the Clean Growth Strategy – low-carbon innovations document. The same year was published The Industrial Strategy (further developed in 2020 by 10-point plan for Green Industry Revolution) (UKBEIS 2017; The UK Government 2017). Nonetheless, binding together both legislations are leverage for competitiveness and affordability in development of climate change mitigation targets.

Furthermore, in June 2019, six months before the EGD was first introduced, the UK government furthered its ambitious goal by setting a legal target to achieve net zero GHG emissions across in the UK by 2050, thereby making the UK the first major global economy to legislate a net zero target (The UK Government 2019).

### 3.2.2. UK GHG emission

Since 1990 the UK's total net emission decreased by 44 % (Fig. 6). According to the IEA report about the UK's Energy Policy coal usage in the power & heat sector fell by 83.9 % over the period 2007–2011 thus to strong increase share of RES in TES and strengthened the UK carbon price floor (IEA 2019).

In 2019 the UK's domestic transport was responsible for almost one quarter of total net GHG emissions (more in supplementary materials: Table 2). In 2018 The Automated and Electric Vehicles Act came into law, providing framework for new regulations for such issues as: legal regulations of charging stations, hydrogen refuelling points, insurance for automated and electric vehicles (Automated and Electric Vehicles Act 2018). With support EV's programs and the Clean Growth Strategy its set up several goals to develop electromobility combined with net-zero emission form transport sector. Furthermore, published in 2018 the Road to Zero strategy set out a framework for zero and low-emission vehicles with the target to make at least 50 % (and as much as 70 %) of new car sales ultra-low emission by 2030, ending sales of new conventional gasoline and diesel cars and vans by 2040, aiming for every car and van to be zero-emission by 2050 (UKBEIS 2018).

Next after transport is energy sector, in which GHG emissions are primary from combustion fossil fuels with natural gas that has the biggest contribution (in GEP natural gas was responsible for 40.37 % produced GWh, followed by RES and biofuels: 37.80 %; solid fossil fuels was responsible only for 2.13 % GWh of GEP – more in supplementary materials: Table 4). The reduction of GHG emissions from the energy sector is due to the continuous closure of coal-fired power plants, the conversion of existing ones to biomass/waste fuels, the development of combined cycle gas turbines (CCGT) power plants, and the development of renewable energy sources.

### 3.2.3. Energy-intensive industries overview

According to National GHG Inventory Report, in 2019 in Industrial Processes and Product Use emission category (CRF2), mineral industry was responsible for 6.84 % of total domestic GHG emissions (Brown et al., 2021), with following sectoral breakdown: mineral industry 17.6 % (with cement production account for 70.28 % of it) (Brown et al., 2021), chemical industry 12.82 % (Brown et al., 2021) and metal industry 26.69 % (Brown et al., 2021). Despite that, from 1990 to 2020, there has been a more than 80 % cut in GHG emissions from the industrial process sector (Brown et al., 2021; Waite, 2019).

### 3.2.4. CCUS possibilities

As shown in Table 4, the UK is leading in Europe and it's in top 5 global leaders in CCUS projects development (The UK Government 2022). Due to the Industrial Decarbonization Strategy set by the UK's government in March 2021, the CCUS has a solid support (The UK Government 2021a). In addition, the UK has a potent reservoirs for underground storage of $CO_2$ (Holloway, 2009; Höller and Viebahn,

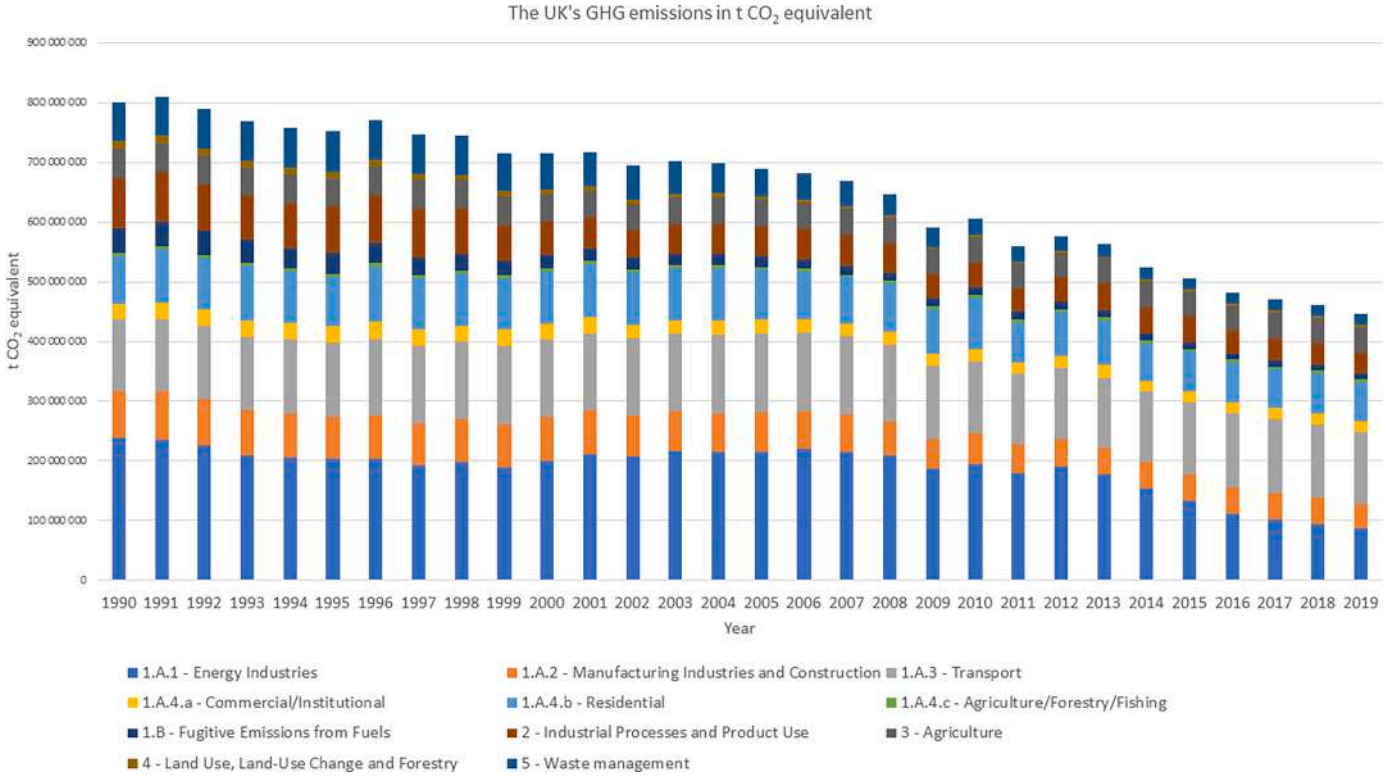


**Fig. 6.** The UK's GHG emissions over period 1990–2019 (based on the Eurostat data).

2011). According to the government's UK Investors CCUS roadmap ambition is to capture 20–30 $MtCO_2$, including 6 $MtCO_2$ of industrial emissions, per year by 2030, with net-zero emission target by 2050 (The UK Government 2022).

Concerning geological situation the UK has potent opportunities in carbon storage. The UK Storage Appraisal Project (UKSAP) is a £4 million endeavour in developing the UK's first $CO_2$ storage appraisal database (Gammer et al., 2011). It was carried out through a partnership between academia and industry partners. The database is available online through a publicly accessible website named $CO_2$ Stored (CO2 Stored Project Homepage 2023). According to the website and project reports, there are more than 500 possible storage sites, which have a theoretical capacity of about 78 Gt with 50 % certainty (P50). Most of these are saline aquifers (about 60 Gt) (CO2 Stored Project Homepage 2023; Bentham et al., 2014). 70 Gt of potential storage capacity is in offshore geological formations. The UK oil and gas fields have about 8 Gt of potential capacity, excluding possible new storage volumes that may be gained from further hydrocarbon extraction. The main regions where storage capacity is being evaluated are: the Southern, the Centre and the Northern North Sea (UKSAP Consortium 2011; UKSAP 2012).

Additionally, as part of climate action and efforts to net-zero emissions in the industrial area, in 2020 government presented a 10-point action plan for the Green Industrial Revolution, in which one of the key actions is the implementation of CCUS technology (The UK Government 2020). It outlines some of the highly industrialized areas more broadly identified by, for example, Calvillo et al. (2022) and Griffin et al. (2016, 2018) (Calvillo et al., 2022; Griffin et al., 2016; Griffin et al., 2018). Moreover, in the area of some clusters there are ongoing projects for the development and implementation of CCUS, such as Humber and Teesside Cluster, the Acorn Project. Furthermore, according to government update on the business model for Industrial Carbon Capture, decarbonization of industry cannot be performed with net-zero target without support from CCUS project with specific insistence on utilisation part (The UK Government 2021a).

Moreover, to leverage Carbon Budget Six (CB6) and net-zero 2050 target, low carbon hydrogen is essential commodity. The UK's government set in 2021 the UK Hydrogen Strategy, aiming for 5 GW low-carbon hydrogen production by 2030, with goal of 250–460 TWh in 2050 produced (approximately 20–35 % of final energy consumption) (The UK Government, 2021).

### 3.2.5. CCUS projects

*3.2.5.1. Humber – heart of uk decarbonization.* The Humber industrial region is one of the top 6 major UK's industrial clusters, and it's emitting more $CO_2$ than any other industrial cluster (37 % of the UK's $CO_2$ emissions, 30 % more than the following major industrial cluster) (ZCH, 2019). Thus, it has developed as a critical industrial cluster for the UK as a significant contributor to the domestic economy, with £18 billion being generated in the region each year and 360,000 jobs created in industries such as refining, petrochemicals, energy production and manufacturing, and related supply chains (ZCH, 2019; HICP 2023).

There are initiatives, projects and collaborations between industry, academia and government institutions working together to decarbonize the region. Major project is Zero Carbon Humber (ZCH) (Drax Group PLC 2022a).

Zero Carbon Humber is a carbon capture and storage (CCS), hydrogen production and transmission project, combining into one vision projects such as: H2H Saltend, Keadby 4 and Keadby Hydrogen Power Station, Drax BECCS power plant. In addition, ZCH has partnerships with Equinor, British Steel, National Grid and is part of the Northern Endurance Partnership (a collaboration with Net Zero Teesside) (Drax Group PLC 2022a).

*3.2.5.1.1. Humber zero.* Humber Zero is an industry decarbonization project in partnership with Phillips 66 Ltd and VPI Immingham, located in the North Lincolnshire. The project will remove up to 8 Mtpa of $CO_2$ within the next few years from VPI Immingham combined heat and power station (approximately 3.3 Mtpa of $CO_2$) and Phillips 66 Humber Refinery (approximately 3.8 Mtpa $CO_2$; it's the only European producer of synthetic graphite) (Wood PLC, 2022). Planned start of carbon capture is 2026 (Wood PLC, 2022). Following, $CO_2$ will be transported to offshore storage site in the North Sea, 120 km off the coast (Humber Zero Homepage, 2022a).

Additionally, as part of the project, a new facility next to the current VPI Immingham power plant will produce blue hydrogen with a production capacity of more than 170,000 tonnes per year. One of the gas turbines at the VPI Immingham CHP will be converted to run on hydrogen (Humber Zero Homepage, 2022b).

*3.2.5.2. STOREGGA and the Acorn Project.* Storegga is a research & development company, a developer of carbon capture, transport, and storage technologies. The company's origins date back to 2007, when the $CO_2$DeepStore was founded in Aberdeen, Scotland. Then in 2013, the company became the Pale Blue Dot, contributing to the development of the Acorn carbon storage site in the North Sea. Finally, Storegga acquired the Pale Blue Dot in 2020 (Storegga Group, 2022a).

Nowadays, it has a number of projects dedicated to research and development of the CCS chain, blue and green hydrogen, as well as other projects, in order to help achieve the UK government's 2050 climate targets.

The Acorn Project (Storage and Transportation, Hydrogen, Carbon Capture) is the top project led by Storegga, in partnership with Harbour Energy and Shell Limited (Alcalde et al., 2019; Allen et al., 2020). It is being supported by the UK government and the EU financing (Shell UK Ltd 2023). The main objectives of the project are to create the essential CCS and hydrogen infrastructure in the North East Scotland (the Scottish Cluster) to advance the UK government's climate goals by decarbonizing carbon-intensive industries (Alcalde et al., 2019; Allen et al., 2020; Acorn, 2022).

As shown on Fig. 7 Storegga is also leading other major projects. Together with Mitsui & Co., Ltd, Storegga is planning to build the UK's first DAC installation, with a small footprint (100 acres) in the area of the Scottish Cluster, and utilizing a storage infrastructure of the Acorn project. The unit is expected to be capable of capturing between 0.5 to 1 million tons of $CO_2$ per year. The project was awarded a £249,000 grant by the UK Government's BEIS (Storegga Group, 2022b).

Moreover, in May 2022, Storegga, and Scottish Power, announced plans to build a 50 MW green hydrogen plant to be used in heating processes at nearby whiskey distilleries, include global producers Diageo, Glenmorangie, and Whyte & Mackay (Storegga Group 2022d). Furthermore, about 30 % of the UK's natural gas is produced at St. Fergus (Shell UK Ltd 2023), while the Acorn Hydrogen intends to use natural gas as a feedstock for hydrogen production where more than 95 % of the carbon emissions from the production process will be captured and stored in the Goldeneye reservoir (Storegga Group 2022c).

*3.2.5.3. Drax power station with beccs.* BECCS stand for Bioenergy Carbon Capture and Storage and all over the world there are few operating BECCS plants, with most of them located in the USA (The High Level Panel 2022).

Drax Power Station located in Selby, North Lincolnshire, had six boilers, four of which have now been converted to biomass, with two coal units ceased commercial operation in March 2021. Its wooden biomass capacity is approximately 2595 MW (Drax Group PLC, 2022b; The SCCS Group 2022; IEA, 2021b).

In 2019 first pilot facility with C—Capture (patented solvent-based carbon capture technology, developed by Department of Chemistry at the University of Leeds (C-Capture Ltd 2022)) began operational with capacity to capture a tonne of $CO_2$ a day, during the pilot stage. Further, in 2020 Mitsubishi Heavy Industries installed a pilot scale facility which

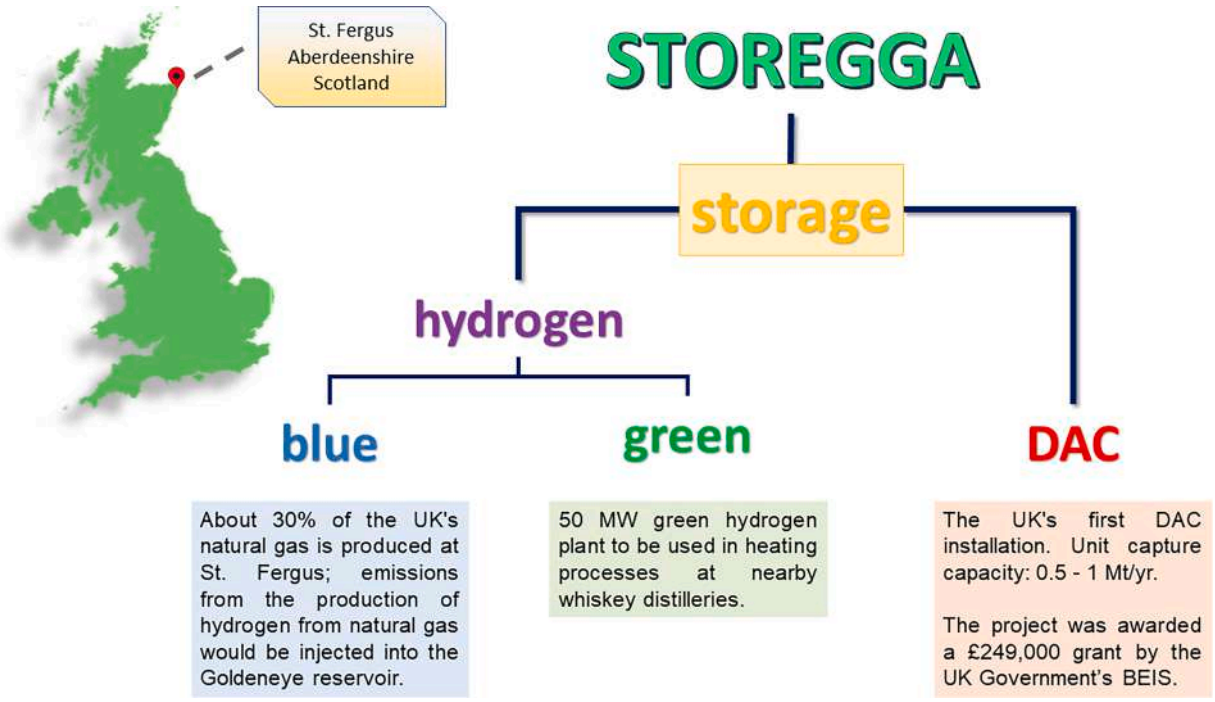


**Fig. 7.** the main areas of Storegga's operations (Storegga Group, 2022b, Storegga Group, 2022c, Renews Ltd 2022, Storegga Group, 2022d).

resulted in the long-term agreement for the capture technology - Advanced KM CDR process™ (Drax Group PLC, 2021).

Noteworthy is the three-month trial started in May 2022 to capture $CO_2$ using metal-organic frameworks (MOFs) technology. Project was held in collaboration between Drax with the University of Nottingham and the Promethean Particles (University of Nottingham, 2022; Drax Group PLC, 2022c).

Moreover, in 2018 there was held a dialogue between Drax and the British Beer & Pub Association in advanced to utilise part of captured $CO_2$ for fizzy drinks production (Drax Group PLC, 2018).

Based on Drax's experience with BECCS, Donnison et al. (2020) explored the possibilities that would arise with the development and implementation of BECCS in other locations within the UK, taking into account the impact of these units on social welfare parameters along with the relationship linking location to this parameter (Donnison et al., 2020).

*3.2.5.4. Keadby 3 ccs project.* The second project being developed by the Scottish & Southern Energy (SSE) and Equinor is the Keadby 3 CSS, which is planned to capture at least 1.5 million tons of $CO_2$ per year (SSE Thermal PLC, 2022a). Developed as part of the decarbonization of the East Coast Cluster and Zero Carbon Humber projects - supporting the decarbonization of the UK's largest carbon-intensive industrial region (SSE Thermal PLC, 2022a).

The Keadby power station, with a 910 MW CCGT unit, is located west of Scunthorpe in the North Lincolnshire. It is connected to a common CCS infrastructure via the East Coast Cluster with a storage site under the southern North Sea (SSE Thermal PLC 2022b).

*3.2.5.5. Keadby hydrogen power station.* One of four eco joint-project between Equinor and the SSE Thermal is Keadby Hydrogen Power Station. Developed as part of decarbonization the East Coast Cluster. Keadby Hydrogen Power Station would generate 100 % carbon-free power, with peak demand of 1800 MW hydrogen fuel which potentially account for a third of the UK's Government 5 GW blue hydrogen production target (SSE Thermal PLC, 2022c). Its launch is planned before 2030 (SSE Thermal PLC, 2022d).

*3.2.5.6. Peterhead CCS project.* In 2011 the Peterhead Power Station was chosen by the UK government as a potential candidate for the £1bn pilot project grant but 4 years later it was announced that the grant for developing project was no longer available (Tucker and Tinios, 2017). The project were postponed until 2019 when the UK commitment to be a net-zero economy by 2050 (The UK Government 2019), and brought the Peterhead Project back to life.

The Peterhead CCS Project is a joint project between the Scottish & Southern Energy and Shell company, as well as its the key customer for the Acorn Project, with the planned start of operation in the '20s (SSE Thermal and Equinor, 2022). The Peterhead Power Plant is the Scotland's major thermal power station, located in Aberdeenshire. It consists one turbine Combined Cycle Gas Turbine (CCGT) unit with a total electricity output of up to 910 MW (SSE Thermal PLC, 2022e, Shell UK Ltd 2015). Construction of Carbon Capture Unit has been planned to start in 2023 if government permissions will be granted. Approximately it will capture 1 mln tonne of $CO_2$ per year from CCGT unit flue gases, using amine-based technology developed by Shell (Cansolv®) (Shell UK Ltd 2015). Captured $CO_2$ will be stored in the Goldeneye reservoir in the North Sea, with an operational period estimated between 10 and 15 years (SSE Thermal and Equinor, 2022, Shell UK Ltd 2015).

*3.2.5.7. Teesside.* The Net Zero Teesside (NZT) is project developed in association with the Northern Endurance Partnership (NEP), as well as with Zero Carbon Humber (Fig. 8). In its current status it look forward to take the Final Investment Decision (FID) in early 2023, with first injection planned for 2026 (The UK Government, 2021b).

The Teesside Cluster is part of the East Coast Cluster. Teesside industries account for 5.6 % domestic industrial emissions, and its home for 5 from the top 25 UK's $CO_2$ industrial emitters (Howe, 2021). Combined project NZT and ZCH will allow to decarbonise up to 50 % of the UK's industry (Net Zero Teesside OGCI, 2022a). As well as ZCH project it will become carbon hub for combined industry and power $CO_2$ emission sources.

*3.2.5.8. Blue hydrogen projects.* Among detailed above projects there are also several ongoing projects, presented in Table 6, focus on merging hydrogen production from natural gas through the process of methane

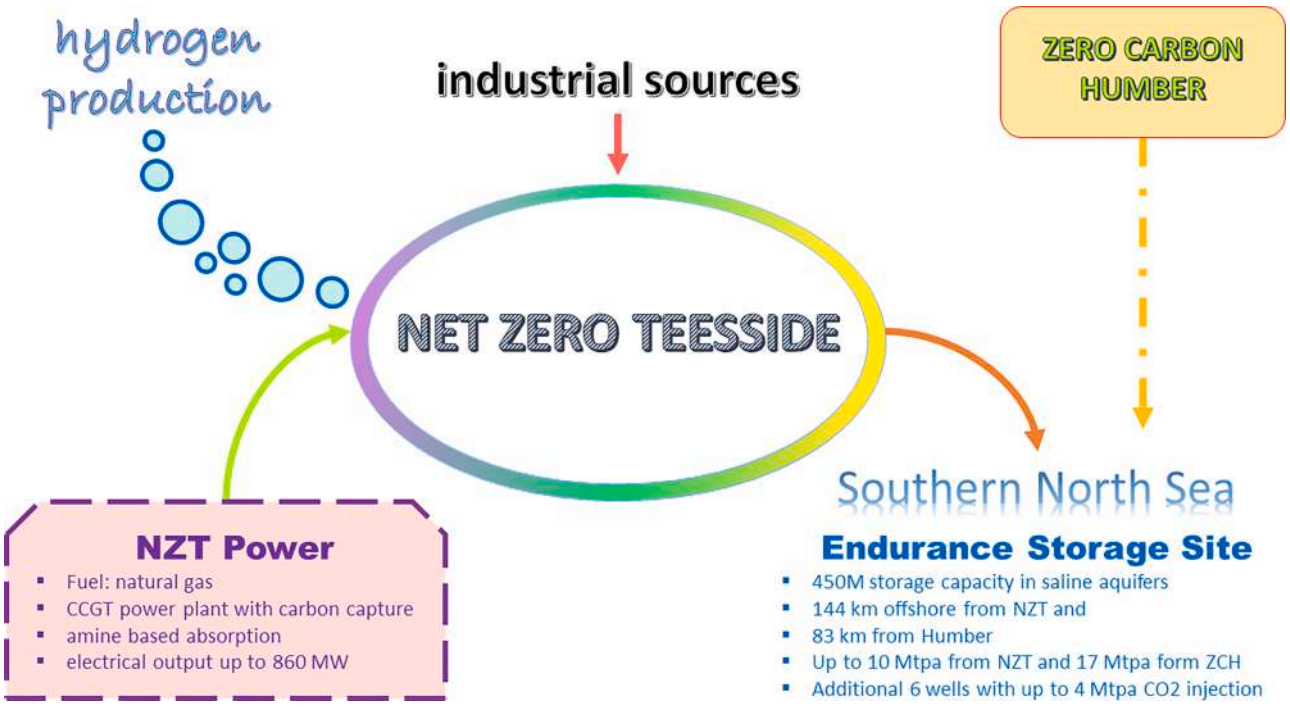


**Fig. 8.** The Net Zero Teesside project in numbers - author's compilation based on (The UK Government, 2021b, Net Zero Teesside OGCI, 2022a, McCormac, 2020, Net Zero Teesside OGCI, 2022b).

reforming combined with CCS.

#### 3.2.6. *Overview summary*

The development of a numerous CCUS projects along with a wide range of storage options, coupled with the development of nuclear power, hydrogen, RES and multi-million pound government funding projects makes the UK a country whose climate ambitions are seems to moving towards realization in time.

### 3.3. *The netherlands*

#### 3.3.1. *Introduction*

The Netherlands is one of the founder member of the European Union as well as the Organisation of Economic Cooperation and Development (OECD), and the International Energy Agency (IEA).

Since 1992, when the Dutch government signed the United Nations Framework Convention on Climate Change, through the Kyoto Protocol (1997) and the Paris Agreement, the Netherlands has committed to several international agreements on climate change mitigation and environmental protection. As part of the European Energy and Climate Package, the Netherlands established targets for: (1) a 14 % share of RES in gross final energy consumption, (2) energy efficiency targets of no more than 2.186 PJ of final energy consumption and no more than 2.541 PJ of primary energy consumption, (3) a 16 % reduction in non-ETS emissions by 2020 compared to 2005 levels (extended as the reduction level was 17 % in 2018) (IEA, 2020a).

On May 28th 2019, the Dutch government ratified the Climate Act, establishing climate targets to reduce GHG emissions in the Netherlands by 49 % by 2030 and 95 % by 2050 in comparison to 1990 levels. As part of the Climate Act, there are: the Climate Plan, the National Energy and Climate Plan (NECP) and the National Climate Agreement (Ministerie van Economische Zaken en, 2019).

The government is obliged to establish a Climate Plan every 5 years for a period of 10 years (first was adopted in 2020 for period 2021–2030). This identifies and updates measures to ensure climate targets will be meet (Ministerie van Economische Zaken en, 2019).

The National Climate Agreement was elaborated through the Dutch Polders system (collaboration system). The agreement identifies pathways and measures to achieve the climate targets, focusing on 5 sectors: electricity, industry, the built environment, mobility and agriculture, and the environment (Ministerie van Economische Zaken en Klimaat 2019).

In addition, the Dutch government is developing a new energy law to modernise outdated electricity and natural gas regulations as a part of

**Table 6**
Blue hydrogen with CCS projects.

| Project name | Funding | Localization | Additional information's | Ref. |
|---|---|---|---|---|
| Acorn Hydrogen Production | Storegga | the Scottish Cluster (Aberdeenshire) | Planned capacity for Acorn Hydrogen Unit units: Unit 1 200 MW; Unit 2; 200 MW, Unit 3: 300 MW | (Storegga Group, 2022c, One-of-a-kind project that will provide a clear pathway to support the UK to meet its net-zero targets 2022, Dumenil, 2021) |
| HyNet | multi-partner consortium led by the Eni UK | the North West England, the North Wales | 3 TWh annum by 2025, rising to 30 TWh by 2030; PSA unit for carbon capture | (HyNet North West 2022, HyNet North West 2021, Eni, 2022) |
| H2H | Equinor | the Humber Cluster the Saltend Chemicals Park | 600 MW auto thermal reformer (ATR) | (Rogers, 2002, Equinor ASA, 2022) |
| H21 | Equinor, Cadent | Leeds City | 4 SMRs reactors with total production capacity of 1025 MW located at Teesside; 1.5 mln tonnes of $CO_2$ storage annum | (H21 \| FAQs 2022, Sadler et al., 2008, The H21 Leeds City Gate Project. H21 Executive Summary Report, 2016.) |

the implementation of the Climate Agreement.

According to the combined Hydrogen Strategy and National Climate Agreement, the Dutch government aiming at approximately 500 MW installed green hydrogen production capacity by 2025, scale up to 3–4 GW by 2030 (Ministerie van Economische Zaken en, 2020). Additionally, the blue hydrogen projects receive support by merging it with CCS. For green hydrogen development Dutch government planning to allocate existing Climate Budget funds (approximately €35 million per annum) for this purpose (Ministerie van Economische Zaken en, 2020).

### 3.3.2. GHG emission

In 2019 total GHG emissions (excluding LULUCF) were 18 % lower in compare to base year 1990 (Ruyssenaars et al., 2021). In the same period of time (1990–2019) the Netherlands economy growth more than 80 % (Ruyssenaars et al., 2021). Energy consumption is identified as majors source of GHG emissions (Fig. 9), accounted for 83 % of it (Eurostat Data browser 2023, Ruyssenaars et al., 2021). In 2019 energy sector was responsible for 25.21 % emission, followed by international shipping (15.82 %) and industry (15.53 %) (more in supplementary materials: Table 2). Leading contributors to industrial GHG emissions in 2019 were chemical industry (category 1A2c, 12.96 Mt $CO_2$ eq., approximately 5.59 % (Ruyssenaars et al., 2021)) and iron and steel production (category 1A2a, 4,90 Mt $CO_2$ eq., approximately 2.11 % (Ruyssenaars et al., 2021)). Additionally, five major Dutch refineries exporting approximately 50 % of their products to the EU market (Ruyssenaars et al., 2021). Furthermore, in GEP major part took natural gas (58.57 %) (Eurostat Data browser 2023), followed by RES on second place (18.87 %) (Eurostat Data browser 2023) and solid fossil fuels (14.66 %) (Eurostat Data browser 2023), yet coal is successively decreasing (from 2018 to 2019 by 22 %) (Eurostat Data browser 2023). This gave the Netherlands the 7th place as the European GHG emitter, but the 1st place in percentage share of fossil fuels in TES and the 4th place in percentage share of fossil fuels in GEP (Table 3; additional information in supplementary materials: Tables 2-4).

### 3.3.3. Energy-intensive industries overview

In 2019 in Industrial Processes and Product Use emission category (CRF2), mineral industry was responsible for 4.11 % of a total domestic GHG emissions (Ruyssenaars et al., 2021), with following sectoral breakdown: mineral industry 12.04 % (with cement production account only for 0.55 % of it) (Ruyssenaars et al., 2021), chemical industry 68.30 % (Ruyssenaars et al., 2021) and metal industry 1.86 % (Ruyssenaars et al., 2021).

### 3.3.4. CCUS possibilities

On December 2nd 2022 the Dutch government introduced a multi-year energy and climate infrastructure programme (Meerjarenprogramma Infrastructuur Energie en Klimaat – MIEK), in which it identified several industrial complexes together with the key CCUS projects that could be leveraged to transform the Netherlands to net-zero emissions, achieving the Dutch climate targets (van Algemene Zaken, 2023, Ministerie van Algemene Zaken 2022).

According to the governmental documents the Netherlands has storage capacity in gas fields (current and former) estimated at 2.7 Gt to 3.2 Gt (excluding the Groningen gas field with approximately 9 Gt) of which about 1.5 Gt to 2 Gt is onshore and about 1.2 Gt is offshore (The Dutch Government 2015). In case of storage capacity of the Groningen gas field it is still uncertain how much of this capacity will be available for $CO_2$ storage (The Dutch Government 2015).

### 3.3.5. CCUS projects

*3.3.5.1. Aramis.* In collaboration with TotalEnergies, Shell, Energie Beheer Nederland (EBN) and Gasunie, the Aramis transport and storage project was created (TotalEnergies 2023). The Aramis collection hub is located in Maasvlakte in the Port of Rotterdam, with storage site 200 km away – in the Dutch North Sea. The $CO_2$ will be stored approximately 5 Mtpa, in depleted offshore gas fields with 400 Mt capacity (Aramis 2022). Planned start of facility is set in between 2026 and 2027 (Aramis 2022). The philosophy guiding the project is open access for industrial

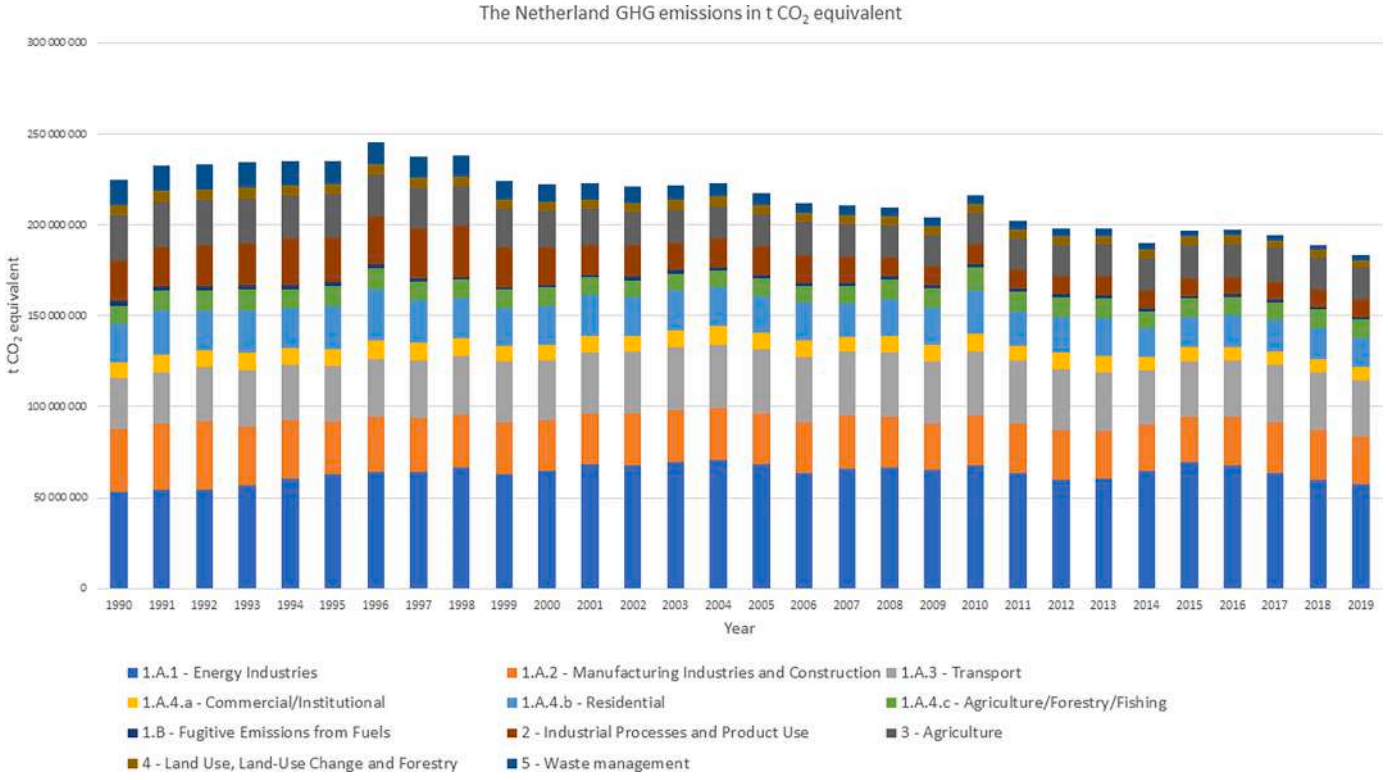


**Fig. 9.** The Netherland GHG emissions (based on the Eurostat data).

customers that can be added incrementally to the Aramis system (Aramis 2022). Project was chosen in MIEK as key in decarbonization the Schelde-Deltaregio Cluster (Zeeland) and as a part of the Carbon Connect Delta (Ministerie van Algemene Zaken 2022).

*3.3.5.2. AVR-Duiven.* The AVR-Duiven started construction of $CO_2$ capture facility in early 2018, finished one year later and started operation in October 1st 2019 (AVR Afvalverwerking, 2019). For capturing process is use monoethanolamine (MEA) as a solvent, which removes up to 85 % of $CO_2$ from flue gas (AVR Afvalverwerking, 2019, Lim et al., 2023, AVR Afvalverwerking, 2022). Next, captured $CO_2$ is prepared for transport by compression and cooled down to store in tanks as liquid gas. $CO_2$ is distributed by the AVR partner – Air Liquid – and it's primary used in horticulture (approximately 60 ktpa), as crops growth promoter, and as a coolant in fire extinguishers. In future, AVR is aiming to capture 800 ktpa with further development of next facility in Rotterdam (AVR Afvalverwerking, 2019, AVR Afvalverwerking, 2022).

*3.3.5.3. H-Vision.* The H-Vision is a swift solution for cut-off GHG emissions in the Rotterdam region, as it produces hydrogen from industry residual gases (initially – refineries). Post-refining residual gases are piped to a central hydrogen plant. $CO_2$ from this process is captured and storage in depleted reservoirs in the North Sea (but could be also redirected into utilisation facilities e.g. for methanol production) (H-vision 2022). The first plant will be completed by late 2026/early 2027, with approximately capacity of 750 MW. Second facility can increase total capacity up to 1500 MW by 2032 (H-vision 2022). The H-Vision solution allows not only to supply high volumes of hydrogen for industry sector as well as power&heat, in order to meet ambitious goals of the Dutch Climate Agreement but also enables Rotterdam to become first world low-carbon hydrogen port hub.

The project was identified in the MIEK as one of the key ones for the Rotterdam-Moerdijk Cluster (Ministerie van Algemene Zaken 2022).

*3.3.5.4. Porthos.* Porthos stands for the Port of Rotterdam $CO_2$ Transport Hub and Offshore Storage and its led by the Port of Rotterdam, Gasunie and EBN (Porthos $CO_2$ 2022). Its chosen in MIEK for decarbonization the Rotterdam-Moerdijk Cluster (Ministerie van Algemene Zaken, 2022). Porthos aim to store 2.5 Mtpa for 15 years operation, in depleted gas field of porous sandstone with capacity approximately 37 Mt, 3 km beneath the North Sea seabed (Porthos $CO_2$ 2022, Hong, 2022). Transport of $CO_2$ will be via pipeline – 30 km onshore construction and approximately 22 km offshore from the compressor station at Maasvlakte (Veltman 2022). Project will contribute to reduce ca. 15 % of the Dutch GHG emissions (Ministerie van Algemene Zaken 2022, Veltman 2022, Porthos, 2022).

Nowadays, project is in advance development stage, with planned start of injection set on 2025. It's got delayed due to political issues, focusing on permit procedures and awaiting to get FID in 2023. Porthos got 2 grants from the European Commission: €6.5 mln for FEED Phase in 2018, €102 mln for realisation of infrastructure in February 2021 (Porthos $CO_2$ 2022).

In contrast to similar project ROAD (the Rotterdam Storage and Capture Demonstration Project – cancelled (Read et al., 2019, Akerboom et al., 2021), more about project can be found in the literature (Read et al., 2014)) Porthos is focused on decarbonization industries with little alternatives such as oil refineries and chemical industry.

### 3.3.6. Overview summary

The Netherlands is an important European hub for natural gas and oil, as their geographical localisation makes them a natural transit and trade hub with extensive port infrastructure and extensive cross-border and offshore oil and gas pipelines and electricity connections. Although, the Groningen field earthquakes in January 2018 and May 2019 made the Netherlands a net importer of gas in 2018 (OGJ editors, 2019). After these events, public opinion strongly pushed the Dutch government to take a decision to phase out the Groningen field in the coming years (Rijksoverheid 2022). Additionally, the Netherlands is shifting away from natural gas to hydrogen and green fuels in its zero-carbon plan e.g. the Natural-gas Free Districts Programme, which forbids new gas connections from 2018 and further supports for transition into renewable energy (IEA, 2020).

On the other hand, as Akerboom et al. (2021) mentioned, CCS in the Netherlands has long journey from workbench, by pilot scale into commercial (e.g. AVR-Duiven). Not only public opinion, but government support caused hindered for several project over past 2 decades. Moreover, utilisation possibilities are rather small in compare to storage potential offered by depleted gas fields in the North Sea (Akerboom et al., 2021).

Moreover, as Ravi et al. (2017) point out, that with capture & compression major contribution to cost, in the Netherlands with different transport scenarios, there are possibility to capture approximately 54 Mtpa and storage possibility for 25 years, with price vary between €47.8 billion and €52.4 billion for different case studies (Ravi et al., 2017). Moreover interesting scenario was proposed in paper, assuming central capture unit can be considered as cost-effective, even with necessity of pre-treated flue gas transportation (Ravi et al., 2017).

Additionally, the Netherlands economy is facing few major issues: (1) it is home for large amount of emission-intensive industries such as oil-refining or chemical industries, (2) it remains heavily-reliant on fossil fuels, (3) key-source is natural gas mainly extracted from Groningen field. With ambitious government zero-emission climate targets until 2050, this poses a threat to the national economy (IEA, 2020).

Considering the intensive contribution of industry to GHG emissions, as well as the high dependence on fossil fuels and the challenging climate policy, further development of CCUS projects, accelerating the development of a hydrogen and RES could be crucial to achiev the climate goals.

## 3.4. Germany profile

### 3.4.1. Introduction

After the Kyoto Protocol (signed in 1998), Energiewende stands for the policy foundation in Germany's energy transformation and it was launched as part of the Energy Concept of Germany in 2010. The key principles were to expand renewable energy, increase energy efficiency and phase out nuclear power. Within this framework, the Germany government set the first key targets and pathways for them. More than a decade later, the Energiewende is still shaping Germany's climate policy (IEA, 2020).

It has influenced the shaping of the Climate Action Programme 2020 (Aktionsprogramm Klimaschutz 2020) that was approved in December 2014 (Ministry for the Environment 2014) as well as followed by it the Climate Action Plan 2050 (Klimaschutzplan 2050) (Ministry for the Environment 2016).

On November 16th 2016 Germany strategy was redefined in the Climate Action Plan 2050 by replacing the Climate Action Programme 2020. It set up long-term targets, specific for each economy sector goals, overall aimed at progressive GHG reduction by 40 % until 2020, 55 % by 2030 (upgraded to 65 %), 70 % by 2040 and 80–95 % by 2050 (Ministry for the Environment 2016).

For energy sector the Climate Action Plan 2050 set two main targets: 80 % share of RES by 2030 and progressively phase out fossil fuels and nuclear energy. On the other hand, due to the energy crisis in Europe in 2022, the German government have been planning to extend the operation of nuclear power plants (Partridge, 2020, Deutsche Welle 2022, BBC News 2022). In the case of plan for the industry sector, it set a target of halving emissions by 2030, by implementing CCUS solutions for subsectors such as: steel, chemical, cement production (Ministry for the Environment 2016).

Additionally, the establishment of the National Hydrogen Strategy

(Nationale Wasserstoffstrategie) is another step toward closing fossil-fueled power plants, as part of the fulfilment of Germany's decarbonization policy (Energiewende) and in its involvement in the Paris Agreement (Ministry for the Environment 2020).

### 3.4.2. GHG emission

In 2019 Germany was the first EU economy in total net GHG emissions (with international transport inc.), with the 7th place in percentage share of fossil fuels in TES (28,32 % share of fossil fuels in GEP) (Eurostat Data browser 2023). On the other hand, RES account for 40.68 % in GEP (Eurostat Data browser 2023). Divided by sectors significant contribution in Germany GHG emissions (Fig. 10) is account for energy sector (31.48 % of total net emission), followed by industry (22.40 %) and domestic transport (20.20 %) (additional information in supplementary materials: Tables 2-4).

Over the period 1990–2019, total GHG emissions (calculated as $CO_2$ equivalent) decreased by 35.1 % (Federal Environment Agency 2021). GHG emissions profile reflects the country's high industrialization (Federal Environment Agency 2021).

### 3.4.3. Energy-intensive industries overview

In 2019 in Industrial Processes and Product Use emission category (CRF2), mineral industry was responsible for 7.31 % of total domestic GHG emission (Federal Environment Agency 2021), with following sectoral breakdown: mineral industry 32.48 % (with cement production account for 68.44 % of it) (Federal Environment Agency 2021), chemical industry 10.79 % (Federal Environment Agency 2021) and metal industry 30.43 % (Federal Environment Agency 2021).

### 3.4.4. CCUS possibilities

According to Höller and Viebahn (2011), and Esken (2010) Germany estimated storage capacity is approximately 5 Gt with potential range of 5 up to 18.6 Gt, although depending on the authors compiled in Esken's (2010) study, these values can range from 3 to 44 Gt (Höller and Viebahn, 2011, Esken et al., 2010).

On the other hand, public opinion in Germany is in opposition to $CO_2$ sequestration. In 2019 Chancellor Angela Merkel brought back topic of it, pointing out necessity of CCS, especially in industry sector as it lacks other swift decarbonization solutions (Cameron, 2020, Wettengel, 2019).

Nowadays, in Germany political debates on CCUS are still ongoing (Vögele et al., 2018), with the main indication of this technology as a remedy for industries where other forms of decarbonization would be economically unjustifiable, e.g. steel, chemical, cement industries (Dütschke and Duscha, 2022).

### 3.4.5. CCUS projects

*3.4.5.1. H2morrow.* H2morrow is a pilot CCOS type of project (Carbon Capture and Offshore Storage), announced in 2019 and led by Equinor and Open Grid Europe (OGE) (Equinor ASA 2019). Natural gas imported from Norway will be reformed in Germany as a supply for the blue hydrogen domestic demand (especially for industrial cluster in the North Rhine-Westphalia). Furthermore, captured $CO_2$ will be transported by maritime transport into storage site located in the North Sea. Its planned to supply approximately 8.6 TWh of hydrogen per annum, which is considered as avoided carbon emission up to 1.9 Mtpa (Equinor ASA 2019).

*3.4.5.2. $H_2$ercules.* The $H_2$ercules project was drafted by OGE in partnership with RWE, with estimated cost of the project implementation is set about 3.5 billion euro (Open Grid Europe GmbH 2023).

In the $H_2$ercules project, 1 GW electrolysers for green hydrogen production with storage facilities will be connected to approximately 1500 km pipeline infrastructure (part of it will be upgraded natural gas transmission infrastructure), further connected to industrial customers in the western, eastern and southern Germany, as well as to an international customers (Open Grid Europe GmbH 2023, RWE Aktiengesellschaft 2022). Due to the planned involvement of the Dutch, Belgian, Czech and Norwegian infrastructures, this will contribute to

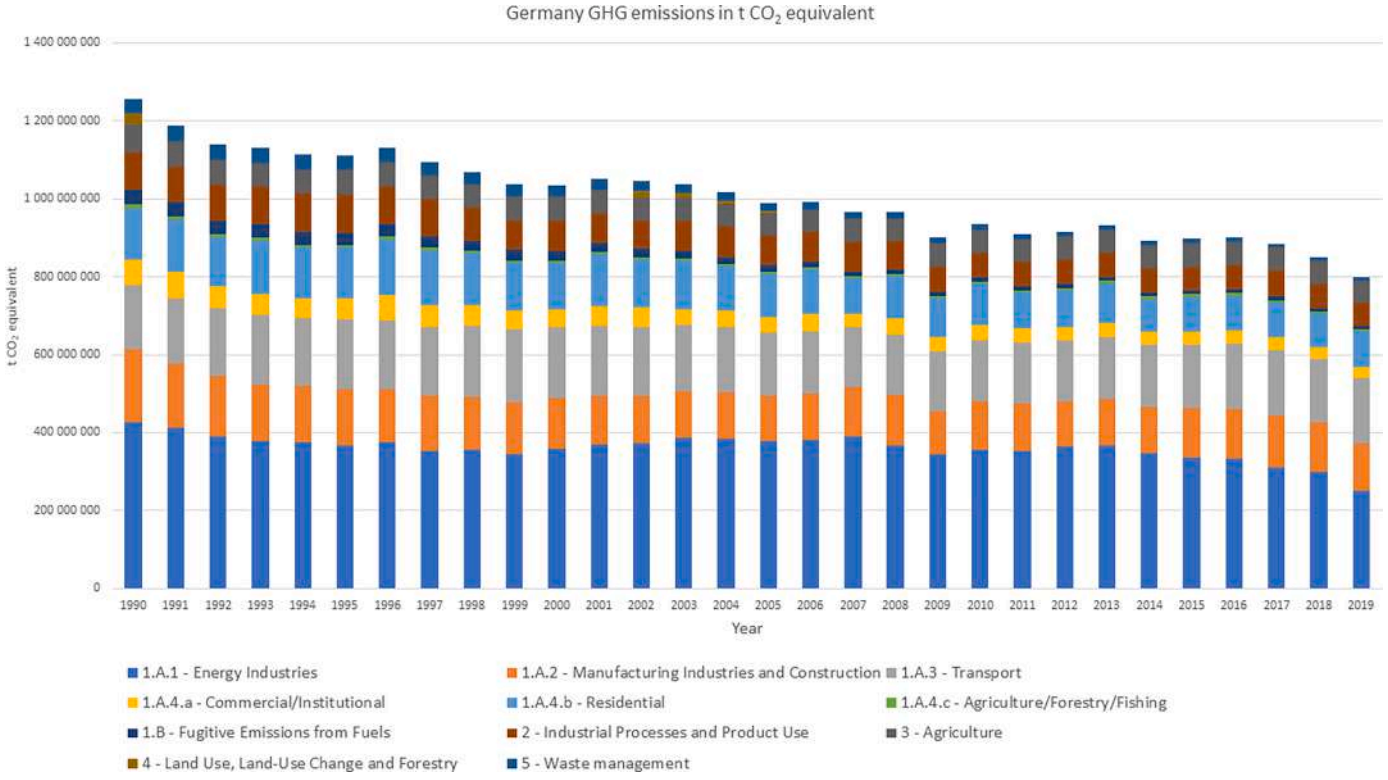


**Fig. 10.** Germany GHG emissions (based on the Eurostat data).

development and expansion of the European hydrogen market (RWE Aktiengesellschaft 2022).

Additionally, natural gas power stations (with joint capacity about 2 GW) might be converted into hydrogen fuel as further development of the project (Open Grid Europe GmbH 2023).

*3.4.5.3. Westküste 100 – deep circular economy.* Westküste 100 project was submitted on April 2019, by Raffinerie Heide (project coordinator). This multi-industry partnership involved companies such as: EDF Germany, Holcim Germany, OGE, Ørsted but academics as well (Westküste University of Applied Science) (Westküste 2022a). It is planned to install over period of 5 years a 30 MW electrolyser, for green hydrogen production, supplied with electricity from offshore wind farm (Westküste 2022b). During the research it was also examined to use oxygen produced during process, to be supplied to cement plant for oxy-fuel combustion. $CO_2$ from that process would be captured and used for biofuels production such as methanol or dimethyl ether (DME) (Gray et al., 2021). Additionally, Westküste 100 project is also aiming to supply green fuel for aviation as well as recycling residue heat from industry processes (Westküste 2022b, Gray et al., 2021).

On April 7th 2021 project received funding of €6.5 mln form the Federal Ministry of Economic Affairs and Energy (BWMi) to expand and reinforced a cavern for hydrogen storage (Westküste 2022a).

### 3.4.6. Overview summary

As Dickel (2020) mentioned, Germany's green transition should consider transformation processes with a blue hydrogen as a temporary fuel, with an ultimate transition to a green hydrogen, the volumes of which are not sufficient at the moment, and to provide a key factor in the 2030 climate targets (Dickel, 2020).

Moreover, Schmid and Hahn (2021) have made detailed studies of the potential for the use of captured $CO_2$ for disposal in various industrial sectors in Germany, estimated demand of about up to 234–423 Mt of $CO_2$ annually (Schmid and Hahn, 2021).

Furthermore, the development of a clear framework for $CO_2$ sequestration seems to be essential not only for high energy-demanding industries but also as leverage for the transition from a blue into a green hydrogen.

## 4. Discussion

### 4.1. Methodology

The applied methodology allowed to look at a vast spectrum of environmental indicators combined with each other.

One of the main observation from applied benchmarking methodology is that high contribution to GHG emissions or vast impact of energy and/or industry sector on domestic GHG emissions was not always combined with the popularity of CCUS development in certain member states (e.g. Germany was the main contributor in the EU GHG emissions but has a lower amount of CCUS projects in development than the United Kingdom which is second in total net emission criteria).

Further finding was that few countries which were in the top 10 among chosen 4 benchmarking categories were without a single CCUS project (e.g. Cyprus, Malta, Estonia) or their share of fossil fuels in total domestic net emissions was significant but on the other hand, energy and/or industry sectors had not so significant impact on total domestic GHG emissions (e.g. Malta or Cyprus had the highest% contribution of fossil fuel share in GEP, but energy sector has no major impact on domestic GHG emissions).

Last but not least, the vast majority of the EU member states depend on natural gas or oil (with slowly, but steady increase of RES in TES) with solid fossil fuels mainly dominate in share of the total net emission among the EU-15 countries.

Furthermore, if other selection criteria were taken into consideration, comparisons could be made between completely different countries. The following group of countries seem promising for further study: Bulgaria (energy supply: 48.36 %, industry: 28.61 %), Cyprus (31.40 %, 16.81 %), Czech Republic (39.16 %, 19.26 %), Estonia (54.54 %, 8.87 %), Finland (38.14 %, 27.97 %), Germany (31.48 %, 22.40 %), Greece (34.42 %, 17.17 %), Romania (36.43 %, 30.74 %), Slovenia (38.50 %, 23.17 %), Sweden (36.8 %, 62.4 %) – for all information see supplementary materials.

Thus, according to findings and further conclusions, it's important for a holistic and comprehensive overview during applying benchmarking for such analysis. Further development or merging of benchmarking methodology with statistical analysis could provide some further interesting results. Thus, benchmarking was a decent methodology for a general overview. But to pick up comparable countries is needed to be done a vast and comprehensive overview of several factors with additional in-depth country environmental profile analysis.

Lastly, noteworthy may be the difference between the percentage share of fuels or certain industry sectors presented in the Eurostat database and in national inventory reports - both of which were used in this paper. The difference is due to the differentiation of a variable defined as domestic emission (in the case of this paper authors referred all calculations to total net emission with international transport).

### 4.2. CCUS – discussion over study

CCUS technology is indicated not only by the IPCC or the EU as a path to climate neutrality. It is also a solution rescuing countries whose energy sector and other energy-intensive industries are heavily dependent on fossil fuels. Moreover, it is an opportunity for countries - whose main export commodity are fossil fuels - to continue exploiting these fields.

According to the Zero-Emission Platform – the EC's technical advisor – there are 66 on-going CCUS projects all-over the EU and the European Economic Community (EEC), with most of them about $CO_2$ transport and storage or implementation in industry (Zero-Emission Platform, 2023a). However, the ZEP website doesn't consider all existing projects – only those that were submitted (e.g. lack of the Poland's FLEXIS project). On the other hand, using only this data tendency could be seen as projects focused on CCS are in majority.

A number of factors may be responsible for this state of development. The foremost of these is the simplicity of developing projects dedicated to the transport and storage of $CO_2$, which can use existing infrastructure of the exploitation and transport of natural gas. In addition, $CO_2$ utilisation technology requires recipients for captured gas, but may provide a cost-effective solution (Tcvetkov, 2021, Lin et al., 2022, Vikara et al., 2018).

Thus, by using economic and environmental analysis tools, e.g. such as Life Cycle Assessments (LCA) it is possible to assist the decision-making process in identifying an optimal solution for captured $CO_2$.

In turn, the increased interest in the development of CCS in industry rather than in energy sector may be due to the zero-carbon objectives for which member states are embracing a policy of phasing out fossil fuels. Implementing CCS technology as an effort to sustain fossil-fuel-based power generation appears to be an unnecessarily cost-effective path, given the opportunities offered by a hydrogen, nuclear or renewables-based transition.

Furthermore, even for those member states whose energy sector is heavily based on fossil fuels, major consideration has to be taken with the issue of the average age of the majority of solid fuel power plants in operation in Europe (more information could be find in literature: (Farfan and Breyer, 2017)). A temporary commitment to build new units with a CCS-Ready technology seems to be a solution, but this is only a backstop to the net-zero emission transition time period. With the average construction time of a power plant units, the 20s of this century is the last time for this type of plant to be built if the 2050 target is to be met.

Further, in the UK, it is planned that CCUS will capture from 20 up to 30 Mtpa of $CO_2$ per year by 2030, which corresponds to 4.04.-6.06 % of the UK's total net emission with international transport in 2019. On the other hand, the Netherlands is focusing on a scenario with hydrogen generation supported by CCS. Although CCUS in both cases is not the solution responsible for 100 % of the national reduction, it nevertheless takes a large share of the overall decarbonization, and its impact on climate targets cannot be ignored. In contrast, technology is at hiatus in Germany, which is betting more heavily on the development of a RES in the power sector than on CCUS (IEA 2020b). Legislative problems are also an issue in Germany, where CCS has so far played a negligible role in the transformation of the economy (Krämer, 2018, Otto et al., 2022).

On the other hand, the Polish government finally made a revision of the legislative package for underground $CO_2$ storage, which was until very recently important bottleneck for CCS development. After that, CCUS with an intensive deployment programme ($CO_2$ to geothermal, as well as CCUS pathway for decarbonization the Upper Silesia industrial cluster seems to have considerable potential) can leverage efforts towards the polish zero-net emission target. Otherwise, if CCUS stays at the current stage of development in Poland - it may be a temporary solution for the industry, but not for the power sector, whose transformation is already taking place - towards nuclear power plants and RES (the largest increase in RES in Europe is in Poland in recent years - (Igliński et al., 2022a, 2022b)).

Furthermore, in Poland sequestration is focused on off-shore storage pathway, compared to the Netherlands and/or the UK. Poland's heavily coal-based economy with its heavy industry needs support for decarbonization. However, projects focused on the CCU option are not restricted by any storage restrictions, so the development of those projects should be widely supported not only by the European Union, but also from national funds as a fast track in the decarbonization.

Moreover, a blue hydrogen could be seen as a fair transition solution for member states with a high percentage share of natural gas in GEP. Those countires may set a pathway in the transition of domestic energy system for blue hydrogen, where CCS plays a support role in achieving net-zero emission goal. Thus, energy system transition from natural gas to blue hydrogen could be a solution for GHG emissions reduction targets, but only as a part of wider development, with country-specific consideration.

Both – domestics and European hydrogen policy could be strong leverage in hydrogen transition pathway, showing CCS as a supplementary tool, that could be easily developed over time, not a mandatory solution. In turn, international cooperation is crucial, especially for CCUS, for the development and exploitation of the existing transnational pipeline infrastructure needed for transport captured carbon dioxide and/or blue/green hydrogen.

As Lipponen et al. (2017) and Holz et al. (2021) pointed out, CCUS technology needs financial support from government and the European funds. Several projects in the UK, Germany and the Netherlands had hiatus during financial stage (e.g., the Peterhead CCS Project) (Lipponen et al., 2017, Holz et al., 2021).

It is also noteworthy, that CCUS could be major contributor for achieving net-zero emission targets but not for all the EU member states this pathway will be the same, as each of countries have different environmental, energy, industry and policy profile with various possibilities for storage. Thus, $CO_2$ could be treated as international commodity in the way of utilisation path, to open wider perspective in its treatment.

### 4.3. European Green Deal – discussion over study

Sustainability with fair transition are one of the main goals of the EGD. Each disputed member states have its own approach to its realization as described earlier in this paper. On the other hand, it is noteworthy that while the EGD sets paths in the effort to tackle climate change, it is only a form of launch for the further legislations that follows it, which must then be regulated by corresponding packages of regulations in each state.

As many authors indicate, (Arta and Fogarassy (2021), Bernstein et al. (2022), Eckert and Kovalevska (2021)) the EGD should be considered as a form of algorithm or set of good (recommended) activities, and it should be taken into account that such a form has not only numerous advantages - but no less many drawbacks and disadvantages (Arta and Fogarassy, 2021, Bernstein et al., 2022, Eckert and Kovalevska, 2021).

Setting ambitious goals could be challenging but in different ways for different countries. EU-15 member states had different issues with energy market than the EU's founding states. As mentioned in section 4.1 set of the EU-15 countries could be interesting field of further study in case of energy sector transformation and CCUS possibilities. The EGD could be good solution if all the EU member states were on similar level in terms of energy, industrial and environmental profile. Countries highly depend on clean energy sources or nuclear energy, with less industry share in GHG emissions are more likely to achieve the EGD goals (i.e. Iceland, which% share of RES in TES is 99.99 %) (Mikhaylov, 2020).

Finally, the EGD only works for the EU member state countries, unlike e.g., the Kyoto Protocol or the Paris Agreement. The European Union as worldwide economy should not only set ambitious goals for its member states but also push forward global climate targets as global warming is worldwide concern of all matters.

## 5. Conclusions

Based on observations and findings from a review of the selected EU member states which pathway into climate neutrality could be hindered, several conclusions could be drawn.

First of all, the role of CCUS in both – the European and national decarbonization and/or energy transitions programs – should be reassessed in case of meeting climate targets by 2050. Furthermore, a special emphasize should be put on the European and national CCUS development founds which can be a leaver for kickstarting small and full-scale CCUS projects. As shown in several examples (i.e. the Acorn Project in the UK) those funds and cost-competitiveness have special importance.

Moreover, the implementation of a top-down EU initiative on CCUS deployment may help strengthen the exchange of experience and the implementation of international projects. Those countries with a high share in the European GHG emissions (e.g. Germany, Poland, the Netherlands, Italy), as well as those with a high share of fossil fuels in the energy mix (e.g. Poland, the Netherlands, Germany, Italy), and ones which have problems with the use of $CO_2$ storage due to geological conditions (e.g. Italy, Malta, Cyprus) may particularly benefit from such solution.

Additionally, the idea of industrial clusters re-worked in parallel to the idea of smart cities should be applied as often as possible by policymakers (the Netherland and the UK as excellence examples). Joint cooperation between local authorities, academia and industry could benefit from shared experience. Setting a cluster projects for industrial-intensive regions (such as the Upper Silesia in Poland or the Ruhr region and the Rhineland Industrial Area in Germany) should always take into consideration potential international carbon transportation pathways and hubs.

Last but not least, both national and the European hydrogen strategies should always be considered with RES and/or CCUS technology, to change the blue hydrogen into a low-carbon blue or green hydrogen (as in the UK, Germany and the Netherlands).

Lastly, the European Union should redevelop the European Green Deal into a new global climate agreement of united world economies for the climate to achieve updated targets based on the goals from the Paris Agreement. The EGD should not only set member states under pressure to swift significant economy transformation. It's also pathway for several possibilities for a new green industries, and enhancing the utilization of the United Nations Sustainable Development Goals.

## CRediT authorship contribution statement

**Paulina Popielak:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Visualization, Writing – original draft. **Izabela Majchrzak-Kucęba:** Project administration, Supervision, Validation. **Dariusz Wawrzyńczak:** Supervision, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

All data were obtained from public available databased such as: Eurostat, European Environmental Agency.

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## Supplementary materials

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## References

Acorn | Growing Our Decarbonised Future. Acorn n.d. https://www.theacornproject.uk/ (accessed December 30, 2022).

Agreement on the withdrawal of the United Kingdom of Great Britain and Northern Ireland from the European Union and the European Atomic Energy Community. vol. 384/1. 2019.

Akerboom, S, Waldmann, S, Mukherjee, A, Agaton, C, Sanders, M, Kramer, GJ., 2021. Different this time? the prospects of CCS in the Netherlands in the 2020s. Front. Energy Res., p. 9.

Akimoto, K, Sano, F, Oda, J, Kanaboshi, H, Nakano, Y., 2021. Climate change mitigation measures for global net-zero emissions and the roles of CO2 capture and utilization and direct air capture. Energy Climate Change 2, 100057. https://doi.org/10.1016/j.egycc.2021.100057.

Alcalde, J, Heinemann, N, Mabon, L, Worden, RH, de Coninck, H, Robertson, H, et al., 2019. Acorn: developing full-chain industrial carbon capture and storage in a resource- and infrastructure-rich hydrocarbon province. J. Clean. Prod. 233, 963–971. https://doi.org/10.1016/j.jclepro.2019.06.087.

Allen, MJ, Faulkner, DR, Worden, RH, Rice-Birchall, E, Katirtsidis, N, Utley, JEP., 2020. Geomechanical and petrographic assessment of a CO2 storage site: application to the Acorn CO2 Storage Site, offshore United Kingdom. Int. J. Greenhouse Gas Control 94, 102923. https://doi.org/10.1016/j.ijggc.2019.102923.

Alper, E, Yuksel Orhan, O., 2017. CO2 utilization: developments in conversion processes. Petroleum 3, 109–126. https://doi.org/10.1016/j.petlm.2016.11.003.

Aramis, 2022. Aramis Project. Aramis CCS Homepage. https://www.aramis-ccs.com/ (accessed January 6, 2023).

Arta, K, Fogarassy, C., 2021. European green deal policy for the circular economy. HAE 65–73. https://doi.org/10.17676/HAE.2021.39.65.

Automated and Electric Vehicles Act 2018 n.d. https://www.legislation.gov.uk/ukpga/2018/18/contents/enacted (accessed January 6, 2023).

AVR Afvalverwerking BV. First tons of CO2 captured from residual waste supplied to greenhouse horticulture. AVR - too good to waste 2019. https://www.avr.nl/en/co2-installation/first-tons-of-co2-captured-from-residual-waste-supplied-to-greenhouse-horticulture/ (accessed January 7, 2023).

AVR Afvalverwerking BV. AVR - $CO_2$ capture plant. AVR - Too Good to Waste 2022. https://www.avr.nl/en/optimal-process/co2-capture-plant/ (accessed January 7, 2023).

Bachmann, M, Kätelhön, A, Winter, B, Meys, R, Jan Müller, L, Bardow, A, 2021. Renewable carbon feedstock for polymers: environmental benefits from synergistic use of biomass and CO 2. Faraday Discuss. 230, 227–246. https://doi.org/10.1039/D0FD00134A.

Baleva, S, Shtjefni, D, Tzimas, E, Lonning, E, et al., Commission, European, Centre, Joint Research, 2021. SET plan progress report 2021: contributing to the EU Green Deal and the path forward to a green recovery. Publications Office. 10.2760/804820.

Batuecas, E, Liendo, F, Tommasi, T, Bensaid, S, Deorsola, FA, Fino, D., 2021. Recycling $CO_2$ from flue gas for $CaCO_3$ nanoparticles production as cement filler: a Life Cycle Assessment. J. $CO_2$ Util. 45, 101446 https://doi.org/10.1016/j.jcou.2021.101446.

BBC News, 2022. Germany extends nuclear power amid energy crisis. BBC News. https://www.bbc.com/news/world-europe-63294697 (accessed January 9, 2023).

Bentham, M, Mallows, T, Lowndes, J, Green, A., 2014. CO2 STORage Evaluation Database (CO2 Stored). The UK's online storage atlas. Energy Procedia 63, 5103–5113. https://doi.org/10.1016/j.egypro.2014.11.540.

Bernstein, M, Franssen, T, Smith, R, de Wilde, M., 2022. The European Commission's Green Deal is an opportunity to rethink harmful practices of research and innovation policy. Ambio 1–10. https://doi.org/10.1007/s13280-022-01802-3.

Bonura, G, Todaro, S, Frusteri, L, Majchrzak-Kucęba, I, Wawrzyńczak, D, Pászti, Z, et al., 2021. Inside the reaction mechanism of direct CO2 conversion to DME over zeolite-based hybrid catalysts. Appl. Catal. B 294, 120255. https://doi.org/10.1016/j.apcatb.2021.120255.

Bourguignon D, Dobreva A, Halleux V. Environmental protection 2019.

Breukers S, Pol M, Upham P, Lis A, Desbarats J, Roberts T, et al. Gaps between current and desired practices and exemplary strategies. 2011.

Brown, P, Cardenas, L, Choudrie, S, Del Vento, S, Karagianni, E, MacCarthy, J, et al., 2021. UK Greenhouse Gas Inventory, 1990 to 2019. science research programme of the department for business. Energy Ind. Strategy.

C-Capture Ltd, 2022. Step Change Technology For CO2 Capture. C-Capture. https://c-capture.co.uk/ (accessed January 2, 2023).

Calvillo, C, Race, J, Chang, E, Turner, K, Katris, A, 2022. Characterisation of UK industrial clusters and techno-economic cost assessment for carbon dioxide transport and storage implementation. Int. J. Greenhouse Gas Control 119, 103695. https://doi.org/10.1016/j.ijggc.2022.103695.

Cameron, R., 2020. Germany Must Put CCS Back On the table, Says Merkel. International Centre for Sustainable Carbon.

Chehrazi, M, Moghadas, BK., 2022. A review on CO2 capture with chilled ammonia and $CO_2$ utilization in urea plant. J. $CO_2$ Util. 61, 102030 https://doi.org/10.1016/j.jcou.2022.102030.

CO2 Stored Project Homepage. CO2 Stored Homepage n.d. http://www.co2stored.co.uk/home/index (accessed January 3, 2023).

Cordero-Lanzac, T, Ramirez, A, Navajas, A, Gevers, L, Brunialti, S, Gandía, LM, et al., 2021. A techno-economic and life cycle assessment for the production of green methanol from $CO_2$: catalyst and process bottlenecks. J. Energy Chem. https://doi.org/10.1016/j.jechem.2021.09.045.

Dütschke, E, Duscha, V., 2022. Is there a future for CCUS in Europe? An analysis of the policy framework and societal support. SSRN J. https://doi.org/10.2139/ssrn.4286232.

De Falco, M, Natrella, G, Capocelli, M, Popielak, P, Sołtysik, M, Wawrzyńczak, D, et al., 2022. Exergetic analysis of DME synthesis from $CO_2$ and renewable hydrogen. Energies 15, 3516. https://doi.org/10.3390/en15103516.

Deutsche Welle. Germany extends lifetime of remaining nuclear plants – DW –10/17/2022. Deutsche Welle News 2022. https://www.dw.com/en/germany-extends-lifetime-of-all-3-remaining-nuclear-plants/a-63466196 (accessed January 9, 2023).

Dickel, R., 2020. Blue Hydrogen As an Enabler of Green hydrogen: The case of Germany. The Oxford Institute for Energy Studies, Oxford.

DNV, AS, 2021. Carbon Limits AS. *Re*-Stream—Study on the Reuse of Oil and Gas Infrastructure For Hydrogen and CCS in Europe. Carbon Limits, Norway.

Donnison, C, Holland, RA, Hastings, A, Armstrong, LM, Eigenbrod, F, Taylor, G., 2020. Bioenergy with Carbon Capture and Storage (BECCS): finding the win–wins for energy, negative emissions and ecosystem services—size matters. GCB Bioenergy 12, 586–604. https://doi.org/10.1111/gcbb.12695.

Drax Group plc, 2018. Drax Could Help Keep the Fizz in the Drinks Sector. Drax Global. https://www.drax.com/press_release/drax-help-keep-fizz-drinks-sector/ (accessed January 2, 2023).

Drax Group plc, 2021. Drax and Mitsubishi Heavy Industries sign Pioneering Deal to Deliver the World's Largest Carbon Capture Power Project. Drax Global. https://www.drax.com/press_release/drax-and-mitsubishi-heavy-industries-sign-pioneering-deal-to-deliver-the-worlds-largest-carbon-capture-power-project/ (accessed January 3, 2023).

Drax Group plc, 2022a. Zero Carbon Humber. Zero Carbon Humber. https://www.zerocarbonhumber.co.uk/ (accessed January 7, 2023).

Drax Group plc. Drax Power Station. Drax Global 2022. https://www.drax.com/about-us/our-sites-and-businesses/drax-power-station/ (accessed January 3, 2023).

Drax Group plc, 2022c. Drax to Pilot More Pioneering New Carbon Capture Technology. Drax Global. https://www.drax.com/press_release/drax-to-pilot-more-pioneering-new-carbon-capture-technology/ (accessed January 3, 2023).

Dubiński, J, Wachowicz, J, Koteras, A., 2010. Podziemne składowanie dwutlenku węgla - możliwości wykorzystania technologii CCS w polskich uwarunkowaniach. Górnictwo i Geologia 5, 15. Zeszyt 1.

Dumenil, T., 2021. Acorn Hydrogen Project Summary Report (HSC-2). Pale Blue Dot.

Eckert, E, Kovalevska, O., 2021. Sustainability in the European Union: analyzing the discourse of the European Green Deal. J. Risk Financ. Manag. 14, 80. https://doi.org/10.3390/jrfm14020080.

Eni S.p.A. HyNet North West: $CO_2$ storage in the UK. Eni Webstie 2022. https://www.eni.com/en-IT/operations/united-kingdom-hynet-north-west.html (accessed December 30, 2022).

Equinor ASA, 2019. H2morrow. OGE.

Equinor ASA, 2022. H2H Saltend. Equinor Homepage. https://www.equinor.com/energy/h2h-saltend (accessed January 2, 2023).

Esken A, Höller S, Luhmann H-J, Pietzner K, Vallentin D, Viebahn P. RECCS plus : comparison of renewable energy technologies with carbon dioxide capture and

storage (CCS) ; update and expansion of the RECCS study 0329967/07000285 ; final report 2010.
European Commission. Athens Treaty of Accession. 2003.
European Commission. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - A European strategic energy technology plan (SET-plan) - "Towards a low carbon future." 2007.
European Commission. Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide. 2009.
European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - The European Green Deal. 2019.
European Commission. Proposal for a regulation of the European Parliament and of the Council for establishing a Union certification framework for carbon removals. vol. 2022/0394(COD). 2022.
European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 - on the promotion of the use of energy from renewable sources. vol. L 328/82. n.d. 2023.
European Commission. Sustainable Carbon Cycles 2023. https://doi.org/10.1163/2210-7975_HRD-4679-0058.
European Environment Agency, 2021. EEA greenhouse gases - data viewer — European Environment Agency. European Environment Agency Official Website. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (accessed October 24, 2022).
Komunikat Komisji do Parlamentu Europejskiego, Rady Europejskiej, Rady, Komitetu Ekonomiczno-Społecznego, Komitetu Regionów Europejski Zielony Ład n.d. 2023.
Eurostat Data browser. Population change - Demographic balance and crude rates at national level (demo_gind). Eurostat 2022. https://ec.europa.eu/eurostat/cache/metadata/en/demo_gind_esms.htm (accessed October 24, 2022).
Eurostat Data browser. Real GDP per capita (sdg_08_10). Eurostat 2022. https://ec.europa.eu/eurostat/cache/metadata/en/sdg_08_10_esmsip2.htm (accessed October 24, 2022).
Eurostat Data browser. Energy balances (nrg_bal). Eurostat 2023. https://ec.europa.eu/eurostat/cache/metadata/en/nrg_bal_esms.htm (accessed December 6, 2022).
Farfan, J, Breyer, C., 2017. Aging of European power plant infrastructure as an opportunity to evolve towards sustainability. Int. J. Hydrogen Energy 42, 18081–18091. https://doi.org/10.1016/j.ijhydene.2016.12.138.
Federal Environment Agency, 2021. National Inventory Report For the German Greenhouse Gas Inventory 1990 –2019. Federal Environment Agency.
Fella, S, Ferguson, D, Webb, D, Jozepa, I, Ares, E, Kennedy, S., 2020. The UK-EU Trade and Cooperation Agreement: Summary and Implementation. The House of Commons Library.
Flexis, 2020. FLEXIS secure €2M funding to expand its research into reducing the CO2 in our atmosphere. Flexis. https://www.flexis.wales/blog/flexis-secure-e2m-funding-to-expand-its-research-into-reducing-the-co2-in-our-atmosphere-2/ (accessed December 23, 2022).
Gładysz, P, Sowiżdżał, A, Miecznik, M, Pająk, L., 2020. Carbon dioxide-enhanced geothermal systems for heat and electricity production: energy and economic analyses for central Poland. Energy Convers. Manage. 220, 113142 https://doi.org/10.1016/j.enconman.2020.113142.
Gammer D, Green A, Holloway S, Smith G. The Energy Technologies Institute's UK CO2 storage appraisal project (UKSAP). Society of Petroleum Engineers - Offshore Europe Oil and Gas Conference and Exhibition 2011, OE 2011 2011;2.
Gray, N, McDonagh, S, O'Shea, R, Smyth, B, Murphy, JD, 2021. Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv. Appl. Energy 1, 100008. https://doi.org/10.1016/j.adapen.2021.100008.
Griffin, P.W., Hammond, G.P., Norman, J.B., 2016. Industrial energy use and carbon emissions reduction: a UK perspective: Industrial energy use and carbon emissions reduction. WIREs Energy Environ 5, 684–714. https://doi.org/10.1002/wene.21.
Griffin, PW, Hammond, GP, Norman, JB., 2018. Industrial energy use and carbon emissions reduction in the chemicals sector: a UK perspective. Appl. Energy 227, 587–602. https://doi.org/10.1016/j.apenergy.2017.08.010.
Höller, S, Viebahn, P., 2011. Assessment of CO2 storage capacity in geological formations of Germany and Northern Europe. Energy Procedia 4, 4897–4904. https://doi.org/10.1016/j.egypro.2011.02.458.
H-vision, 2022. H-vision Homepage. H-Vision Homepage. https://www.h-vision.nl/en (accessed January 7, 2023).
H21 | FAQs n.d. https://h21.green/faqs/ (accessed December 28, 2022).
Hafner, M, Raimondi, PP., 2020. Priorities and challenges of the EU energy transition: from the European Green Package to the new Green Deal. Russian J. Econ. 6, 374–389. https://doi.org/10.32609/j.ruje.6.55375.
Harding, FC, James, AT, Robertson, HE., 2018. The engineering challenges of $CO_2$ storage. Proc. Inst. Mech. Eng. Part A J. Power Energy 232, 17–26. https://doi.org/10.1177/0957650918756542.
Hendriks, CA, Blok, K., 1993. Underground storage of carbon dioxide. Energy Convers. Manage. 34, 949–957. https://doi.org/10.1016/0196-8904(93)90041-8.
Herold, A, Monni, S, Erda, L, Meyer, M, Flugsrud, K, 2010. Methodological choice and identification of key categories. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change vol. Vol. 1.
Herold, J, Ruester, S, Von Hirschhausen, C., 2011. Carbon capture; transport and storage in Europe: a problematic energy bridge to nowhere? SSRN J. https://doi.org/10.2139/ssrn.1736496.
HICP, 2023. What is the HICP? HICP. https://www.humberindustrialclusterplan.org/ (accessed January 7, 2023).
Holloway, S., 2009. Storage capacity and containment issues for carbon dioxide capture and geological storage on the UK continental shelf. Proc. Inst. Mech. Eng. Part A J. Power Energy 223, 239–248. https://doi.org/10.1243/09576509JPE650.
Holz, F, Scherwath, T, Crespo Del Granado, P, Skar, C, Olmos, L, Ploussard, Q, et al., 2021. A 2050 perspective on the role for carbon capture and storage in the European power system and industry sector. Energy Econ. 104 https://doi.org/10.1016/j.eneco.2021.105631.
Hong, WY., 2022. A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO2 emissions future. Carbon Capture Sci. Technol. 3, 100044 https://doi.org/10.1016/j.ccst.2022.100044.
Howe, J., 2021. Net Zero Teesside Project. Land at and in the Vicinity of the Former Redcar Steel Works Site, Redcar and in Stocktonon-Tees. Net Zero Teesside, Teesside.
Humber Zero Homepage, 2022a. About Humber Zero. Humber Zero. https://www.humberzero.co.uk/what-is-humber-zero/ (accessed January 7, 2023).
Humber Zero Homepage, 2022b. Hydrogen For Energy. https://www.humberzero.co.uk/hydrogen-for-energy/ (accessed January 7, 2023).
HyNet North West. HyNet Low Carbon Hydrogen Plant: BEIS Hydrogen Supply Competition. 2021.
HyNet North West. About HyNet. Hynet North West 2022. https://hynet.co.uk/about/ (accessed December 28, 2022).
Guidelines No 6 Integrating the Environment and Climate Change Into EU International Cooperation and Development Towards sustainable Development, 2016. Directorate-General for International Cooperation and Development, European Commission, Brussels, Luxembourg.
IEA. Energy Policies of IEA Countries: united Kingdom 2019 Review. 2019.
IEA, 2020a. The Netherlands 2020 - Energy Policy Review. IEA Publications, France.
IEA, 2020b. Germany 2020 - Energy Policy Review. IEA Publications, France.
IEA, 2021a. About CCUS. International Energy Agency, Paris.
IEA, 2021b. CCUS Around the World - Drax BECCS Analysis. IEA. https://www.iea.org/reports/ccus-around-the-world/drax-beccs (accessed January 3, 2023).
Igliński, B, Piechota, G, Kiełkowska, U, Kujawski, W, Pietrzak, MB, Skrzatek, M., 2022a. The assessment of solar photovoltaic in Poland: the photovoltaics potential, perspectives and development. Clean Technol. Environ. Policy. https://doi.org/10.1007/s10098-022-02403-0.
Igliński, B, Pietrzak, MB, Kiełkowska, U, Skrzatek, M, Kumar, G, Piechota, G., 2022b. The assessment of renewable energy in Poland on the background of the world renewable energy sector. Energy 261, 125319. https://doi.org/10.1016/j.energy.2022.125319.
International Energy Agency, 2022. Poland 2022 Energy Policy Review. OECD. https://doi.org/10.1787/2075436d-en.
IPCC, 2000. Special Report On Emissions scenarios: a Special Report of Working Group III of the Intergovernmental Panel On Climate Change. editor. Cambridge University Press, Cambridge; New York.
Jeszke, R, 2019. Climate For Poland - Poland For Climate. editor, 1st ed. Instytut Ochrony Środowiska - Państwowy Instytut Badawczy, Warszawa.
Kaiser, M, Zimmer, R, Brunsting, S, Mastop, J, Pol, M., 2014. Development of CCS Projects in Poland. How to communicate with the local public? Energy Procedia 51, 267–273. https://doi.org/10.1016/j.egypro.2014.07.031.
Kali, RFS, Fan, D, Hazel, N, Striolo, A., 2022. Techno-socio-economic analysis of geological carbon sequestration opportunities. Environ. Sci.: Adv. 1, 138–155. https://doi.org/10.1039/D1VA00036E.
Koytsoumpa, EI, Bergins, C, Kakaras, E., 2018. The CO2 economy: review of CO2 capture and reuse technologies. J. Supercrit. Fluids 132, 3–16. https://doi.org/10.1016/j.supflu.2017.07.029.
Kozak, M, Nield, K., 2001. An overview of benchmarking literature: its strengths and weaknesses. J. Qual. Assurance Hosp. Tourism 2, 7–23. https://doi.org/10.1300/J162v02n03_02.
Krämer, L., 2018. Chapter 4. Germany: A Country Without CCS. Carbon Capture and Storage : Emerging Legal and Regulatory Issues. Hart Publishing, pp. 59–74. https://doi.org/10.5040/9781509909599.
Kyrö, P., 2004. Benchmarking as an action research process. Benchmarking 11, 52–73. https://doi.org/10.1108/14635770410520302.
Leung, DYC, Caramanna, G, Maroto-Valer, MM., 2014. An overview of current status of carbon dioxide capture and storage technologies. Renewable Sustainable Energy Rev. 39, 426–443. https://doi.org/10.1016/j.rser.2014.07.093.
Lim, LH, Tan, P, Chan, WP, Veksha, A, Lim, T-T, Lisak, G, et al., 2023. A techno-economic assessment of the reutilisation of municipal solid waste incineration ash for CO2 capture from incineration flue gases by calcium looping. Chem. Eng. J. 464, 142567 https://doi.org/10.1016/j.cej.2023.142567.
Lin, Q, Liang, X, Lei, M, Zhang, Y, Pan, Y, Wang, N., 2022. CCUS: what is it? how does it cost? Techno-Econ. Anal., pp. 109–179. https://doi.org/10.1007/978-981-16-4310-1_4.
Lipponen, J, McCulloch, S, Keeling, S, Stanley, T, Berghout, N, Berly, T., 2017. The Politics of Large-scale CCS Deployment. Energy Procedia 114, 7581–7595. https://doi.org/10.1016/j.egypro.2017.03.1890.
Majchrzak-Kucęba, I, Wawrzyńczak, D, Zdeb, J, Smółka, W, Zajchowski, A., 2021. Treatment of flue gas in a CO2 Capture Pilot Plant for a. Commercial CFB Boiler. Energies 14, 2458. https://doi.org/10.3390/en14092458.
McCormac, E., 2020. Net Zero Teesside Economic Benefits. Vivid Economics Ltd, London, UK.
Mika-Brysk, M, Wróblewska, E., 2015. Polskie podejście do CCS w świetle aktualnego statusu rozwoju tej technologii. Przegląd Geologiczny 63, 4.
Mikhaylov, A., 2020. Geothermal Energy Development in Iceland. Int. J. Energy Econ. Policy 10, 31–35. https://doi.org/10.32479/ijeep.9047.
Ministerie van Algemene Zaken. MIEK Overzicht 2022 - Meerjarenprogramma Infrastructuur Energie en Klimaat - Rapport. Rijksoverheid Main Website 2022.

https://www.rijksoverheid.nl/documenten/rapporten/2022/12/02/ezk-miek-overzicht-2022-meerjarenprogramma-infrastructuur-energie-en-klimaat (accessed January 6, 2023).
Ministerie van Economische Zaken en Klimaat. National climate agreement - The Netherlands - publicatie - Klimaatakkoord 2019. https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands (accessed January 8, 2023).
Ministerie van Economische Zaken en Klimaat. Climate policy - climate change - government.nl 2019. https://www.government.nl/topics/climate-change/climate-policy (accessed January 8, 2023).
Ministerie van Economische Zaken en Klimaat. Government strategy on hydrogen - publication - government.nl 2020. https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen (accessed January 7, 2023).
Ministerstwo Klimatu i Środowiska - Polityka Energetyczna Polski do 2040 r. Streszczen. pdf n.d. 2023.
Ministry for the Environment, 2014. Nature Conservation, Building and Nuclear Safety. The German Government's Climate Action Programme 2020 - Cabinet decision of 3 December 2014, 1st ed. Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Germany.
Ministry for the Environment, 2016. Nature Conservation, Building and Nuclear Safety. Climate Action Plan 2050, 1st ed. Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Berlin, Germany.
Ministry for the Environment, 2020. Nature Conservation, Building and Nuclear Safety. The National Hydrogen Strategy, 1st ed. Federal Ministry for Economic Affairs and Energy, Berlin, Germany.
Ministry of Climate and Environment, editor. Polish Hydrogen Strategy until 2030 with an outlook until 2040 - Summary. Ministry of Climate and Environment; 2021.
Monteiro, J, Roussanaly, S., 2022. CCUS scenarios for the cement industry: is $CO_2$ utilization feasible? J. $CO_2$ Util. 61, 102015 https://doi.org/10.1016/j.jcou.2022.102015.
Neele, F., Hendriks C., Brandsma R., Blomen E., EU GeoCapacity assessing European capacity for geological storage of carbon dioxide. Geol. Surv. Netherlands, 2006.
Net Zero Teesside OGCI, 2022a. Net Zero Teesside - The UK's First Decarbonised Industrial Cluster. Net Zero Teesside Oil and Gas Climate Initiative Website. http://www.netzeroteesside.co.uk/ (accessed January 4, 2023).
Net Zero Teesside OGCI. Net Zero Teesside- Technology overview. Net Zero Teesside Oil and Gas Climate Initiative Website 2022. https://www.netzeroteesside.co.uk/technology/ (accessed January 4, 2023).
OGJ editors, 2019. Netherlands becomes a net gas importer. Oil Gas J.
Okoye-Chine, CG, Otun, K, Shiba, N, Rashama, C, Ugwu, SN, Onyeaka, H, et al., 2022. Conversion of carbon dioxide into fuels—a review. J. CO2 Util. 62, 102099 https://doi.org/10.1016/j.jcou.2022.102099.
Olecka A, Bebkiewicz K, Chłopek Z, Kanafa M, Kargulewicz I, Rutkowski J, et al. Krajowy raport inwentaryzacyjny 2021 Inwentaryzacja gazów cieplarnianych w Polsce dla lat 1988-2019. 2021.
One-of-a-kind project that will provide a clear pathway to support the UK to meet its net-zero targets n.d. https://www.genesisenergies.com/case-study/acorn-hydrogen-project (accessed December 28, 2022).
Open Grid Europe GmbH, 2023. H₂ercules. OGE. https://oge.net/en/sustainable/projects/our-hydrogen-projects/h2ercules (accessed January 9, 2023).
Otto, D, Pfeiffer, M, de Brito, MM, Groß, M., 2022. Fixed amidst change: 20 years of media coverage on carbon capture and storage in Germany. Sustainability 14. https://doi.org/10.3390/su14127342.
Partridge J. Germany at a crossroads: what a nuclear power station tells us about its energy dilemma. The Guardian 2020. https://www.theguardian.com/world/2022/dec/09/neckarwestheim-delay-phasing-out-nuclear-power-dividing-german-village (accessed January 9, 2023).
Monitor Polski. Obwieszczenie Ministra Klimatu i Środowiska z dnia 2 marca 2021 r. w sprawie polityki energetycznej państwa do 2040 r. 2021.
Porthos $CO_2$. Porthos $CO_2$ Project. Porthos $CO_2$ Homepage 2022. https://www.porthosco2.nl/en/project/(accessed January 7, 2023).
Porthos, $CO_2$, 2022. $CO_2$ Reduction Through Storage Under the North Sea. Porthos $CO_2$ Homepage. https://www.porthosco2.nl/en/ (accessed January 7, 2023).
Przybojewska, I., 2018. Legal possibilities of carbon capture and storage in Poland. Law and Administration in Post-Soviet. Europe 5, 18–27. https://doi.org/10.2478/lape-2018-0003.
Rahman, FA, Aziz, MMA, Saidur, R, Bakar, WAWA, Hainin, MR, Putrajaya, R, et al., 2017. Pollution to solution: capture and sequestration of carbon dioxide (CO2) and its utilization as a renewable energy source for a sustainable future. Renewable Sustainable Energy Rev. 71, 112–126. https://doi.org/10.1016/j.rser.2017.01.011.
Ravi, NK, Van Sint Annaland, M, Fransoo, JC, Grievink, J, Zondervan, E., 2017. Development and implementation of supply chain optimization framework for CO2 capture and storage in the Netherlands. Comput. Chem. Eng. 102, 40–51. https://doi.org/10.1016/j.compchemeng.2016.08.011.
Read, A, Tillema, O, Ros, M, Jonker, T, Hylkema, H, 2014. Update on the ROAD project and lessons learnt. Energy Procedia 63, 6079–6095. https://doi.org/10.1016/j.egypro.2014.11.640.
Read, A, Gittins, C, Uilenreef, J, Jonker, T, Neele, F, Belfroid, S, et al., 2019. Lessons from the ROAD project for future deployment of CCS. Int. J. Greenhouse Gas Control 91, 102834. https://doi.org/10.1016/j.ijggc.2019.102834.
Renews Ltd. ScottishPower, Storegga back Cromarty Firth freeport bid. reNEWS - renewable energy news 2022. https://renews.biz/78860/scottishpower-storegga-back-cromarty-firth-freeport-bid/ (accessed December 30, 2022).
Rijksoverheid. Aardbevingen Groningen. Rijksoverheid Main Website 2022. https://dashboardgroningen.nl/aardbevingen-groningen (accessed February 7, 2023).
Rogers M. H2H Saltend project to develop clean hydrogen plant in the UK – Energy Northern Perspective. Energy Northern Perspective 2002. https://energynorthern.com/2020/07/02/h2h-saltend-project-to-develop-clean-hydrogen-plant-in-the-uk/ (accessed December 28, 2022).
Ruyssenaars P, Coenen P, Rienstra J, Zijlema P, Arets E, Baas K, et al. Greenhouse gas emissions in the Netherlands 1990–2019. Rijksinstituut voor Volksgezondheid en Milieu; 2021. https://doi.org/10.21945/RIVM-2021-0007.
RWE Aktiengesellschaft, 2022. Hydrogen Fast track: OGE and RWE Present National Infrastructure Concept "H2ercules. Essen, Germany.
Sadler D, Anderson HS, Sperrink M. H21 North of England Core Team. 2008.
Schmid, C, Hahn, A., 2021. Potential CO2 utilisation in Germany: an analysis of theoretical CO2 demand by 2030. J. CO2 Util. 50, 101580 https://doi.org/10.1016/j.jcou.2021.101580.
Sejm Rzeczypospolitej Polskiej. Ustawa z dnia 16 czerwca 2023 r. o zmianie ustawy – Prawo geologiczne i górnicze oraz niektórych innych ustaw. vol. Dz. U. z 2023 r. poz. 633. 2023.
Shell UK Ltd, 2015. Peterhead CCS Project. Shell U.K. Limited.
Shell UK Ltd. Shell Fife NGL Plant | About Shell UK n.d. https://www.shell.co.uk/about-us/what-we-do/oil-and-gas/shell-fife-ngl.html (accessed September 24, 2023).
Siddi, M., 2020. The European Green Deal: asseasing its current state and future implementation. FIIA 14.
Sowiżdżał, A, Machowski, G, Krzyżak, A, Puskarczyk, E, Krakowska-Madejska, P, Chmielowska, A., 2022a. Petrophysical evaluation of the Lower Permian formation as a potential reservoir for CO2 - EGS – case study from NW Poland. J. Clean. Prod. 379, 134768 https://doi.org/10.1016/j.jclepro.2022.134768.
Sowiżdżał, A, Starczewska, M, Papiernik, B., 2022b. Future Technology Mix—Enhanced Geothermal System (EGS) and Carbon Capture, Utilization, and Storage (CCUS)—an overview of selected projects as an example for future investments in Poland. Energies 15, 3505. https://doi.org/10.3390/en15103505.
SSE Thermal, PLC, Equinor, ASA., 2022. Powering the Next Generation Peterhead low Carbon CCT Power Station With Carbon Capture Technology Amended, 1st ed. Work Crative Ltd.
SSE Thermal PLC. Keadby 3 Carbon Capture Power Station 2022. https://www.ssethermal.com/flexible-generation/development/keadby-3-carbon-capture/ (accessed December 28, 2022).
SSE Thermal PLC, 2022b. Powering the next generation. SSE Thermal. Equinor.
SSE Thermal PLC. Keadby Hydrogen Power Station. Keadby Hydrogen Power Station 2022. https://www.keadbyhydrogen.com (accessed January 2, 2023).
SSE Thermal PLC, 2022d. SSE Thermal and Equinor join Forces On Plans For First-Of-A-Kind Hydrogen and Carbon Capture Projects in the Humber. Keadby Hydrogen Power Station. https://www.keadbyhydrogen.com/news/major-boost-for-ccs-and-hydrogen-projects-as-east-coast-cluster-captures-track1-status-y3f7n (accessed January 2, 2023).
SSE Thermal PLC. Peterhead low carbon CCGT power station project. 2022.
Storegga Group, 2022a. UK's Leading Carbon Capture and Storage Project | Storegga. Storegga Earth. https://storegga.earth/co-storage (accessed December 30, 2022).
Storegga Group, 2022b. Storegga - Direct Air Capture project awarded funding under Government plans to make UK world leader in Greenhouse Gas Removals. Storegga Earth. https://storegga.earth/news/2021/news/direct-air-capture-project-awarded-funding-under-government-plans-to-make-uk-world-leader-in-greenhouse-gas-removals (accessed December 30, 2022).
Storegga Group, 2022c. Green Hydrogen Projects with Storegga Earth. Storegga Earth. https://storegga.earth/hydrogen (accessed December 28, 2022).
Storegga Group. Storegga - ScottishPower and Storegga form green hydrogen partnership to 'transform industry in the Highlands.' Storegga Earth 2022. https://storegga.earth/news/2022/press-releases/scottishpower-and-storegga-form-green-hydrogen-partnership-to-transform-industry-in-the-highlands (accessed December 30, 2022).
Śliwińska, A, Strugała-Wilczek, A, Krawczyk, P, Leśniak, A, Urych, T, Chećko, J, et al., 2022. Carbon capture utilisation and storage technology development in a region with high CO2 emissions and low storage potential—a case study of upper silesia in Poland. Energies 15, 4495. https://doi.org/10.3390/en15124495.
Tarkowski, R, Uliasz-Misiak, B., 2019. Prospects for the use of carbon dioxide in enhanced geothermal systems in Poland. J. Clean. Prod. 229, 1189–1197. https://doi.org/10.1016/j.jclepro.2019.05.036.
Tcvetkov, P., 2021. Climate Policy Imbalance in the Energy Sector: time to Focus on the Value of CO2 Utilization. Energies 14, 411. https://doi.org/10.3390/en14020411.
The Dutch Government, 2015. Policy Document on the North Sea 2016-2021. The Dutch Ministry of Infrastructure and the Environment The Dutch Ministry of Economic Affairs, The Netherlands.
Leeds City Gate.H21 Executive Summary, 2016.
The High Level Panel. BECCS done well - conditions for success for bioenergy with carbon capture and storage. The High Level Panel; 2022.
The SCCS Group. Drax BECCS Pilot Plant Details. The SCCS Website 2022. https://www.geos.ed.ac.uk/sccs/project-info/2261 (accessed January 3, 2023).
The UK Government. Climate Change Act 2008. Statute Law Database; 2008.
The UK Government. The UK's Industrial Strategy. 2017.
The UK Government. UK becomes first major economy to pass net zero emissions law. GOVUK 2019. https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law (accessed December 23, 2022).
The UK Government, 2020. The Ten Point Plan for a Green Industrial Revolution. UK HM Government, London.
The UK Government. Carbon Capture, Usage and Storage: an update on the business model for industrial Carbon Capture. 2021.
The UK Government, 2021b. Net Zero Teesside & Northern Endurance Partnership Technology Plan. Department for Buissnes, Energy & Industrial Strategy (BEIS).

The UK Government, 2022. CCUS Investor Roadmap, 1st ed. UK Department for International Trade, London.
The UK Government, 2021. UK Hydrogen Strategy, 1st ed. London.
Tomaszewski, K., 2020. The Polish road to the new European Green Deal – challenges and threats to the national energy policy. Polityka Energetyczna – Energy Policy J. 23, 5–18. https://doi.org/10.33223/epj/123411.
TotalEnergies, 2023. Netherlands: TotalEnergies, Shell Netherlands, EBN and Gasunie Form Partnership to Develop the Offshore Aramis CO2 Transport and Sequestration Project. TotalEnergiesCom. https://totalenergies.com/media/news/press-releases/partnership-to-develop-aramis-offshore-ccs-project (accessed September 26, 2023).
Tucker, O, Tinios, L., 2017. Experience in Developing the Goldeneye Storage Permit Application. Energy Procedia 114, 7466–7479. https://doi.org/10.1016/j.egypro.2017.03.1880.
UKBEIS, 2017. Clean Growth Strategy, 1st ed. Department for Business, Energy and Industrial Strategy, London.
UKBEIS, 2018. The Road to Zero, 1st ed. United Kingdom Department for Transport, London.
UKSAP. Storage appraisal – project insights 2012. https://doi.org/10.5286/UKERC.EDC.000093.
UKSAP Consortium. Storage appraisal - UK storage appraisal project - final report 2011. https://doi.org/10.5286/UKERC.EDC.000110.
United Nations, 'Documentation and downloads Table 2: trends in the Human Development Index, 1990-2021', United Nations. Accessed: Oct. 24, 2022. [Online]. Available: https://hdr.undp.org/data-center/documentation-and-downloads.
University of Nottingham, 2022. Promethean Particles captures collaboration with power giant in race to cut carbon emissions. Nottingham.
Vögele, S, Rübbelke, D, Mayer, P, Kuckshinrichs, W., 2018. Germany's "No" to carbon capture and storage: just a question of lacking acceptance? Appl. Energy 214, 205–218. https://doi.org/10.1016/j.apenergy.2018.01.077.
Ministerie van Algemene Zaken. Kabinet neemt regie bij vijf nieuwe energie-infrastructuurprojecten. Rijksoverheid Main Website 2022. https://www.rijksoverheid.nl/actueel/nieuws/2022/12/02/kabinet-neemt-regie-bij-vijf-nieuwe-energie-infrastructuurprojecten (accessed January 6, 2023).
Vangkilde-Pedersen, Thomas, Kirk, Karen, Smith, Nikki, Maurand, Nicolas, Wójcicki, Adam, Neele, Filip, et al., 2009a. Assessing European Capacity For Geological Storage of Carbon Dioxide. GeoCapacity, Denmark.
Vangkilde-Pedersen, Alier, Anghe, Anthonsen, bossie-codreanu D, Car C, et al. WP2 report – storage capacity. EU GeoCapacity project – assessing european capacity for geological storage of carbon dioxide. 2009.
Veltman, 2022. Porthos Standard $CO_2$ Transport and Storage Conditions. Porthos $CO_2$, Utrecht.
Vikara, D, Shih, C, Guinan, A, Lin, S, Wendt, A, Grant, T, et al., 2018. Assessing key drivers impacting the cost to deploy integrated CO2 capture. Util. Transp. Storage (CCUS).
Wójcicki, A., 2013. Rozpoznanie Formacji i Struktur Do Bezpiecznego Geologicznego Składowania CO2 Wraz z Ich Programem monitorowania. vol. 1. Państwowy Instytut Geologiczny, Warszawa.
Wachowiak, J., 2021. EU–UK climate cooperation post- Brexit: a case for optimism? Eur. Policy Center 4.
Waite C. 2019 UK Greenhouse Gas Emissions, Final Figures 2021.
Wall, C, Bernstone, C, Olvstam, M-L, et al., 2005. International and European legal aspects on underground geological storage of CO2. In: Rubin, ES, Keith, DW, Gilboy, CF, Wilson, M, Morris, T, Gale, J, et al. (Eds.), Greenhouse Gas Control Technologies 7. Elsevier Science Ltd, Oxford, pp. 971–978. https://doi.org/10.1016/B978-008044704-9/50098-7.
Wawrzyńczak, D, Majchrzak-Kucęba, I, Nowak, W., 2014. Możliwości zastosowania metody adsorpcyjnej do usuwania CO2 ze spalin kotłowych. Scientific Lett. Rzeszow Univ. Technol. - Mechanics 31, 285–293. https://doi.org/10.7862/rm.2014.32.
Wawrzyńczak, D, Majchrzak-Kucęba, I, Srokosz, K, Kozak, M, Nowak, W, Zdeb, J, et al., 2018. The pilot dual-reflux vacuum pressure swing adsorption unit for CO 2 capture from flue gas. Sep. Purif. Technol. 209 https://doi.org/10.1016/j.seppur.2018.07.079.
Westküste. WESTKÜSTE100 receives fund-ing approval for the stor-age of green hydrogen - Westküste100. Westküste Website 2022. https://www.westkueste100.de/en/westkuste100-receives-funding-approval-for-the-storage-of-green-hydrogen/ (accessed January 9, 2023).
Westküste. Westküste100 Project overview. Westküste Website 2022. https://www.westkueste100.de/en/ (accessed January 9, 2023).
Wettengel, J., 2019. Merkel Puts Contentious CCS Technology Back On German agenda. Clean Energy Wire.
Wood PLC, 2022. Humber Zero Technology Selection Report. Immingham, UK.
Zanella, A, Camanho, A s, Dias, T., 2012. Benchmarking countries' environmental performance. J. Oper. Res. Soc. 64 https://doi.org/10.1057/jors.2012.62.
ZCH. Capture for growth report. Zero Carbon Humber, 2019.
Zero-Emission Platform. CCS/CCU projects. Zero Emissions Platform n.d. https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/ (accessed November 23, 2022).
Zero-Emission Platform. ZEP Structure. Zero Emissions Platform n.d. https://zeroemissionsplatform.eu/about-zep/zep-structure/ (accessed September 24, 2023).
Zuiderwijk, A, Piranejad, A, Susha, I., 2021. Comparing open data benchmarks: which metrics and methodologies determine countries' positions in the ranking lists? Telemat Inform. 62, 101634 https://doi.org/10.1016/j.tele.2021.101634.

## 1.2 Carbon Capture Utilization and Storage

### 1.2.1 Technology overview

Carbon Capture Utilization and Storage (CCUS) is a process in which $CO_2$ from industry i.e., the power sector (Hasan et al. 2022), fuel (Zhang et al. 2015, 2023; Young et al. 2019), metallurgy (Kang et al. 2022), and cement industries (Monteiro and Roussanaly 2022; Wawrzyńczak et al. 2022a) or other sources like atmospheric air (van der Giesen et al. 2017) is (1) separated, (2) and transported for (3) utilization, for example, through conversion to fuel as Power-to-Fuel (Anika et al. 2022), and/or (3) stored in the way of permanent underground storage (Zero Emission Platform 2019; Zahasky and Krevor 2020). Figure 1 shows the schematic diagram, which includes the most important elements of the CCUS supply chain.

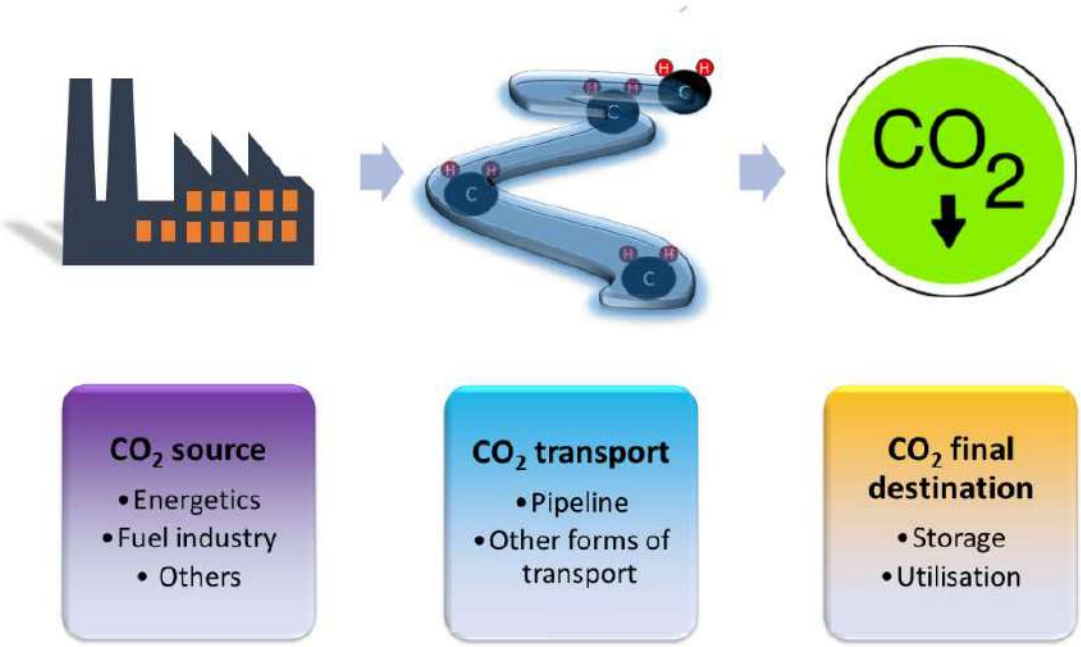



Figure 1 General concept of CCUS technology supply chain.

Since the 1930s, $CO_2$ capture equipment has been used in industry to purify natural gas, hydrogen, and other gas streams, among other applications. For the first time in 1972, captured $CO_2$ was used to enhance oil recovery (Parker et al. 2009).

### 1.2.1.1 Carbon capture

According to (European Commission 2019; European Commission et al. 2021; Mikunda et al. 2021), CCUS is one of the key technologies in climate change mitigation, as it can significantly reduce greenhouse gas (GHG) emissions and support the transition to a low-carbon economy. $CO_2$ can be captured from the source in three different ways: before the combustion process (pre-combustion) (Theo et al. 2016), after the combustion process (post-combustion) (Wawrzyńczak et al. 2022a), and with the development of oxy-combustion (oxy-combustion process) (Yadav and Mondal 2022). In addition, there is a fourth process, unrelated to the previous three, and it is the technology of capturing $CO_2$ directly from the air called Direct-Air-Capture (DAC; more about it in the literature (Deutz and Bardow 2021; McQueen et al. 2021; Mostafa et al. 2022)). In each of the abovementioned technologies, the following $CO_2$ share enrichment methods presented in Figure 2 could be adopted.

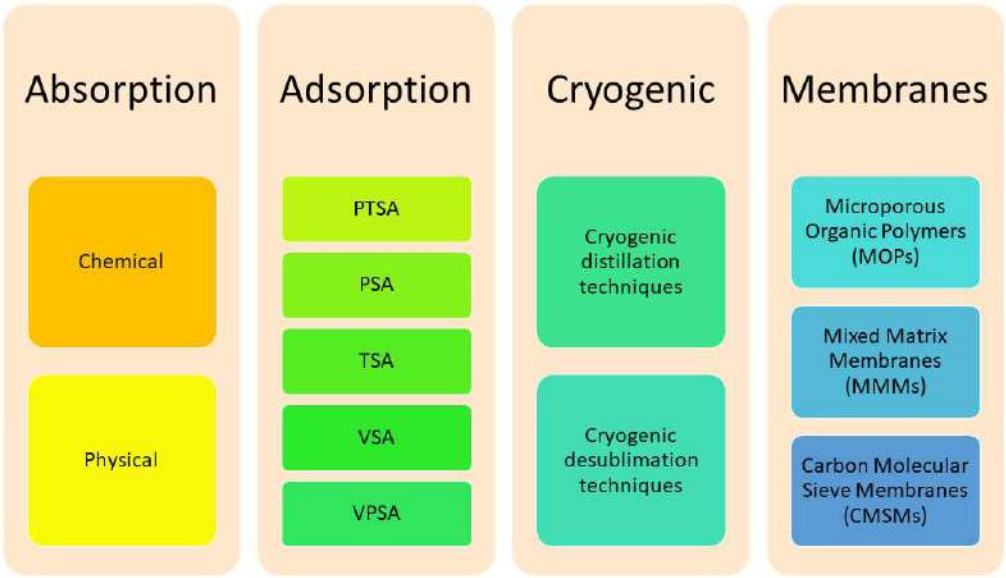



Figure 2 Carbon capture methods.

Furthermore, each capture technology offers different purities of the $CO_2$-enriched stream, with the highest purity offered by post-combustion technologies (~99.6%), followed by the $CO_2$ stream from pre-combustion capture (~98%) and lastly by a oxy-combustion capture (~96%) (Majchrzak-Kucęba 2022). The detailed summary of $CO_2$-enriched stream purity is presented in Table 1.

Table 1 The impurities in $CO_2$-enriched stream from different carbon capture technologies (Majchrzak-Kucęba 2022).

| Composition | Units | Oxy-fuel combustion | Pre-combustion | Post-combustion |
|---|---|---|---|---|
| **$CO_2$** | % | 99.3-99.4 | 95-99 | 99.6-99.8 |
| **$N_2$** | % | 0.01- 0.2 | 0.0195-1 | 0.045- 0.29 |
| **$O_2$** | % | 0.01-0.4 | 0 | 0.015-0.0035 |
| **Ar** | % | 0.01- 0.1 | 0.0001- 0.15 | 0.0011- 0.021 |
| **$SO_2$** | ppmv | 37-50 | 25 | 0-61.1 |
| **$NO_x$** | ppmv | 33-100 | 400 | 20-38.8 |
| **$H_2O$** | ppmv | 0-100 | 0.1-600 | 100-640 |
| **CO** | ppmv | 50 | 0-2000 | 1.2-10 |
| **$H_2S$/COS** | ppmv | - | 0.2-34 | - |
| **$CH_4$** | ppmv | - | 0-112 | - |
| **$H_2$** | ppmv | - | 20-130 | - |

Accordingly, depending on the assignment of $CO_2$-enriched stream it is possible that further purification will be required. The following subsections describe these issue in more detail. The next, but not least issue is the technological readiness of $CO_2$ capture technologies for industrial application. As shown in Table 2, capture technologies are already being used on an industrial scale in natural gas processing or for ammonia production, but capture technologies for the cement or pulp and paper industry have yet to leave the pilot scale.

Table 2 Summary of carbon capture technology readiness in selected economic sectors (author's compilation based on (Global CCS Institute 2016; Wawrzyńczak et al. 2022a)).

| Economy sector | Scale of plant | | |
|---|---|---|---|
| | laboratory | pilot | industry |
| **Natural gas** | | x | x |
| **Ammonia production** | | | x |
| **Biofuels** | | x | x |
| **Hydrogen production** | | x | x |
| **Iron & Steel** | x | x | x |
| **Cement industry** | x | x | |
| **Fuels** | x | x | |
| **Pulp & paper industry** | x | x | |

### 1.2.1.2 $CO_2$ transport

The captured $CO_2$ has to be transported to the place of final destination. This is the necessary intermediate step between capture and storage or utilization.

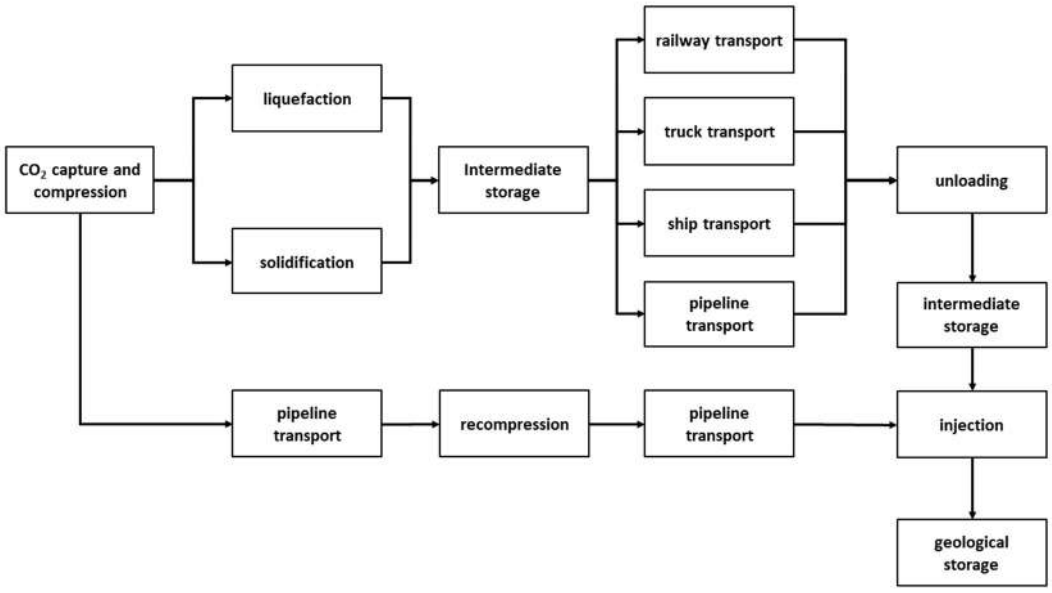



Figure 3 The $CO_2$ transport supply chain based on (Wildbolz 2007).

As shown in Figure 3 the $CO_2$ can be transported by pipeline, ship, railway or truck. The $CO_2$ can be transported in solid or liquid state hence, transport in the solid state (dry ice) is technically possible, although, as presented in Herold et al. 2011 (Herold et al. 2011) the amount of energy required to cool $CO_2$ (375 kWh/t$CO_2$) is four times higher than for transport in the liquid state (96 kWh/t$CO_2$). Of all the methods, pipelines are a highly developed and established technology that is also the most widespread method of transporting liquid and gaseous commodities either locally or globally. This technology shares many similarities with the technology and economics of natural gas transport. The pipeline network can be planned and constructed as a point-to-point or in the meshed network system. However, in order to transport captured $CO_2$, its enriched stream must meet certain purity requirements. The recommended impurity limits for $CO_2$ transport for storage are summarized in Table 3.

Table 3 Recommended impurity requirements in $CO_2$ enriched stream (Shirley and Myles 2019).

| **Component** | **Unit** | **Carbon steel pipeline** | | **EOR** | | **Saline reservoir storage** | |
|---|---|---|---|---|---|---|---|
| | | Conceptual design | Range in literature | Conceptual design | Range in literature | Conceptual design | Range in literature |
| **$CO_2$** | vol% | 95 | 95-99.8 | 95 | 95-99.8 | 95 | 95-99.8 |
| **$H_2O$** | ppmv | 500 | 20-650 | 500 | 20-650 | 500 | 20-650 |
| **$N_2$** | vol% | 4 | 0.01-7 | 1 | 0.01-2 | 4 | 0.01-7 |
| **$O_2$** | ppmv | 10 | 10-40000 | 10 | 10-13000 | 10 | 10-40000 |
| **$SO_2$** | ppmv | 100 | 10-50000 | 100 | 10-50000 | 100 | 10-50000 |
| **$NO_x$** | ppmv | 100 | 20-2500 | 100 | 20-2500 | 100 | 20-2500 |

Furthermore, essential for pipeline transport of captured $CO_2$ is the nominal pressure (usually above 8 MPa) and pressure gradient in the pipeline. It is important to correct the pressure gradient in intermediate compression stations to avoid two-phase flows and increase gas density (Herold et al. 2011). Furthermore, at the compression stage,

it is crucial to have an effective system to remove dust and water droplets before the compression train to avoid corrosion of the compressor blades (Anheden et al. 2005).

#### 1.2.1.3 $CO_2$ storage

As mentioned in **Chapter 1.1, P1** by Popielak et al. 2024 (Popielak et al. 2024) further paths for captured $CO_2$ can be divided into utilization and/or storage. The captured $CO_2$ is transported and subsequently injected under pressure to the final storage site. $CO_2$ storage can be categorized as onshore and offshore methods, subsequently expanding on the specific variety of geological formations in which $CO_2$ storage occurs i.e. (1) saline formations. (2) depleted (and depleting) oil and natural gas reservoirs, (3) unmineable coal beds, (4) basalt formations and (5) shale formations (Leung et al. 2014; Kearns et al. 2017; Turgut et al. 2021). As mentioned by Harding et al. 2018 (Harding et al. 2018), to perform underground storage of $CO_2$ three main principles have to be met: (1) the identified capacity should be capable of holding large amounts of $CO_2$, (2) there should be a possibility to inject a $CO_2$ into the underground formation at site, and (3) $CO_2$ should be safety stored in the formation for indefinitely time. Lastly, noteworthy is the fact, that Europe has strong possibilities to underground storage of $CO_2$ (Neele et al. 2006; Vangkilde-Pedersen et al. 2009a, b) as well as to transport it via vast network of oil and natural gas pipelines (DNV AS and Carbon Limits AS 2021).

#### 1.2.1.4 $CO_2$ utilization

On the other hand, for utilization $CO_2$ is treated as a feedstock (with or without conversion) for other industrial processes, for example, the production of fuels (Bonura et al. 2021; De Falco et al. 2022; Okoye-Chine et al. 2022), chemicals (Alper and Yuksel Orhan 2017; Koytsoumpa et al. 2018a; Cordero-Lanzac et al. 2021; Chehrazi and Moghadas 2022), polymers (Bachmann et al. 2021), building components (Batuecas et al. 2021; Monteiro and Roussanaly 2022), in the food industry for the production of fizzy drinks (Hosseini et al. 2023), the horticulture industry for plant growth enhancement (Marchi et al. 2018). Each carbon dioxide utilization technology not only has its requirements in terms of the quality and parameters of the $CO_2$ stream but also the potential and efficiency with which the captured $CO_2$ can be converted into

a new product as presented in (**Chapter 1.1, P1 - Chapter 2 Fig.3** (Popielak et al. 2024)). The highest $CO_2$ feedstock purity is required for the food industry, while mineral carbonation production has one of the lowest purity requirements. More details are presented in Table 4.

Table 4 $CO_2$ stream purity requirements in selected sectors application.

| Sectors of industry | $CO_2$ purity (%) | Purity requirements | Ref. |
|---|---|---|---|
| **EOR** | 95-99 | $CO_2$ above 95%, impurities such as water, sulphur oxides ($SO_x$), nitrogen oxides ($NO_x$ < 100 ppm), oxygen ($O_2$ < 100 ppm), and hydrocarbons must be minimized as they can corrode pipes and equipment in oil fields, and affect process efficiency | (Ho et al. 2019; Majchrzak-Kucęba 2022) |
| **Mineral carbonation** | 6-99.9 | Impurities, such as $NO_x$ and $SO_x$, present in the $CO_2$ stream do not affect the carbonation reaction | (Ho et al. 2019; Nogueira et al. 2022) |
| **Chemicals and fuels conversion** | 95-99 | The presence of impurities can affect catalysts, chemical reactions, and product quality. Even a small concentration of, e.g., hydrogen sulfide totally deactivates the catalysts with sulphur and arsenic compounds are common poisons for metals in hydrogenation, dehydrogenation, and steam reforming reactions. The reaction catalysts must be selected to suit the impurities contained in the enriched $CO_2$ stream, and be able to operate at a high $CO_2$ concentration in the waste gas stream. | (Ho et al. 2019; Majchrzak-Kucęba 2022) |
| **Food industry** | 99 | Impurities like aldehydes, alcohols, nitrogen oxides, and carbon oxides must be almost completely removed to prevent flavour, odour, and food safety issues | (Ho et al. 2019; Van Peteghem et al. 2022; Hosseini et al. 2023) |

Due to $CO_2$ purity requirements, there are several possible techniques for cleaning gas stream have been developed e.g.: physical adsorption (Belmabkhout et al. 2010), chemical adsorption (Pan et al. 2012), chemical absorption (Dumée et al. 2012), physical absorption (Zhang et al. 2008), membrane separation (Adewole et al. 2013).

Although $CO_2$ utilization is and can be applied in the production of chemicals, oil extraction, food, and metallurgical industries, and other numerous industrial and

economic sectors, the largest estimated demand for $CO_2$, in the order of 100 Mt/year, is for the production of urea (Global CCS Institute and Parsons Brinckerhoff 2011; Wawrzyńczak et al. 2022a). A detailed analysis is presented in the author's publication (**P1**) (Popielak et al. 2024), and more detail in the following literature (Cuéllar-Franca and Azapagic 2015a; Patricio et al. 2017; Koytsoumpa et al. 2018b; Chauvy and De Weireld 2020). Furthermore, the following paragraphs outline in detail the selected $CO_2$ utilisation methods – $CO_2$ conversion into dimethyl ether, methanol and manufacturing of carbonate concrete.

**Dimethyl ether production**

Dimethyl ether (DME - $C_2H_6O$) is an almost odourless, colourless gas under ambient conditions. It's the simplest aliphatic ether, which can be used as a fuel or be blended with existing ones such as diesel oil (e Silva 2006; Kim et al. 2008; Anggarani et al. 2014; Catizzone et al. 2017a, 2021; Fortin et al. 2020; De Falco et al. 2022). Nowadays it's considered as an alternative and green fuel. DME production reaction in the way of direct synthesis stands as follows:

$$2CO + 4H_2 \rightarrow 2CH_3OH \quad (1)$$

$$2CH_3OH \rightarrow CH_3OCH_3(DME) + H_2O \quad (2)$$

$$H_2O + CO \rightarrow H_2 + CO_2 \quad (3)$$

In total:

$$3CO + 3H_2 \rightarrow CH_3OCH_3(DME) + CO_2 \quad (4)$$

The second method of obtaining DME is by methanol dehydration:

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \quad (5)$$

Methanol formation

$$CO_2 + 3H_2 \rightarrow CH_3OH \quad (6)$$

Methanol dehydration

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \quad (7)$$

Reverse water-gas shift (rWGS)

$$CO_2 + H_2 \rightarrow CO + H_2O \quad (8)$$

Net reaction

$$2CO_2 + 6H_2 \rightarrow CH_3OCH_3 \quad (9)$$

The substrate in the DME reaction process could be carbon dioxide which when combined with hydrogen (which supply issues are described in details further in this Chapter), especially produced with energy support from renewable energy sources (RES), can be a very economical and environmentally friendly way of consuming this gas (Catizzone et al. 2017a; Makoś et al. 2019; De Falco et al. 2022; Wawrzyńczak et al. 2022a).

**Methanol**

Methanol is a colourless, flammable liquid (under ambient conditions) with a characteristic odour, with a very good solute and blends easily with water, alcohols and organic solvents. As a key substrate in many syntheses of chemical compounds, including formaldehyde, acetic acid and chloromethane (De Falco et al. 2022). The demand for methanol is steadily increasing, e.g from 47 Mtpa in 2011 (Ott et al. 2012) to 100 Mtpa in 2021 (IRENA and Methanol Institute 2021). According De Falco et al. 2022 (De Falco et al. 2022) and report from the International Renewable Energy Agency (IRENA and Methanol Institute 2021), in 2021 only 0.2% of the world's methanol production came from RES, with more than 60% from fossil fuels.

Methanol can be synthesized from gas containing carbon monoxide or carbon dioxide, and the reaction is based on an exothermic hydrogen synthesis reaction:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad (10)$$

$$CO + 2H_2 \rightarrow CH_3OH + H_2O \quad (11)$$

The main properties of DME and MeOH in comparison with LNG and diesel oil are shown in Table 6 (De Falco et al. 2022). Additionally, several potential major applications of DME and MeOH are summarized in Table 5.

Table 5 Potential application of DME and MeOH (De Falco et al. 2022).

| Application of DME or methanol | Possible potential of application |
|---|---|
| **LPG substitute** | High |
| **Power generation** | High |
| **Aerosol Propellant** | Medium |
| **Chemical industry** | High |
| **Diesel Oil Substitute** | High |

Table 6 Properties of DME and methanol in comparison to other fuels (De Falco et al. 2022).

| Properties | DME (Müller and Hübsch 2000) | Methanol (Ott et al. 2012) | Methane* (PubChem) | Diesel Fuel (2015) |
|---|---|---|---|---|
| **Molecular formula** | $C_2H_6O$ | $CH_4OH$ | $CH_4$ | N/A |
| **CAS Number** | 115-10-6 | 67-58-1 | 74-82-8 | 68334-30-5 |
| **Molar mass [g/mol]** | 46.07 | 32.04 | 16.04 | N/A |
| **Cetane number** | 55 to 60 | ~5 | 0 | 40 to 55 |
| **Melting point [°C]** | -141 | -97.88 | -182.47 | -40 |
| **Boiling point [°C] at 1 atm** | -24.8 | 64.65 | -161.5 | 141 |
| **Density at 25°C and 1 atm [kg/m$^3$]** | 668.3 | 786.68 | 0,657 | 800-910 |
| **Autoignition temperature [°C]** | 235 | 440 | 537 | 250 |
| **Miscible with water?** | Yes | Yes | Yes | No |
| **Miscible with organic solvents?**** | Yes | Yes | Yes | Yes |

* Methane as main part of Liquid Natural Gas (LNG)

** with most popular polar and nonpolar organic solvents

DME is considered to be a new generation of fuels, and methanol can be easily blended with gasoline in various ratios from 3% up to 10% (De Falco et al. 2022). Both – DME and MeOH have very high possible applications as (1) a substitute for LPG and diesel fuel, (2) in power generation (DME in gas turbines, MeOH in methanol-fired

turbines), (3) in the chemical industry (possibilities for MeOH are better as it is widely used in formaldehyde, acetic acid, and chloromethane production; DME can be used as an aerosol propellant in spray cans and substrate in olefins production) (De Falco et al. 2022).

**Hydrogen**

Hydrogen is essential component in aforementioned DME and MeOH production processes. It can be produced in several different ways e.g.: steam-methane reforming (SMR) (Dincer et al. 2018), coal gasification (de Miranda 2019), biomass gasification (Rubinsin et al. 2024), oil and naphtha reforming (Melo and Morlanés 2005), biological hydrogen production (Khetkorn et al. 2017), water electrolysis (El-Shafie 2023). Nowadays about 95% of hydrogen production is fossil-based, mainly from natural gas (which is additionally the EU's energy transition fuel set up in the EGD), where it is called "blue hydrogen" ((**P1**) (Popielak et al. 2024) and (Bonura et al. 2022)). On the other hand the SMR technology is the most widespread hydrogen production process based on a course of reactions of superheated steam with syngas or light hydrocarbons (e.g. methane or biogases) (Dincer et al. 2018). The end products of the various stages, as well as the entire process, are carbon oxides and hydrogen. The efficiency of the process is about 75-80%, with the purity of the hydrogen stream about 95-99.8% (Dincer et al. 2018). The SMR is estimated to emit 9 kg of $CO_2$ per 1 kg of $H_2$ produced (Simons and Bauer 2011; Cetinkaya et al. 2012). Since hydrogen is considered as a fuel of the future and additionally serves as a reactant in the CCUS technology supply chain, it's production should have the least possible impact on the environment. Therefore, hydrogen should be produced by water electrolysis (**P4**) (Facchino et al. 2022), which is more environmentally friendly, allowing the production of a high-purity hydrogen stream without releasing harmful GHGs into the atmosphere (Vidas and Castro 2021). Furthermore, hydrogen transport and storage are two crucial topics. Transportation processes could be by truck (liquefied or compressed), ship (liquefied), or as gaseous hydrogen through a pipeline network (or blended with natural gas in the current natural gas pipeline network), while storage can be done in the way of compression, liquefaction and by chemical processing (Vidas and Castro 2021).

Lastly, noteworthy is the fact that hydrogen can be treated as a carrier for chemical energy storage solution (Tang et al. 2023).

**Carbonate concrete**

As mentioned by Nogueira et al. 2022 (Nogueira et al. 2022) “concrete is the most widely used construction material, being considered fundamental for the development of societies around the world. It has the second highest annual volume consumption, only surpassed by water.” The first step in the carbonate concrete manufacturing process is the preconditioning stage. At this stage, samples are cast and placed in relatively dry conditions for hardening (conditioning parameters: 20-25°C, relative humidity (RH) 40-60%, in comparison to conventional curing conditions: relative humidity higher than 95%). In traditional conditioning, the pores of concrete are saturated, and $CO_2$ is unable to penetrate them. However, preconditioning for mineral carbonation allows the water content in the pores to be reduced, which subsequently allows $CO_2$ to penetrate the pores more freely. The second stage is the carbonation of concrete in a closed or flow-through system. The required environmental conditions are 60-70% relative humidity and 20-40°C temperature for an effective carbonation process. The third and final stage is post-conditioning, in which concrete samples are cured under humid conditions (relative humidity greater than 95%) (Nogueira et al. 2022). The $CO_2$ absorption during the carbonation process is in the range of 20 to 50 kg $CO_2$ per $m^3$ of concrete and is highly dependent on both the conditions of the carbonation stage and the chemical and microstructural properties of the cement-based material to be cured (Nogueira et al. 2022). For the mineral carbonation process, the purity requirements of the $CO_2$ stream are not very high, and impurities, such as $NO_x$ and $SO_x$, present in the $CO_2$ stream from industrial usage do not affect the carbonation reaction. However, it should be acknowledged that higher $CO_2$ concentrations will have a positive effect on the kinetics of the process. Nevertheless, concentrations of less than 25% $CO_2$ can also be used successfully in the mineral carbonatation process (Majchrzak-Kucęba 2022).

## 1.2.2 Policy and implementation

According to the Zero-Emission Platform – the European Commission's technical advisor – there are 66 ongoing CCUS projects all over the EU and European Economic Community (EEC), with most of the projects considering $CO_2$ transport and storage or implementation in industry (Zero-Emission Platform). In **Chapter 1.1, P1, Table 4** (Popielak et al. 2024) the top 10 EU member states are collected and presented together with the number of CCUS projects, from planned to operational.

Furthermore, according to the Global CCS Institute, as of September 2021, there are 135 CCS facilities worldwide (operational and under various development stages) with a total capture capacity of about 150 Mtpa (Dziejarski et al. 2023). For the year 2021, compared to 2020 (approx. 75 Mtpa capture capacity), the number of projects increased by 48% (Global CCS Institute 2021). Additionally, nowadays in 2024, the world's $CO_2$ capture and storage capacity is estimated at 44 million tonnes per year (IEA 2024). The global contribution of CCS technology is estimated to reduce greenhouse gas emissions by 19% by 2050 (U.S. Energy Information Administration 2016).

Although the increase in the new CCUS facilities is greater today than it was a few years ago, the IEA estimates that between 30 and 60 new facilities would need to be commissioned annually over the next few years until 2050 to meet the climate targets (IEA 2017a). Unfavourable policies and hiatus in action from many countries government's side is often cause stagnation in CCUS development (Scrase and Watson 2009; Read et al. 2014; Tucker and Tinios 2017; Vögele et al. 2018; Nikas et al. 2021; Nijborg 2022; Otto et al. 2022). Unfortunately, nowadays, the deployment of CCUS technology is too slow for it to have a significant role in reducing greenhouse gas emissions at the lowest possible cost. In an effort to limit the increase in global temperature above 2°C (relative to the global average temperature before the industrial era) the International Energy Agency (IEA) has proposed a Sustainable Development Scenarios (SDS), which sets out 39 technologies and solutions as a tool to achieve the Paris Agreement goals (IEA 2020). The problem is that only seven technologies are currently applicable, including CCS (Global CCS Institute 2019).

Therefore, support from the governmental side is tremendously important. The European Union can be considered as an example of excellence on a global scale, where the CCUS technology has been supported by several legislations from the European Parliament for several years.

The **Table 1** in **Chapter 1.1, (P1)** summarises the most important legal acts identifying CCUS technology as a resource in the mitigation of climate change, and in the pursuit of climate neutrality - including - in line with the latest climate agenda in force, i.e. the European Green Deal (European Commission et al. 2021).

However, it is worth noting that it is not only the EU that promotes CCUS technology in climate change mitigation. The United States had been a leader in CCS technologies between 2007 and 2017, but the sector has stagnated due to high investment costs. In 2018, the government passed a budget act providing tax credits favourable to Renewable Energy Sources, energy efficiency technologies, nuclear energy, and also including $CO_2$ capture and storage technologies. The law is intended to stimulate investors and help to implement the Paris Agreement (IEA 2018).

Norway, in cooperation with the UK, has been developing and implementing new solutions for storing $CO_2$ in the North Sea for many years (Zero Emission Platform 2019; $CO_2$ Stored Project Homepage). For example, the installation at Sleipner (UK) is one of the more recognizable CCS facilities in the world. It was the first industrial-level installation operating offshore (Furre et al. 2017). In Europe itself, numerous countries are developing roadmaps and projects that provide information on the feasibility of CCUS installations (Halland et al. 2011; IOGP 2019).

As described in (**P1**) (Popielak et al. 2024) in June 2019, six months before the European Green Deal (EGD) was first introduced, the UK government furthered this ambitious goal by setting a legal target to achieve net zero GHG emissions across in the UK by 2050, thereby making the UK the first major global economy to legislate a net zero target (The UK Government 2019). As shown in **Chapter 1.1 (P1) - Table 4 and Table 5**, the UK is leading in Europe and it's in top 5 global leaders in CCUS supply chain projects development (The UK Government 2022). Due to the Industrial Decarbonization Strategy set by the UK's government in March 2021, the CCUS has solid support (The UK Government 2021). In addition, the UK has potent reservoirs for

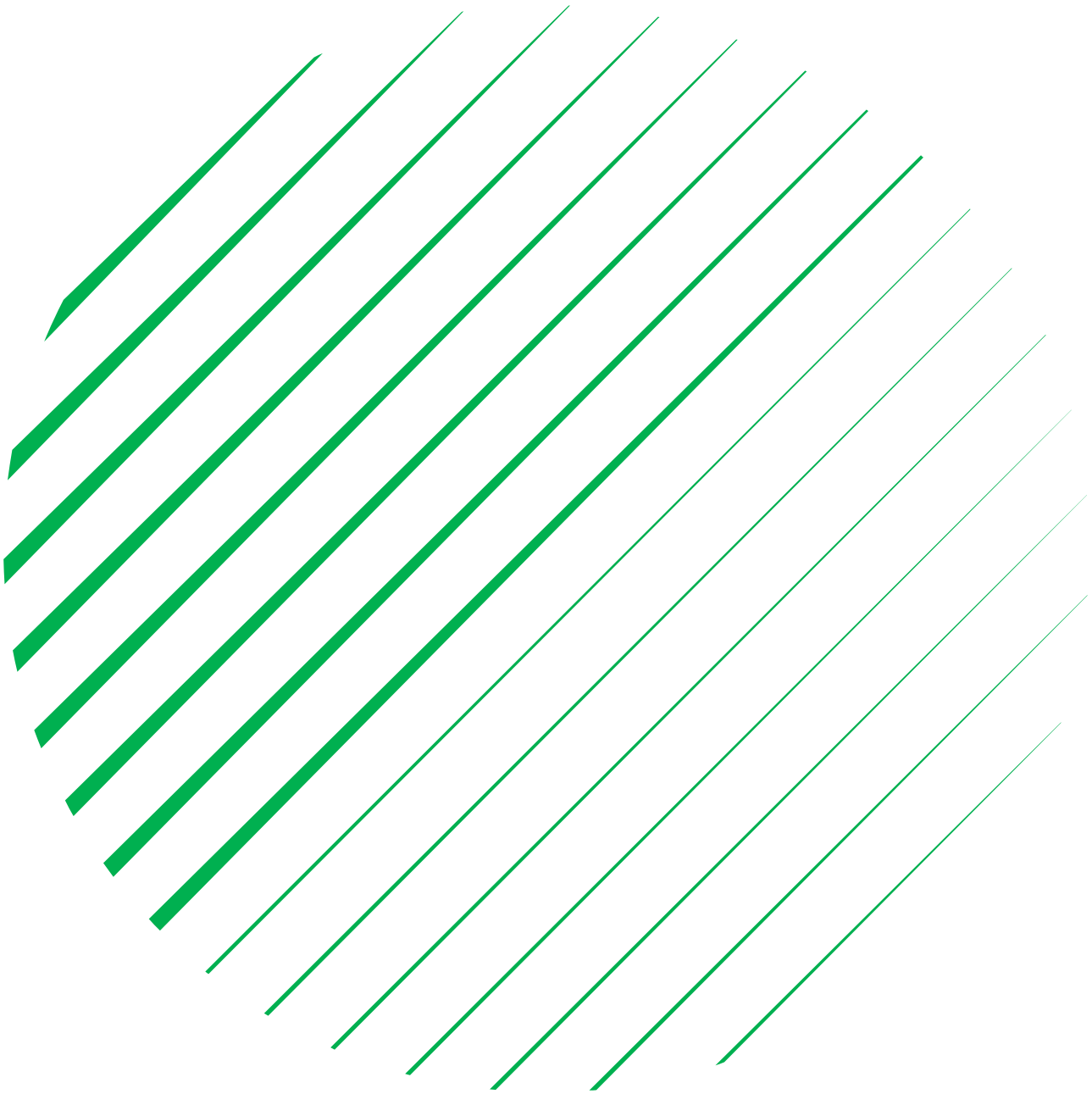
underground storage of $CO_2$ (Holloway 2009; Höller and Viebahn 2011). According to the government's UK Investors CCUS roadmap ambition is to capture 20-30 $MtCO_2$, including 6 $MtCO_2$ of industrial emissions, per year by 2030, with net-zero emission target by 2050 (The UK Government 2022).

Japan's location means that it is under constant risk of seismic shocks, with all their implications. However, this does not hinder research and the search for $CO_2$ storage in offshore caverns. One of the projects is developing near the town of Tomakomai, located on the island of Hokkaido (Gulf Coast Carbon Centre 2018). The port located there is one of the largest in the northern part of Japan. As it is a heavily industrialized area, building a CCS facility there has met with approval from local authorities and investors (Japan CCS Homepage 2024)

China is also not far behind in the climate protection race. As a highly industrialized country, it is also one of the world's largest emitters of greenhouse gases. Although China is not a signatory to the Kyoto Protocol, it is nevertheless one of the world's most rapidly developing centres of new technology. A growing number of renewable energy facilities are currently being built there. In addition, $CO_2$ capture and utilization technology is of interest to the Chinese authorities. It is planned that by 2050, CCS technology will be responsible for reducing national $CO_2$ emissions by as much as 35%. (IEA 2017b; Jiang et al. 2020).

CCUS technology is being considered as a tool to achieve decarbonization, and low or net-zero emissions. However, holistic research on CCUS is needed to determine what environmental benefits and risks it carries. The full CCUS supply chain has to be evaluated, as only in this way it will be possible to identify the environmental hotspots of this technology, and therefore the possibilities for its further development or environmental performance improvement. Such holistic studies, with the use of environmental assessment tools (i.e., Life Cycle Assessment tools), will make it possible to indicate which elements of the CCUS chain require the most development, and which paths should be revised or discounted in the studies due to their disadvantageous environmental impact. Only in this way, by way of a comprehensive environmental assessment, can the technology be evaluated and thus affect its further development and industrial application. Such analyses are also a supporting tool for stakeholders and policymakers.

# Chapter 2 LCA for CCUS: Environmental Impact Assessment



## 2.1 Background and Perspective

Together with environmental awareness increase, the environmental performance of products and processes has become a worldwide issue and can be addressed with a Life Cycle Assessment (LCA) analysis. The LCA analysis is a methodology with a holistic, comprehensive approach to evaluating the environmental impacts of a product or service through its part or entire life cycle (Baitz et al. 2013). It allows for a deep understanding of how environmental impacts are connected to any production process, usage, or service and allows investigation of environmental weak points and hotspots. This is a unique and versatile tool as it considers all emissions and flows into and from the environment (including different compartments of the environment) at each stage of the life cycle of a product or service. It allows for a comprehensive evaluation of the entire supply chain, production, disposal, recycling or end-of-life treatment - from the extraction of raw materials to the end-of-life stage.

The main benefits of performing an LCA for processes and products are:

- Evaluation of the environmental burdens and consequences associated with the studied product.
- Identification of environmental hotspots of the supply chain.
- Quantifying environmental releases to the environment compartments such as air, soil, and water (freshwater and/or seawater) at each stage of the product's life cycle.
- Avoid greenwashing by validation of the environmental benefits of the product.
- Recognition of flow transfer in/out environment compartments with identification of shifting impacts between life cycle stages.
- Supporting environmental-friendly decision-making for policymakers and stakeholders.
- Comparison of products/processes by developing different scenarios.

The first attempt to calculate the impact of the process (cumulative energy requirements for the production of chemical intermediates and products) was made by Harold Smith. He reported his calculation at the World Energy Conference in 1963

(NEPIS 2006). After that, a few years later (in 1978) was founded *The Society of Environmental Toxicology and Chemistry* (SETC) which has been associated with the establishment of two main strands of LCA study: American and European. The milestone was in 1997 when the *International Organization for Standardization* (ISO) established the 1404x documents series, defining certain guidelines for the LCA (Life Cycle Assessment) calculations (Finkbeiner et al. 2006).

Last but not least, LCA is widely used in both – academia and industry - for calculations of environmental performance analysis as well as for Product Environmental Footprint (PEF), almost without limitation regarding field and topic. Therefore, it is a valuable and powerful tool to investigate technologies marked as a tool in climate change mitigation i.e. CCUS (Corsten et al. 2013; Garcia-Garcia et al. 2021).

More details on LCA analysis are described further in **Chapter 5** and in **P2-P4** (Facchino et al. 2022; Falco et al. 2022; Popielak et al. 2024).

## 2.2 An overview of the LCA method

The International Standards Organization (ISO) had standardized efforts to calculate all processes along a product's life cycle in the ISO standards from 14040 to 14044. The procedure for the calculation and preparation of LCA modelling is carried out in four steps, as shown in Figure 4: (1st step) preparation of the goals and scope of work, in which the basic issues that determine the foundation for the calculation are defined, (2nd step) preparation of a set of input and output data along with the connections and links between them (Life Cycle Inventory), (3rd step) making calculations according to the selected methodology (Life Cycle Impact Assessment), and (4th step) the summary and conclusion (Life Cycle Interpretation).

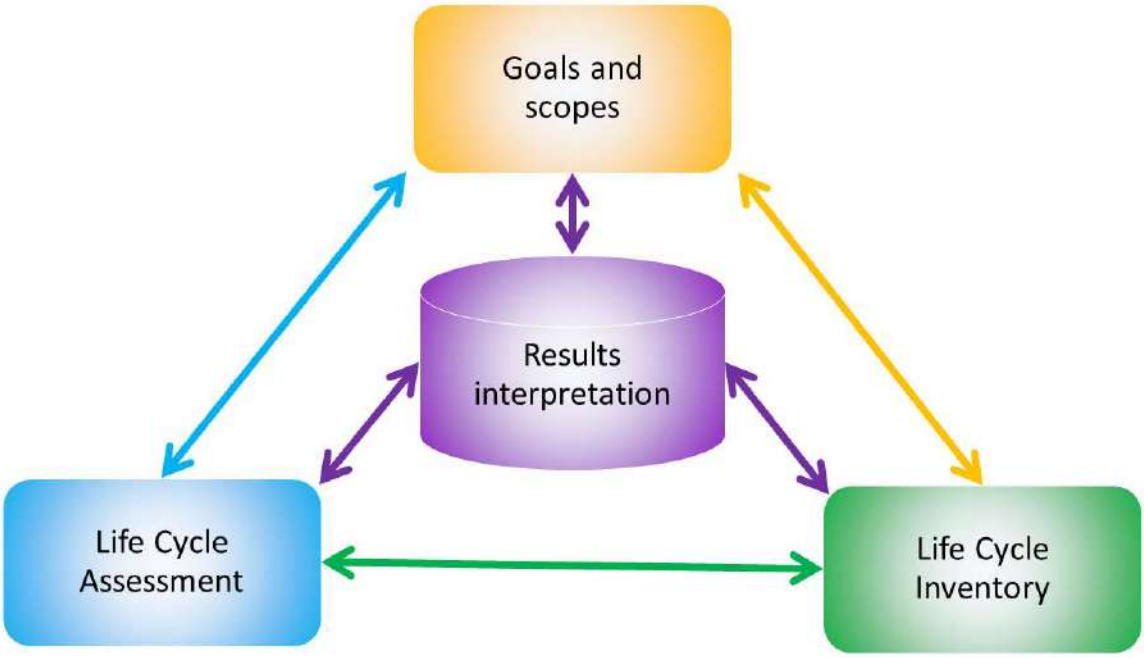



Figure 4 Life Cycle Assessment - main principles.

There are various types of LCA analysis depending on the system boundaries and cut-offs. Therefore, the following types of analysis can be identified: the life cycle of a product or service (product-to-product, cradle-to-grave, cradle-to-cradle, cradle-to-gate, gate-to-gate, gate-to-grave, etc.).

Goals and scopes are first steps of LCA process. For setting up goals the following aspects have to be defined: (1) the purpose of the study, (2) investigated product, process or service, (3) system boundaries and functional unit, (4) target audience of

the study, (5) demanded accuracy of the results together with the way of presenting final report in order to be valuable for defined audience. Especially the last two points are have significant importance, as different will be presentation of LCA results for Product Environmental Footprint (PEF) (EPLCA 2024) declaration and different for an academic manuscript considering different supply chain scenarios. Setting up meaningful goals of LCA analysis could leverage value of obtained data.

At this point, it is also necessary to decide on the availability of foreground and background data - and what quality of data is required for the analysis to be carried out. Related to this question is another one concerning the database in which the analysis is planned to be carried out. For 2024, the largest databases available are Managed Life Cycle Assessment Content Database (MLC DB), ecoinvent and CarbonMinds. Each of these databases has its strengths and limitations, however, each is different and represents a different data quality and dataset. Results from one database should never be compared to results from another database - only within one of them. For the purpose of this thesis and all the articles contributing to it, it was decided to use processes and models from ecoinvent.

It is also important to acknowledgment the distinction between foreground and background data, where foreground system refers to the top level system, the primary model system. The background data are all lower level elements of supply chain, such as: raw material acquisition, energy systems, material production – depending on what is foreground system concerned about. Background dataset should reflect as best as possible concerned technology and geographical representatives of investigated case, corresponding with foreground data, and presents certain level of accuracy and quality.

Defining of functional unit should reflect the function of process or product investigated in the LCA analysis. It should be allow for make systems comparable e.g. 1 kg of product or1 kWh or produced electricity etc. The scope of LCA should correspond with goals of study and set up limitations of the model within system boundaries. It should determine if and what cut-off can be applied with demanded data and results accuracy and what part of entire life cycle of a product or process should be investigated.

Second step is Life Cycle Inventory or Inventory Analysis where all inputs and outputs from each stage of supply chain are identified and quantified. Those inputs and outputs

are so-called “flows” which can be: energy, water, raw materials, emissions to air, soil, waste water discharge etc.

The Life Cycle Impact Assessment is the third step in LCA analysis. The goal of this step is to identify the environmental burdens of the modelled process. All environmental flows (as only these will have an environmental footprint) identified and collected in the model inventory are assigned to their respective environmental impact categories. There is a possibility where one or more of substances appears in different impact assessment categories, additionally affecting different aspects of the environment - known as 'compartments'. Examples of such compartments include emissions to freshwater, seawater, land (soil), air. Each flow present in the inventory, once assigned to the appropriate category and compartment, is multiplied by a characterisation factor determined by the chosen method, to characterize flows to common units for comparison purpose. Specific details on chosen LCIA methods are described later in **Chapter 5** as well as in **Chapters 6-8, P2-P4** of this work.

The last – fourth step is results interpretation, where results given from inventory analysis and LCIA steps are evaluated. Analysis of results should include: (1) define of how applied cut-offs, system boundaries and other assumptions and limitations set up in other steps have an impact on the results, (2) further study recommendations based on findings, (3) consistent and understandable presentation of obtained results. In this step values are not simply the only one indicator to benchmark, when higher value in one impact assessment category means worse than lower value in other category. It is crucial to look at results through set up previously goals and scopes of analysis and it is important not to draw premature conclusions just on the basis of a snapshot analysis of the quantitative findings. It is important to analyse the results obtained carefully and in detail, taking into account different scenarios. In the end, an LCA will still allow for a deeper and more comprehensive understanding of the environmental challenges posed by the product, process or service under investigation. However, it is important to emphasise that an LCA is only a partial analysis of a product or process, and in the broader framework the studied object should also be analysed for technical efficiency and optimisation, as well as social and economic analyses should also be undertaken.

## 2.3 Application of LCA for CCUS supply chain evaluation

As mentioned earlier in this chapter, the LCA analysis is a well-known and commonly used environmental assessment tool with powerful capabilities, additionally standardized by ISO standards. It is indeed an outstanding tool for examining the environmental impacts of the state-of-the-art technologies designated as tools in the effort to address climate change and to achieve climate neutrality goals. LCA analysis makes it possible to model and explore how the environment and the technosphere interact - as shown in the Figure 5.

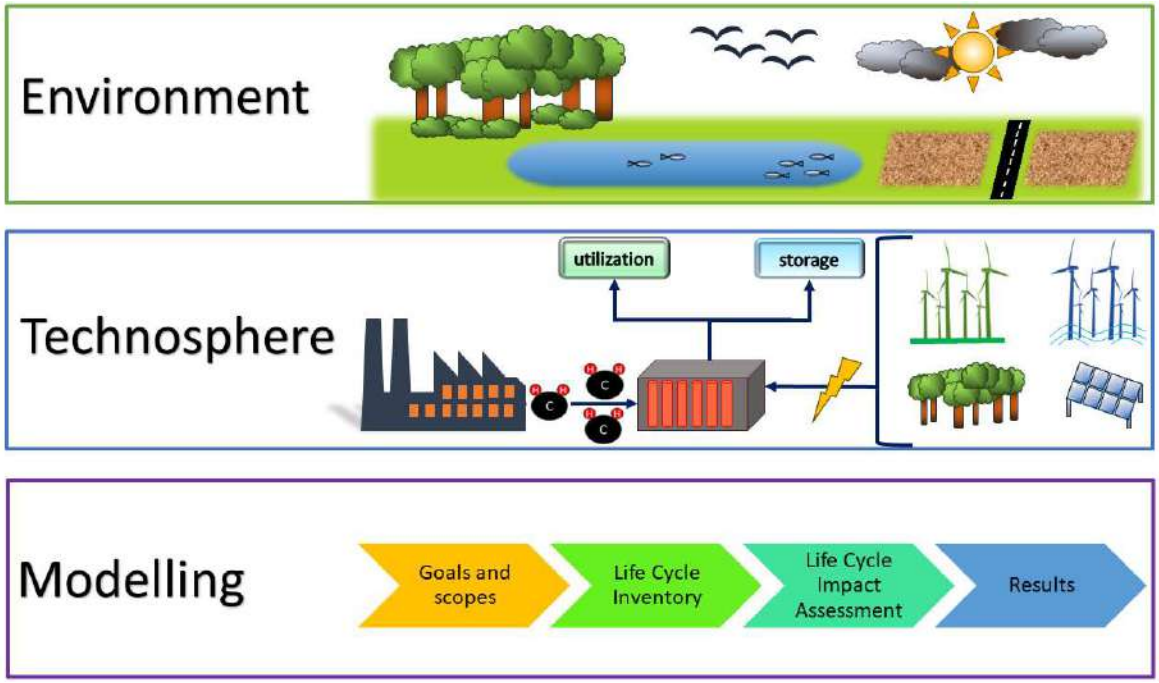



Figure 5 LCA for environment and technosphere evaluation.

In the case of CCUS supply chain, LCA analysis makes it possible to: (1) provide a comprehensive overview of the environmental impact of these technologies (taking into account the various impact assessment categories), (2) examination of CCUS technology supply chain hotspots, i.e. areas where emissions are most significant and can be subsequently reduced, (3) determination of the environmental footprint reduction for primary technology before and after the application of the CCUS technology supply chain, (4) support the design of CCUS technologies in the most environmentally friendly manner, (5) enable benchmarking of CCUS technology supply

chain to identify the one with the greatest benefits for a given case study, (6) to understand the necessity of the actual environmental impact of these technologies and to develop strategies to optimise them for maximum environmental benefit. As shown in Figure 6, there has been an increasing tendency over 2013 – 2019 period for published studies of LCA analysis for CCUS chain evaluation.

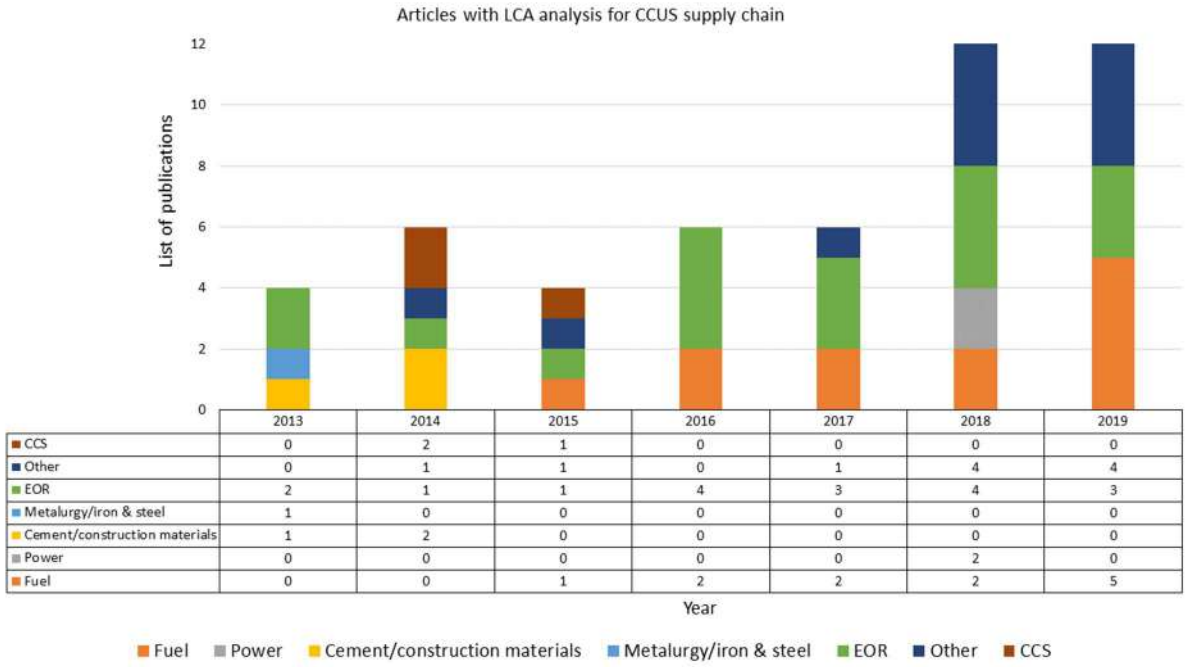



Figure 6 Literature screening for LCA for CCUS supply chain articles in Google Scholar database.

The period of the literature review conducted was limited to 2019 as this was the year in which this dissertation topic has been undertaken, and the literature screening was carried out to justify its selection. The search settings were set to: with all words: LCA, and with the phrase "carbon capture utilisation". However, as proven by a critical review of the literature available in the Google Scholar database, only about a dozen publications considered LCA analysis for the CCUS supply chain. The majority of publications presented in the Google Scholar database for LCA analysis for the energy sector case study were for the EOR (as an example (Hussain et al. 2013; Bielicki et al. 2014; Stewart and Haszeldine 2015; Skone 2016; Wilkins et al. 2016; Morales Mora et

al. 2017; Azzolina et al. 2017; Kolster et al. 2017; Jiang et al. 2018; Jensen et al. 2018; Núñez-López et al. 2019; Nuñez-Lopez et al. 2019b, a)), fuels and chemicals manufacturing (as an example (Cobo Gutiérrez 2015; Morales Mora et al. 2016; Bardow 2017; Fernández-Dacosta et al. 2017; Davis et al. 2018; Aristizábal-Marulanda and Cardona Alzate 2019; Roode-Gutzmer et al. 2019; Rumayor et al. 2019; Driver et al. 2019; Tomatis et al. 2019)).There was also a publication considering guidelines on how to conduct LCA for CCUS models (Zimmermann et al. 2018). The number of publications were focused only on environmental benefits from just carbon capture technology (Cuéllar-Franca and Azapagic 2015b; Armstrong and Styring 2015; Bardow 2017; Morales-Mora et al. 2019; Cormos Ana-Maria et al. 2019). Additionally, in 2019 one manuscript was published with LCA studies on DME production (Tomatis et al. 2019).

Additionally, as identified by critical literature review, summarised and presented in the Table 7, there are currently only one publication with LCA analysis for CCUS supply chain evaluation for Poland. It is author's own publication (**P4**) with amine-based absorption, post-combustion technology and utilization and storage with DME and MeOH production, combined with RES as energy supply for absorption unit (Facchino et al. 2022). One paper is focused on CCS technology with oxy-fuel combustion method (Gładysz and Ziębik 2015a). Rest of publications were focused only on comparison of power plants not even including CCUS/CCS/CCU technology applied. Therefore it became crucial to conduct holistic LCA analysis for CCUS supply chain in Poland.

Table 7 LCA studies for Poland's power sector.

| Authors and year | Methodology | Case study object | Reference |
|---|---|---|---|
| **Adamczyk and Dzikuć (2014)** | Ecoindicator 99 | Combined heat and power (CHP) power plants at Lublin (Poland) and Polkowice (Poland) | (Adamczyk and Dzikuć 2014) |
| **Burchart-Korol et al. (2018)** | ReCiPe midpoint and endpoint | Comparison studies for current and future electricity generation systems (2000-2050, based on energy market trends) in the Czech Republic and Poland | (Burchart-Korol et al. 2018) |
| **Czaplicka-Kolarz et al. (2004)** | Ecoindicator 99 | Operating, extraction, and closing of a hard coal mine located in Poland | (Czaplicka-Kolarz et al. 2004) |
| **Dzikuć (2015)** | Ecoindicator 99 | Comparison between the Dolna Odra power plant (hard coal), and Turów power plant (lignite) | (Dzikuć 2015) |
| **Dzikuć and Dzikuć (2013)** | Ecoindicator 99 | Comparison between Łagisza power plant (hard coal), and Turów power plant (lignite) | (Dzikuć and Dzikuć 2013) |
| **Dzikuć and Piwowar (2015)** | Ecoindicator 99 | Comparison between Legnica, Polkowice, and Chwałowice power plants | (Dzikuć and Piwowar 2015) |
| **Faccino et al. (2022)** | **CML** | **Natural gas combined cycle (NGCC) power plant with CCUS in comparison of energy market between Italy and Poland** | **(Facchino et al. 2022)*** |
| **Gładysz and Ziębik (2015)** | - | Oxy-fuel combustion power plant with CCS – life cycle thermoecological cost analysis | (Gładysz and Ziębik 2015b) |
| **Lelek et al. (2016)** | Impact2002+ | Production and distribution of electrical energy and heat to the final user in the years 2007, 2010, and 2012 | (Lelek et al. 2016) |

* Author's publication

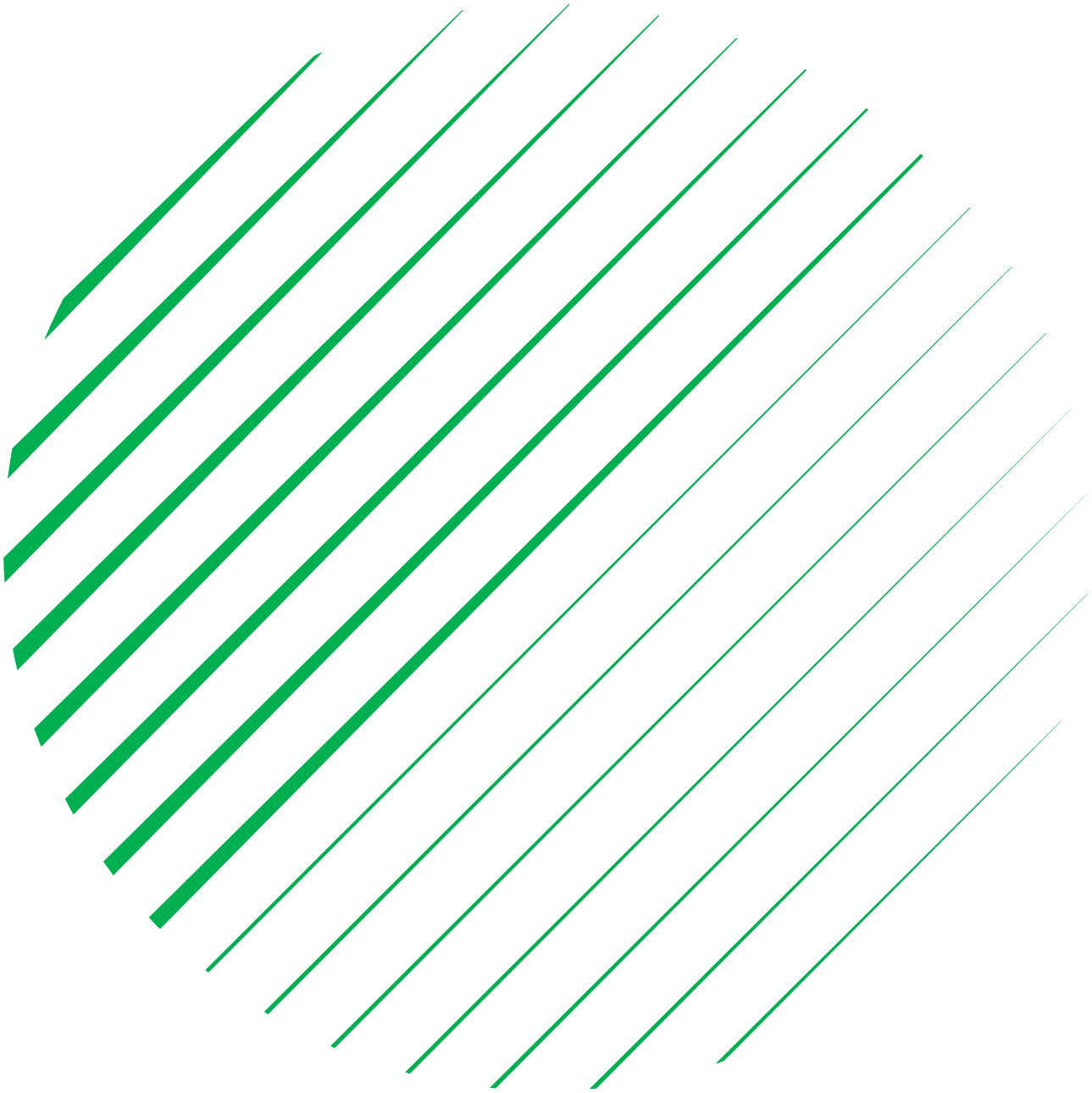
As revealed by the critical literature review described before, there are limited studies dedicated to LCA analyses for the CCUS supply chain. In addition, this issue is also addressed by other researchers e.g. (Chelvam and Hanafiah 2023). There are some studies combined LCA with CCS (Modahl et al. 2012; Tang et al. 2014; Bui et al. 2018;

Li et al. 2023), hence those with CCU or CCUS are very limited (Raadal and Modahl 2022; Facchino et al. 2022; Wawrzyńczak et al. 2022a; Leonzio et al. 2023).

Furthermore, as mentioned above in **Chapter 2.3**, there are several strong arguments, showing that the life cycle analyses for CCUS supply chain, with specific focus on Poland as a case study location were scarce in publications (which, in addition, did not address the topic holistically, and were very limited in scope of work). The country's dependence on fossil fuels (described in detail in **Chapter 1 - P1** and in **P2**) with the energy sector's major impact on domestic GHG emissions makes it an interesting case study country for the implementation of decarbonizing technologies such as Carbon Capture Utilisation and Storage (CCUS). In addition, there is interesting research area focusing on the possible environmental benefits from using natural gas as a transition fuel, as established by the European Union.

Given the arguments above, it was determined that there was a need to carry out the LCA analyses for the CCUS technology supply chain implementation in Poland. It was therefore important to carry out appropriate computer simulations using the LCA calculation software, in terms of the potential to reduce the environmental footprint of selected facilities, representing the most crucial sectors i.e., power sector and cement industry, in majority contributing to national GHG emission, with the hypothetical application of CCUS technology.

# Chapter 3 Literature summary



Sustainability with fair transition are one of the main goals of the EGD. Each EU's member states have its own approach to its realization as described in **Chapter 1.1 (P1)** (Popielak et al. 2024). Although the EGD sets paths in the effort to tackle climate change, it is only a form of launch for the legislation that follows it, which must then be regulated by corresponding packages of regulations in each state (Popielak et al. 2024). And the CCUS supply chain is part of the EGD as a state-of-the-art tool to address climate change and in achieving net-zero target.

In comparison to CCS, the CCU is a step forward in carbon capture technologies. The change of perspective on this substance, where it becomes a substrate from a final product, offers a number of benefits, not only environmental but also economic. Although the **use of $CO_2$ as a feedstock itself appears to be a good solution**, technically the issue is nevertheless challenging. The various options for using the gas mixture with captured $CO_2$ are very often limited by a number of factors. Apart from economic concerns, the two most important ones that stand in the way are the logistics of transport and the purity of the gas stream (**Chapter 1.2.1**). In the case of storage, the most important factors are: (1) storage capacity, (2) the transport issue, and the economic aspect of the endeavour (3). In the case of utilization, the potential customer for $CO_2$ capture and purity requirements are also a factors (**Chapter 1.2.1.3**). Technologically, the transport problems can be solved by building a suitable network with $CO_2$ collectors (meshed network system), which would then redistribute the $CO_2$ to the recipients that cooperate with the $CO_2$ source facility or to utilize a natural gas network pipeline (**Chapter 1.2.1.3**). With first solution, the problem arises where each of the recipients has its own conditions that the $CO_2$ stream must meet in order to be technologically useful to it. The solution to this problem should be an investment on the part of the consumer. However, this may largely inhibit the development and deployment of CCSU technology. The state in whose territory the investment will take place will play a significant role. Support policies facilitate the development of this type of technology.

As mentioned by Popielak et al. 2024 (**P1** (**Popielak et al. 2024**)), **ultimately, CCS and CCU solutions are complementary**, as both require access to a $CO_2$ source with capture facilities, as well as infrastructure and transport services. Thus, both

technologies are valuable assets in the climate agenda and, eventually, Europe's climate neutrality by 2050.

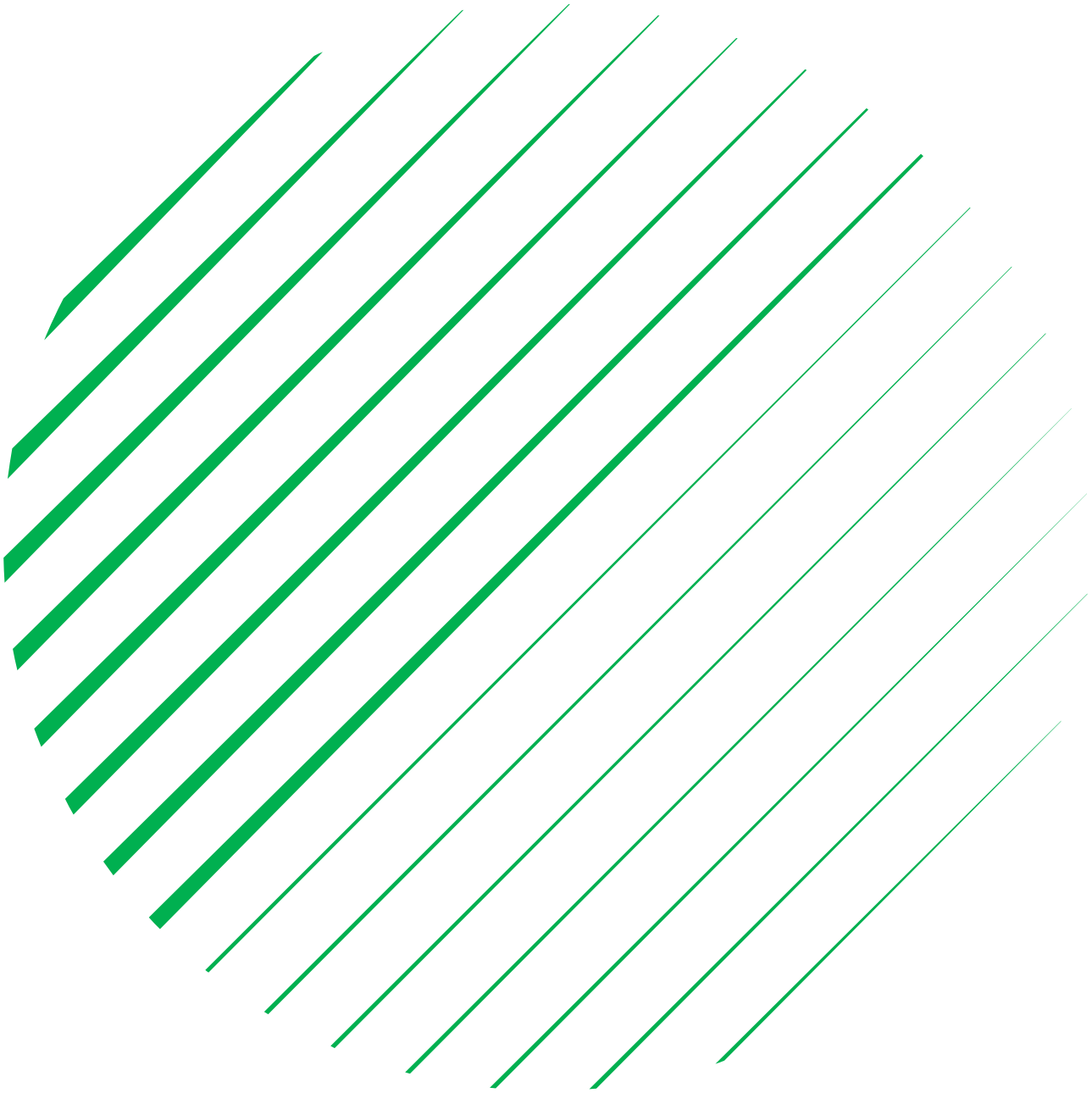
On the other hand, with utilisation for the CCUS supply chain, there are growing questions about the **environmental benefits** to be gained from avoided $CO_2$ emissions converted to a new product i.e. fuel, carbonate concrete etc. Unfortunately, as outlined in **Chapter 1 and Chapter 2**, $CO_2$ utilisation is dependent on a number of factors (e.g. different purities of the $CO_2$ stream) and sometimes requires an additional substrate for a specific process (e.g. hydrogen in $CO_2$-to-fuel or chemical conversions). The necessity of hydrogen for the production of DME or MeOH described in **Chapter 1.2.1.3** is another key topic for the economic but, above all, environmental viability of CCUS technology. **Other question rising in this point is how long emission of $CO_2$ into environment will be avoided by storing carbon element in the synthetic fuel and what measurable benefits for environment it will bring?**

Last but not least, as described in details in **Chapter 2**, LCA analysis is a holistic tool for carrying out environmental evaluations of products and processes. As such, it makes it **possible to assess the environmental impact of CCUS technologies supply chains** over their entire life cycle, from raw material acquisition, manufacturing, transport, use, to $CO_2$ utilization and/or storage. Through LCA analysis, it is possible to get a complete overview of technology as a tool in the climate change mitigation. Furthermore, as proved in **Chapter 2.3** there are significant literature gap in LCA analysis for CCUS supply chain, especially in terms of $CO_2$ utilization to fuels like DME or in terms of carbonate concrete manufacturing.

Therefore, there are justifiable arguments for a thorough investigation of the CCUS supply chain with the LCA tool, and in particular for seeking answers to the questions: **how can the application of the CCUS supply chain to the power and/or industry sector, change the environmental impacts of manufacturing process compared to its conventional production?**

In connection with the problem defined in this way, it became possible to formulate the scientific thesis, goals, and scope of PhD thesis presented in **Chapter 4**.

# Chapter 4 Thesis, goals, and scope of dissertation



## 4.1 Motivation

As a result of the review of the current state of knowledge presented in **Chapters 1-3**, it was noted that there are **significant gaps in the literature** regarding studies dedicated to: (1) environmental impacts assessment for the CCUS supply chain, with a particular focus on the needs of the energy and cement sectors (**P1, P3**), (2) natural gas as a transition fuel together with environmental impacts evaluation (**P4**), (3) environmental analysis for CCUS located in Poland (**P2, P3, P4**). It was noted that there is a need for holistic LCA analyses of the CCUS supply chain, to understand the environmental impact of these technologies, to explore opportunities for further development, to investigate which $CO_2$ utilisation technologies are most beneficial to the environment and which is not, to investigate hotspots in the CCUS supply chain, to choose the most environmental-friendly and beneficial CCUS supply chain. Following the aforementioned background, it has been decided to undertake an environmental analysis using the LCA tool for the following case studies:

1) LCA analysis for environmental impacts of a coal-fired power plant located in Poland and environmental benefits from CCS supply chain application. The scope of the study included a comparative analysis of a case study of a power plant with and without an installed CCS unit. Details of the analysis are described in **Chapter 5** and **Chapter 6** (**P2**).

2) LCA analysis for the comparison of the environmental benefits of CCUS installations for power plants (representative of the power sector) and cement plants (representative of the industry and the decarbonisation of industry concept). Details of the analysis are described in **Chapter 5** and **Chapter 7** (**P3**).

3) LCA analysis of environmental impacts and benefits of natural gas power plant (with and without CCUS), together with taking into account the geographical case study of Italy (one of the top GHG emitters in Europe, natural gas the main fuel in the country's energy mix – **Chapter 8, P4**) and Poland (one of the top GHG emitters in Europe, natural gas a possible transition fuel from coal, identified in EPP2040 – **Chapter 8, P4**). Comparative analysis was carried out for natural gas power plant without and with CCUS installation, together with the use of RES as a supporting element for energy-

intensive $CO_2$ capture installation. Details of the analysis are described in **Chapter 5** and **Chapter 8** (**P4**).

The summary of literature gaps, followed by investigation cases are presented in Figure 7.

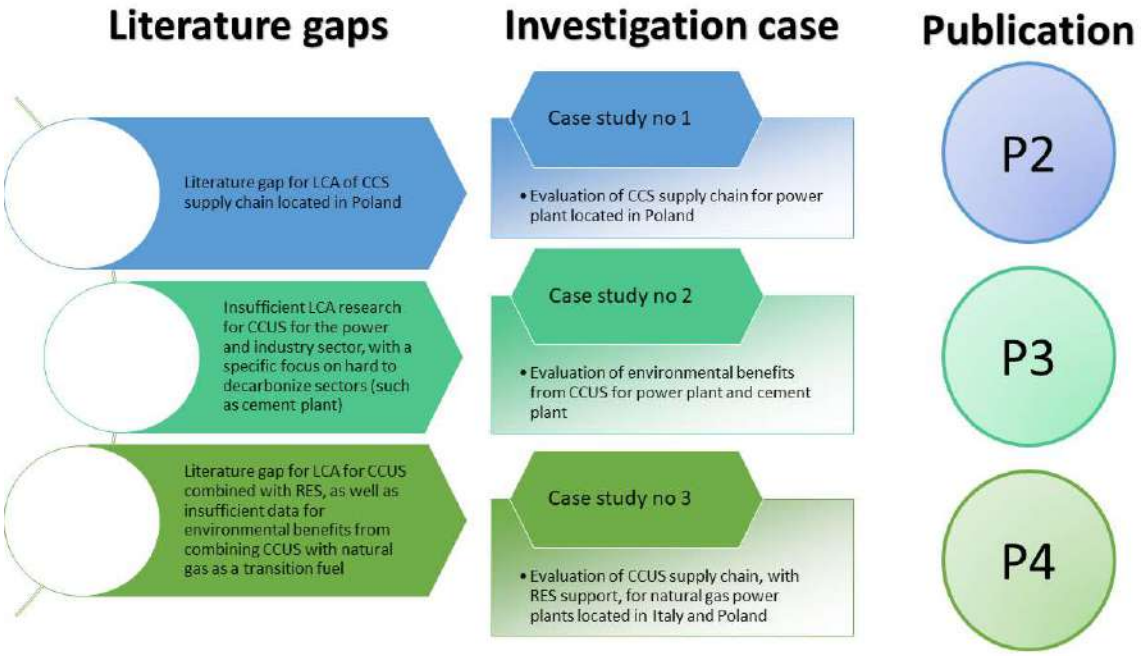



Figure 7 Summary of literature gaps for LCA evaluation of CCUS technology supply chain.

## 4.2 Innovation

- Holistic LCA analyses performed for the CCUS supply chain can significantly contribute to a better understanding of their environmental impacts, support political decisions aimed at reducing $CO_2$ emissions and decarbonizing the energy sector and cement industry.
- Leveraging an interdisciplinary approach, combining environmental science (LCA analysis - **P1-P4**), engineering (based on real results from industry), numerical modelling (data from research conducted in Aspen Plus software in **P3 and P4**), and policy (policy analysis - **P1**) to comprehensively evaluate environmental benefits of CCUS supply chain.

- Evaluating the environmental impacts of CCUS supply chain to for further development strategies and technology environmental hotspot analysis for further improvements.
- Detailed LCA analysis for innovative $CO_2$ utilization methods, such as the manufacturing of construction materials (e.g. carbonated concrete) or synthetic fuels i.e. DME or MeOH (**P3-P4**).
- Comparison of the environmental performance of different $CO_2$ utilization pathways (**P2-P4**).

## 4.3 Thesis and goals

Accordingly, the following theses of the study were formulated:

1. It is possible to reduce the environmental impact of industry facilities emitting $CO_2$, as well as of facilities using carbon dioxide as a feedstock in their production processes, by applying CCUS technology.
2. It is possible to support power and cement industry sector decarbonization by applying the CCUS technology supply chain.

The goals of the work are:

1. To perform numerical environmental analysis by applying LCA tool for power plant and cement plant facilities with and without CCUS supply chain.
2. To evaluate the possibility of decarbonisation by quantifying GWP indicator through LCA analyses for the CCUS supply chain.

## 4.4 Scope of dissertation

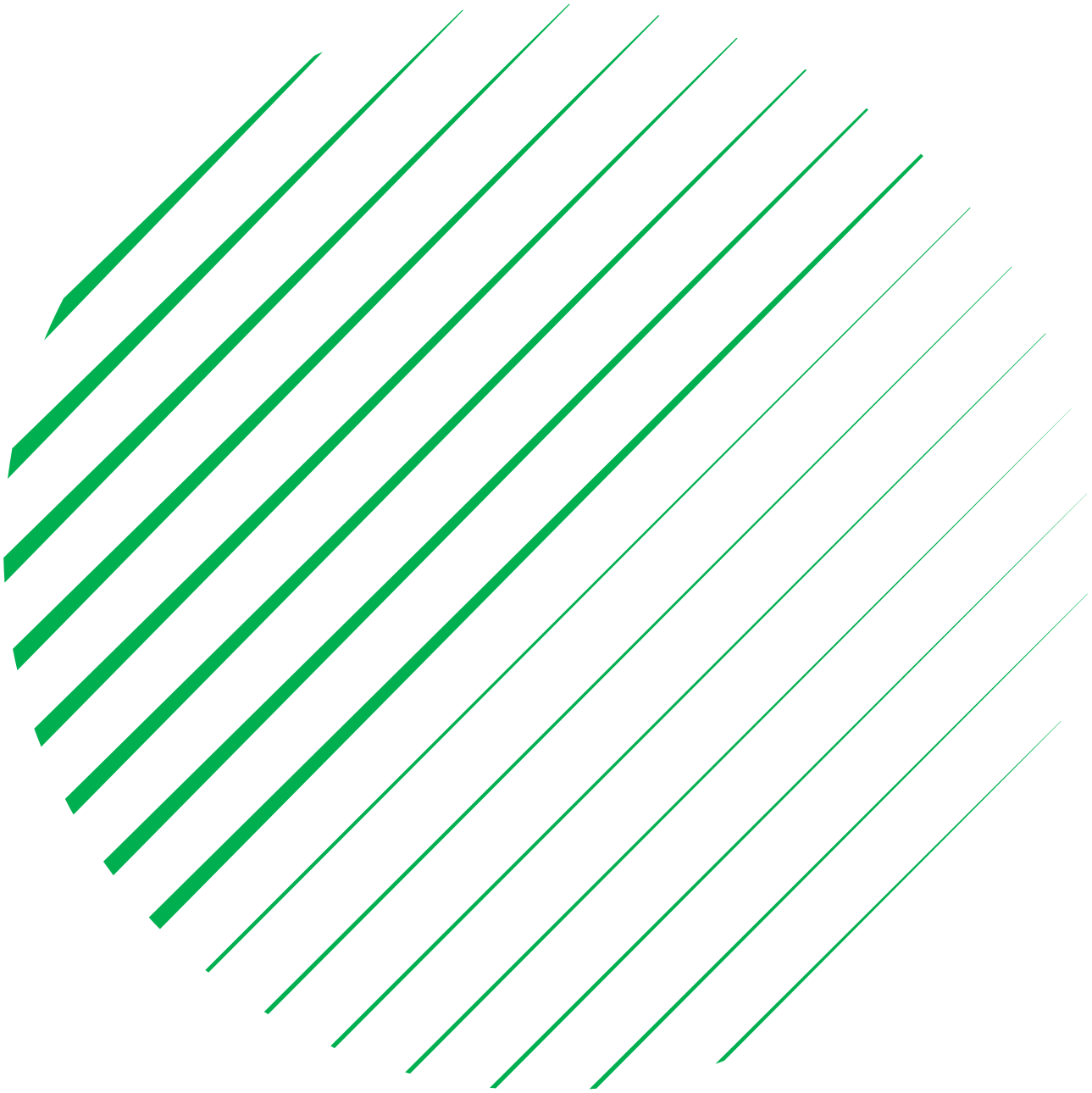
The scope of the dissertation included:

1. First step of the LCA analysis, i.e. establishing the goals and scope of the analysis, i.e. elements such as functional unit, boundary conditions, to be applied impact assessment method (LCIA), determination of cut-off points in system boundaries.

2. Definition of the analysed scenarios for each case study:
    a. $CO_2$ capture and storage supply chain for a coal-fired power plant located in Poland (**P2**),
    b. the CCUS supply chain for power plant and cement plant (**P3**),
    c. the CCUS supply chain for the natural gas power plant, (the EGD's transition fuel) for Italy and Poland as case study countries (**P4**).
3. Collection of literature and experimental data to perform the analysis, identification of background processes taken from the ecoinvent database.
4. Evaluation of the dataset through the application of the LCIA methodology. Assessment of environmental impacts (benefits and threats).
5. Analysis of the results obtained.

The analysis was carried out according to the steps described in **Chapter 2** and the ISO standards of the 14040-14044 series.

# Chapter 5 Research tools and methodology



## 5.1 Methodology

The chapter describes in details methodology applied for selected case studies, presented in **Chapters 6-8**. Additionally, the Chapter describes in details the methodological issues for LCA analysis performed for CCUS technology.

### 5.1.1 Life Cycle Inventory and background data

Data quality is one of the most critical topics in LCA analysis. Without quality-assured data, data from unknown sources or grey literature can affect the results of an LCA analysis in an incomprehensible and incomparable way, providing misleading and inconsistent results. Considering that LCA is a significant tool for academia, industry, policymakers, and stakeholders, the use of inconvenient data should rather be avoided.

We can divide data sources into different categories, where the two most important are:

1. Primary data – data measured and/or calculated on-site, directly modelled in other software such as Aspen Plus® or Flownex® Simulation Environment (SE), data taken directly from the industry facilities.
2. Secondary data – data from scientific papers, technical reports, emissions permits or government statistical tools (i.e., Eurostat).

Data from available databases (e.g., MLC DB, ecoinvent, CarbonMinds) can also be used to perform the LCA analysis. Such data often cover the requirement for background processes or sub-level plans of the investigated process.

### 5.1.2 Multifunctionality in CCUS case studies

According to the ISO 14040 series standard, there are three methods how to tackle multifunctionality in LCA modelling.

The first solution is a subdivision, which loops the additional product outputs back into the same system. It separates aggregated unit process with multiple outputs into several unit processes with single-functional unit (gathering there relevant LCI input

output data for each sub-process). The sub-division should always be applied as a first solution.

The second solution is system expansion/substitution. In this approach the functional unit defined in goals and scopes step has to include product systems functions other than those originally defined. To compare two product systems with multiple outputs, each must have the same functional unit. To do so each system boundaries and the functional unit of the product systems are changed. As described by Zimmermann et al. 2018 (Zimmermann et al. 2018), “to compare a CCU process with two products (a $CO_2$ source product and a $CO_2$ process product) with a conventional system, the main $CO_2$ source product is added to the functional unit and the conventional system is extended with a $CO_2$ source without $CO_2$ capture”.

Substitution is mathematically equal to system expansion, hence it’s a different approach to solve multifunctionality as it does not include additional functions in the functional unit. Instead, a credit is given for the production of a by-product (Zimmermann et al. 2018). The credit represents the environmental burden avoided by substituting a conventional production system that would otherwise have been used. However, this approach can lead to negative results in LCIA step. This means that there is a net benefit from the production of the system, since the overall impact is overcompensated by the avoided impact of co-functions elsewhere in the environment (European Commission et al. 2010).

Lastly, allocation is one the third solution described in the ISO 14040 series (International Organization for Standardization 2014), however it should be applied to the model only if other solutions (subdivision and system expansion) for multifunctionality would not be feasible. Allocation could be done by mass, energy, and market value of the product. Which allocation key is the most suitable for the considered model should be chosen in accordance with ISO 14040 series norm, good modelling practice, and methodology specific to the topic (NEPIS 2006). However, allocation by physical properties should be applied first, and if it is not possible – then economic allocation should be applied.

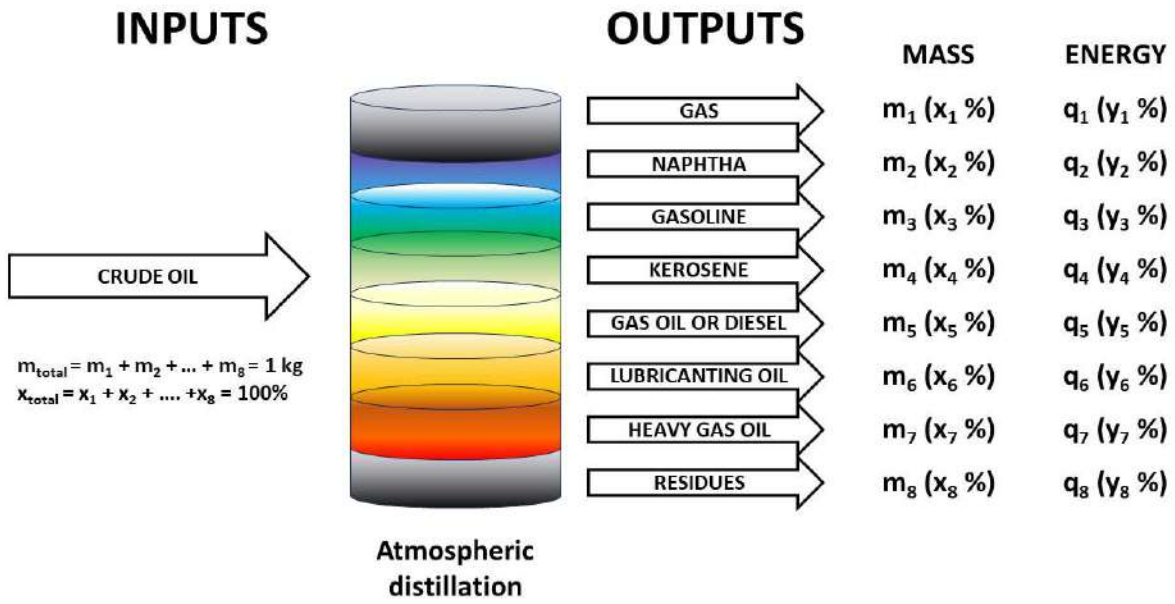



Figure 8 An atmospheric distillation is an example of allocation (simplified).

Figure 8 presents an atmospheric distillation of crude oil, which can be a perfect example of a process with a multifunctionality issue. As presented in Figure 8, this issue could be solved by allocation by mass or by allocation by energy. The applied allocation key (by mass or by energy) should always reflect the primary purpose of manufacturing output products.

### 5.1.3 Assessing impact assessment method and categories

As mentioned in **Chapter 2.2.2** LCIA is third stage of LCA analysis, where evaluation of LCI inputs and outputs linked to impact assessment method categories is performed. With LCIA results there is a possibility to set up a benchmark, comparing two or more different LCA scenarios, for choosing the best possible process, product, production route etc.

The LCIA can be divided into individual following sub-stages:

1. First step is to choose and define which *Impact Method* and which *Impact Method Categories* will be selected specifically for case study. It is often called *Classification*.

2. Second step is *Characterisation* and it refers to the evaluation of the quantity of impact of each output and input flow identified in the LCI, into the relevant impact categories and the grouping of contributions within each category. This is done by multiplying the values of the defined flows by the appropriate characterisation factor for each impact category considered. The characterisation factors are specific to the substance or resource and are defined in the documentation of the chosen method, developed by specialists e.g. International Panel on Climate Change (IPCC). The characterisation factors represent the intensity of the impact on environment by the substance relative to a common reference substance for the impact category.
3. The third and fourth steps are *Normalization* and *Weighting* and both are optional, depending on goals and scopes of the study. Normalization allows to make all impacts results comparable. It is the step in which the results of a life cycle impact assessment are multiplied by normalisation factors to calculate and compare the quantities of their respective contributions to impact categories, relative to a reference unit. The results are dimensionless after normalization step. Weighting is the step following normalisation, where the normalised scores are multiplied by a set of weighting factors (in %) that reflect the relative significance of the life cycle impact categories that have been considered.

According to Müller et al. 2020 and Raadal and Modahl (2021) to avoid misinterpretation of results, only certain and relevant categories should be taken into account while assessing CCUS supply chain such as: climate change, ozone depletion, acidification, abiotic depletion potential (Müller et al. 2020b; Raadal and Modahl 2021). Additional details are presented in Table 8.

Table 8 Description of selected environmental impact categories.

| Impact Category | Indicator | Units | Recommendation level according to (Sala et al. 2012)* | Reference |
|---|---|---|---|---|
| **Global Warming Potential (GWP)** | Measurement of the radiative forcing of all greenhouse gas expressed as a factor of $CO_2$ equivalent in a 100-year time horizon ($GWP_{100}$) | kg $CO_2$ eq. | I | (Solomon et al. 2007) |
| **Ozon Depletion Potential (ODP)** | The deterioration of ozone within the stratosphere by chemicals such as CFCs. | kg CFC-11 eq. | I | (Skone et al. 2018) |
| **Acidification Potential (AP)** | The increased concentration of hydrogen ions in a local environment. | kg $SO_2$ eq. | II | (Bare 2011) |
| **Abiotic Depletion Potential (ADP)** | Energy resources: non-renewable, only fossil fuels. | MJ | II | (Farinha et al. 2021) |

* Level I - recommended and satisfactory; Level II - recommended but in need of some improvements; Level III - recommended, but to be applied with caution.

## 5.2 Research and LCA tools

The following dissertation has selected, prepared and extensively investigated a selected three case studies, described in details in **Chapters 6-8**, based on a critical review of the literature. Below are the methodological details for each of the case studies.

### 5.2.1 Case study no 1

Case study no 1 is presented in **Chapter 6** of this thesis. It has been undertaken as the most basic comparative analysis for a power plant unit without and with CCUS supply chain of carbon capture (adsorption technology), and (underground) storage in a depleted coal mine. A power plant with a supercritical CFB boiler was chosen as the power plant facility. Furthermore, the study presented assumes only the possibility of storing $CO_2$, without the possibility for utilization.

**Goals and Scopes**

The following scenarios were selected to analyse: (1) a coal-fired power plant with a CFB unit without CCS, and (2) a coal-fired power plant with a CFB unit with CCS technology.

To perform an assessment was used the OpenLCA™ software provided by GreenDelta in version 1.10.3, with the ecoinvent database version 3.9.

**Functional Unit**

As a functional unit was chosen 1 kWh of net high-voltage electricity produced in a coal-fired power plant with a CFB boiler unit, located in the Silesia region in Poland.

**System Boundaries**

Models considering CCS consist of five main processes: (1) the primary processes that is the same as reference the model of a power plant without CCS, (2) the flue gas pre-capture purification unit, (3) carbon capture unit, (4) pipeline transport, and the underground storage location (5).

**Impact assessment methods**

The CML v4.8 2016 method was used to conduct the environmental impacts assessment. This method allows performing calculations for several impact categories: acidification, climate change, ecotoxicity freshwater, ecotoxicity marine, ecotoxicity terrestrial, energy resources, mineral resources, eutrophication, human toxicity, ozone depletion potential, photochemical oxidation.

### 5.1.2 Case study no 2

The second case study, presented in details in **Chapter 7**, compares the environmental benefits of implementing CCUS supply chain for the power sector and for the industrial sector (represented by cement plant). The comparison of two plants with two different functional units is impossible from an LCA point of view. However, in such a specific situation, where the aim was to make a general comparison of the potential environmental benefits of implementing CCUS technology in both plants, it was decided to use an atypical unit for LCA analysis, i.e. 1 hour of operation of each unit, assuming full operational performance of both units. It should be re-emphasized that such a comparison is not correct from an LCA perspective, but it does allow for a general view of the situation of the units with the potential benefits brought by the application of the CCUS supply chain. Detailed description of entire case study can be found in (**P3**) (Falco et al. 2022).

**Goals and Scopes**

The main objective was to evaluate the environmental impact of power plant and cement plant with CCU technology supply chain. $CO_2$ captured from power plant has been utilized in 100% to produce DME, and for cement plant $CO_2$ has been redirected for DME and carbonate concrete production.

To perform an assessment was used the OpenLCA™ software provided by GreenDelta in version 1.10.1, with the ELCD database version 3.2, the Ecoinvent 3.7 LCIA methods, and OpenLCA™ LCIA methods v.1.5.7.

**Functional unit**

Due to very specific characterization of both plants and different output products, functional unit has to be sort of a bridge between gap of different facilities' outputs. Therefore, the uncommon functional unit has been applied which is 1 hour of fully operational work of each plant. This functional unit allowed to made comparison of environmental performance of both units – cement plant with CCU vs power plant with CCU.

**System boundaries and LCI**

The model's system boundaries are presented in **Chapter 7 Fig.7.16**, including: (1) a source units for the flue gas streams (power plant and cement plant), (2) a flue gas pre-capture purification units, (3) a $CO_2$ capture facilities (absorption), (4) a renewable energy system to power the flue gas $CO_2$ capture units, (4) a DME production unit (power plant), and (5) a DME production unit together with carbonated concrete production unit (cement plant). A detailed description, including the necessary collection of data for the analysis are presented in ((Wawrzyńczak et al. 2022a) in the following Tables: Table 1.4, Table 3.4, Table 5.1 and Table 6.4.

**Impact assessment method**

Chosen LCIA method was The International Reference Life Cycle Data System (ILCD) method (ILCD 2011, midpoint [v1.0.10, August 2016]). Following impact categories were chosen for analyse: Climate change, Human Toxicity – cancer, Human Toxicity – non-cancer, Ozone depletion, Resource depletion – mineral, fossil and renewables, Resources depletion – water (Falco et al. 2022).

### 5.1.3 Case study no 3

The third case study is focused on global issues, addressing the development of CCUS within the European Union in the leading emitters of greenhouse gases - Italy and Poland. The study was based on a natural gas power plant, considered as the European Union transition fuel. Although natural gas is Italy's primary fuel, it does not represent a large share of the energy mix in Poland. Nevertheless, from the perspective of aiming for zero carbon and meeting the objectives of the European

Green Deal and EPP2040, it was considered reasonable to undertake such an analysis. Subsequently, this analysis was carried out in an even broader spectrum, capturing CCS and CCUS analysis and linking CCUS to green technologies (RES). Detailed description of entire case study can be found in **Chapter 8 (P4)** (Facchino et al. 2022).

### Goals and Scopes

The main scope of this work was to investigate and evaluate the environmental benefits of CCS and/or CCU units with a gas-fired natural gas power plant taking into account specific natural gas markets for each country. The NGCC power plant was chosen as natural gas is treated as a transition fuel in the European Green Deal. The post-combustion amine-based method has been used as a carbon capture method. Methyl diethanolamine (MDEA) was chosen as one of the most commonly used solvent.

To perform an assessment was used the OpenLCA™ software provided by GreenDelta in version 1.10.3, with the ecoinvent database version 3.8 and EuGeos' 15804+A2_IA version 4.1.

The following scenarios were investigated:

- CCS scenario in which a comparative analysis of NGCC power plant system with capture and NGCC power plant system without $CO_2$ capture was carried out.
- The CCUS scenario, in which a comparison was made between NGCC power plant systems with $CO_2$ capture and utilisation and NGCC power plant systems without $CO_2$ capture and utilisation.

### Functional unit

For CCS scenario the functional unit has been set up as a 1 kWh of high-voltage electricity, generated by NGCC power plant. For CCUS scenario there was applied approach with multifunctionality by system expansion, where functional units are: a 1 kWh of high-voltage electricity, generated by NGCC power plant and production of 0.55 kg of DME.

**System boundaries**

The model's system boundaries are presented in detail in **Chapter 8, P4, Fig. 2** including objects such as: (1) a NGCC power plant, (2) customized market for natural gas for case study countries (i.e. Italy and Poland), (3) $CO_2$ capture (absorption) and purification unit with (4) compression train to underground storage (5), (6) hydrogen production unit, (7) DME production unit (Facchino et al. 2022).

**Impact assessment method**

The evaluation of the environmental impacts were performed with CML method, with specific focus on following impact categories: Global Warming Potential (GWP), Cumulated Energy Demand (CED), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Particulate Matter Formation ($PM_{2.5}$) (Facchino et al. 2022).

# Chapter 6 Case study no 1 - The environmental impacts of circulating fluidized bed unit in coal-fired power plant with DR-VPSA carbon capture and $CO_2$-ECBM storage technology in Poland

# The environmental impacts of circulating fluidized bed unit in coal-fired power plant with DR-VPSA carbon capture and $CO_2$-ECBM storage technology in Poland

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## Abstract

*Purpose*: Poland is the 6$^{th}$ largest economy and the second largest emitter of greenhouse gases (GHG) in the European Union (EU). In 2019 Poland's energy sector is responsible for 46.9% of national GHG emissions with fuel combustion accounted for 92.1% of $CO_2$ emissions, with a share of fossil fuels in domestic Gross Electricity Production approx. 84.02%. The country's dependence on fossil fuels with the energy sector major impact on domestic GHG emissions makes it an interesting case study for the implementation of decarbonizing technologies such as Carbon Capture and Storage (CCS).

*Methods:* Two scenarios were developed: (1) gate-to-gate approach for coal-fired power plant with supercritical circulating fluidized bed (CFB) boiler; (2) gate-to-gate approach for coal-fired power plant with supercritical CFB boiler with additional CCS technology implemented. For carbon capture technology was selected Dual-Reflux Vacuum-Pressure Swing Adsorption (DR-VPSA) on activated carbon. As a functional unit in both scenarios were used 1 kWh of electricity, high voltage. The applied impact assessment method was CML v. 4.8. 2016. To perform calculations software OpenLCA™ in v.1.11, with the ecoinvent database v.3.9.1 were used.

*Results and discussion*: The $CO_2$ emission from Łagisza power plant, estimated at 0.756 kg $CO_2$ per kWh, was significantly dropped in the CCS scenario to level 0.669 kg $CO_2$-eq. However, the impacts on other considered categories such as resource depletion and ozone layer depletion significantly increased. These results could occur both as a consequence of the limited approach in the considered system boundary, and due to the increased amount of resources required for CCS processes.

*Conclusions*: As the results of the analysis showed, the application of CCS technology can help to reduce the Global Warming Potential (GWP) of a power plant, but other parameters such as ozone depletion potential or resource depletion increase. The rise in other indicators is attributable to the increased energy input for technological processes. This also confirms the need for a holistic evaluation of technologies aimed at addressing climate change to avoid underestimating environmental performance.

*Recommendations*: It is highly recommended to consider LCA model expansion by adding $CO_2$ utilization possibilities. Furthermore, industrial processes in power plant, as well as carbon capture and purification processes, uses vast amounts of water, thus an in-depth analysis of water depletion impact category should be developed, with proper background in Life Cycle Inventory. Lastly, additional model improvement could occur by developing an exegetic model of the system and Life Cycle Cost Analysis.

## Keywords

carbon capture; carbon sequestration; Life Cycle Assessment; CCS; carbon storage; circulating fluidized bed; DR-VPSA;

## Introduction

Kyoto Protocol, Climate and Energy Package, Paris Agreement, and nowadays – European Green Deal (EGD) – were one of the steps that Poland has taken toward climate change mitigation. On March 2nd, 2021 Minister of Climate and Environment signed the Energy Policy of Poland 2040 (EPP2040), merging Poland's existing climate targets with net-zero neutrality established by EGD (Monitor Polski 2021). EPP2040 set up three fundamentals, further expanded by eight Strategic Objectives as shown in Figure 1. Among them, Carbon Capture Utilization and Storage (CCUS) is highlighted as technology towards decarbonization of energy and industry sectors (e.g., by mandatory CCS-Ready technology for new units in power stations) but this is offset by the statement that this technology will be economically feasible if the $CO_2$ allowance prices exceed 50EUR per tonne on European Union Emission Trading System (EU-ETS system).

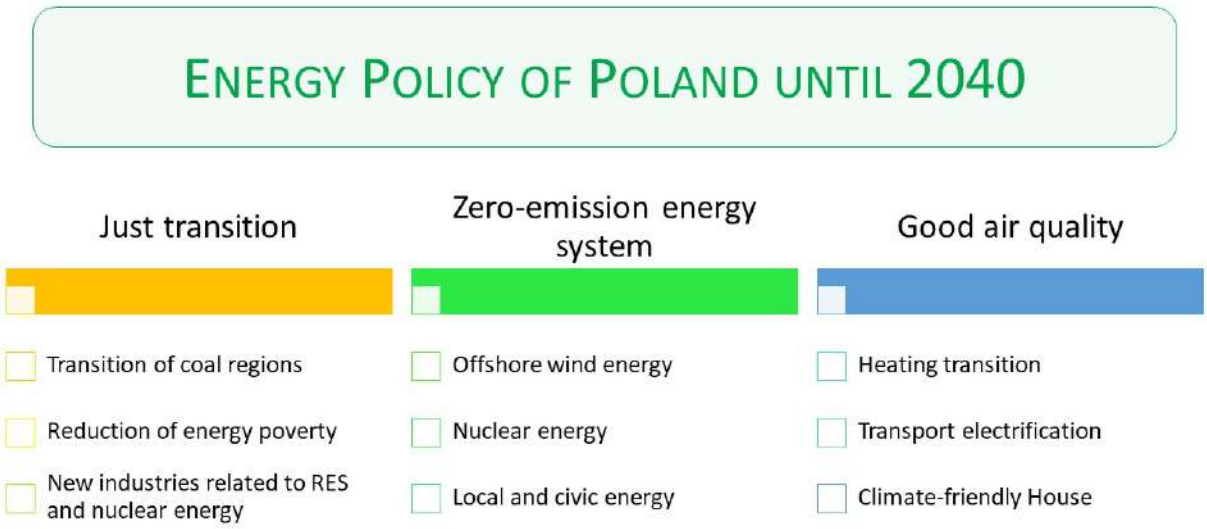


Figure 1 Energy Policy of Poland until 2040 (author's compilation based on (Ministry of Climate and Environment 2021)).

Carbon Dioxide Capture Utilization and Storage technology is a supply chain of interconnected technologies in which $CO_2$ (mainly from flue gases) from air or industry

facility such as the power plant or other sectors (Hong 2022; Monteiro and Roussanaly 2022; Hasan et al. 2022; Kang et al. 2022; Anika et al. 2022; Wawrzyńczak et al. 2022a) is captured, transported and utilized or injected into storage site. There are three basic points in the carbon capture process chain where $CO_2$ could capture take place: pre-combustion , post-combustion and oxyfuel combustion. Moreover, a number of capture technologies are recognized, such as absorption, adsorption, membrane, and cryogenic. Furthermore, another novel trend in $CO_2$ capture is the technology of capturing $CO_2$ from the atmospheric air, i.e. Direct Air Capture (DAC, more about it in the literature (Deutz and Bardow 2021; McQueen et al. 2021; Mostafa et al. 2022)). The most common utilization methods are: in the food industry for the production of fizzy drinks (Hosseini et al. 2023), the horticulture industry for plant growth enhancement (Marchi et al. 2018), production of chemicals and fuels (Catizzone et al. 2017b; Bonura et al. 2021). On the other hand, $CO_2$ storage can be divided into onshore and offshore storage site with further distinction on: underground storage in oil extraction pits (Enhanced Oil Recovery – EOR), saline aquifers, depleted coal bed mines (Leung et al. 2014; Turgut et al. 2021).

# Poland case study

## GHG emissions and energy market in Poland

As shown in Figure 2, in 2019 in European Union Poland was in 5th place, with almost 10% contribution to total European Union net GHG emissions. The timeframe is limited to 2019, the year after UK's withdrawal from the EU occurred. Moreover, it should be also highlighted that in 2020 was a significant drop in levels of emission due to the global Covid-19 pandemic (Ray et al. 2022). Thus, 2019 year was chosen as the endpoint of the range.

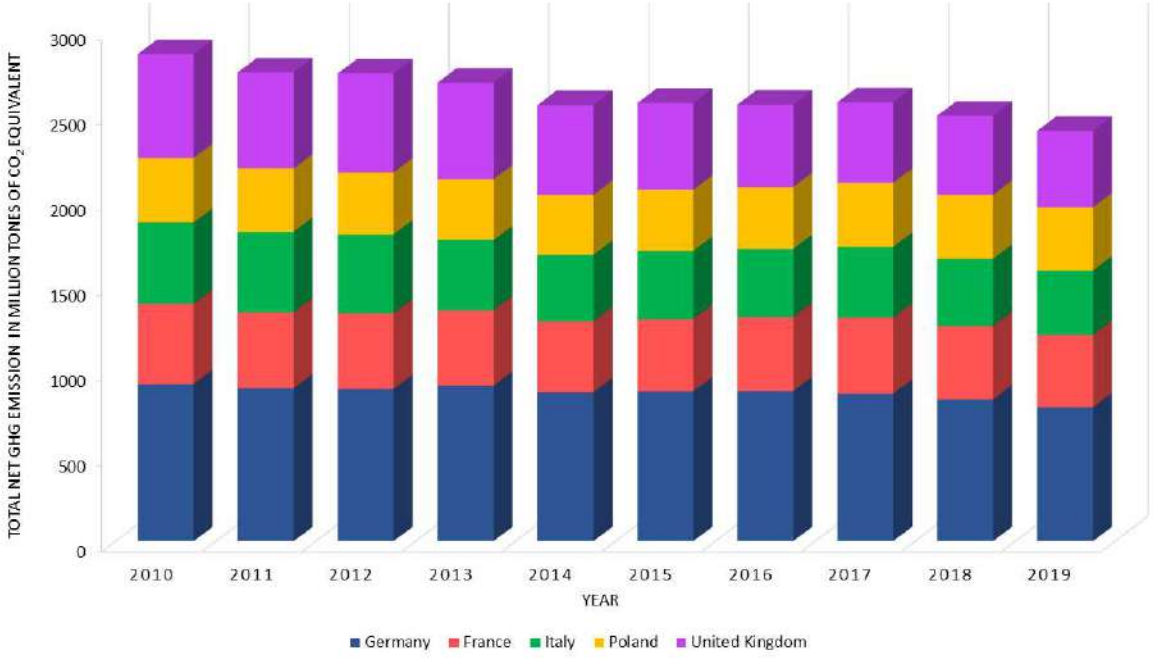


Figure 2 Top 5 contributors in European GHG emission from 2010 to 2019 (author's compilation based on European Environment Agency (EEA) database (European Environment Agency 2021)).

In contrast, as shown in Figure 3, Poland's detailed greenhouse gas emissions for the period from 2010 to 2019, are divided into categories as defined by the Common Reporting Format (CRF), established by the International Panel on Climate Change (Herold et al. 2010).

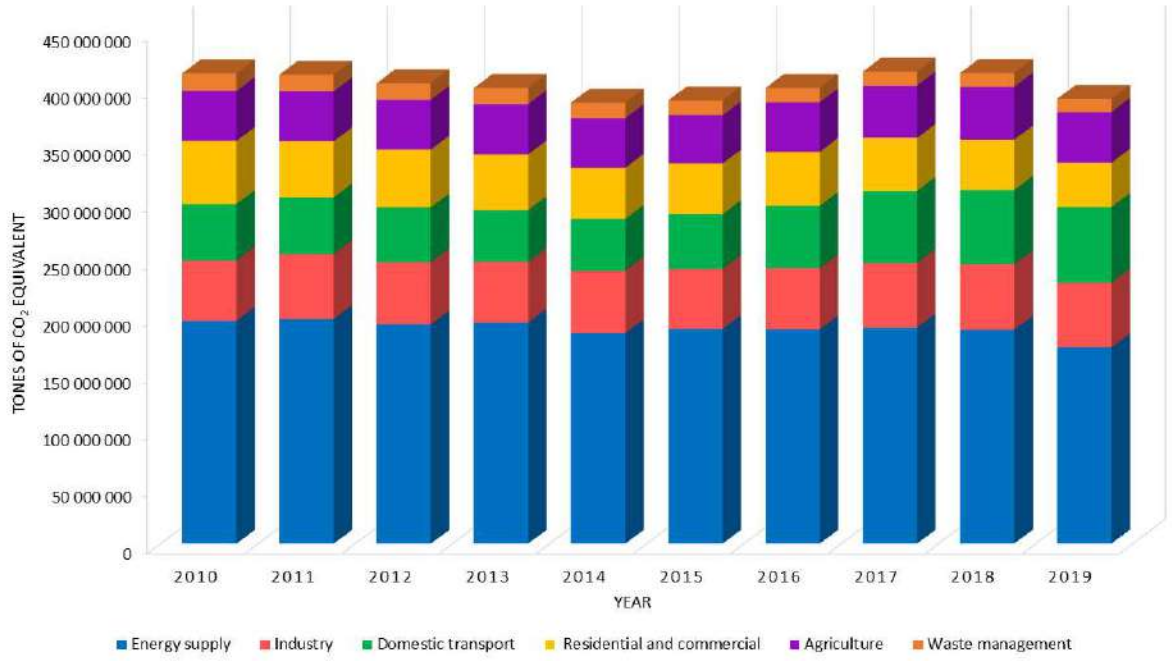


Figure 3 Poland GHG emissions excluding Land Use, Land Use Change, and Forestry (LULUCF), from 2010 to 2019 (author's compilation based on EEA database (European Environment Agency 2021)).

In 2019 Poland's energy sector was responsible for 46.9% of domestic GHG emissions, followed by transport (20.04%), and energy-intensive industry sectors such as iron&steel or cement production, account for 9.7% share of total GHG emissions (excluding LULUCF). Among industrial processes, the mineral industry accounted for the largest share, responsible for 6.84% of total GHG emissions, with its contribution made up of the cement industry (approx. 65%), and chemical and metallurgical industries (approx. 20% and 10% respectively).

Furthermore, according to data obtained from the National Centre for Emission Management (KOBiZE) carbon dioxide was responsible for a significant majority of national GHG emissions equal to 81.8% (of which approx. 92% came from fuel combustion processes), followed by methane – 11.8% and nitrous oxide – 5.4% (Olecka et al. 2021). A significant contribution to the methane emission origins comes from fugitive emissions (approx. 40%) agriculture (approx. 30%) and waste management (approx. 23%).

Poland's energy market is highly dependent on fossil fuels, hence Renewable Energy Sources (RES) have had rapid development in the last decade (further information can be found in the following literature (Marks-Bielska et al. 2020; Pietrzak et al. 2021)). According to Igliński et al. 2022, in 2021 total photovoltaic power could provide about 26% of the domestic electricity demand (Igliński et al. 2022). Nonetheless, as presented in Table 1, coal with other fossil fuels, accounted for almost 90% of the total energy supply in 2019, leaving space for RES in only a 10% share.

Table 1 Total energy supply (TES) by source in Poland in 2019 (based on International Energy Agency (IEA) data (International Energy Agency 2021)).

| **Coal** | **Oil** | **Natural Gas** | **Biofuels and waste** | **Hydro** | **Wind, solar, etc.** | **Percentage share of fossil fuels** | **Percentage share of RES** |
|---|---|---|---|---|---|---|---|
| [TJ] | [TJ] | [TJ] | [TJ] | [TJ] | [TJ] | [%] | [%] |
| 1,842,295 | 1,262,628 | 708,601 | 380,529 | 7,050 | 61,002 | 89.48 | 10.52 |

## $CO_2$ storage capacity in Poland

From 2008 to 2012 the Polish Geological Institute coordinated the National Program "Assessment of formations and structures suitable for safe $CO_2$ geological storage along with their monitoring program", which was conducted by the Central Mining Institute. The estimated storage capacity (static, effective capacity) in major available formations is shown in Figure 4.

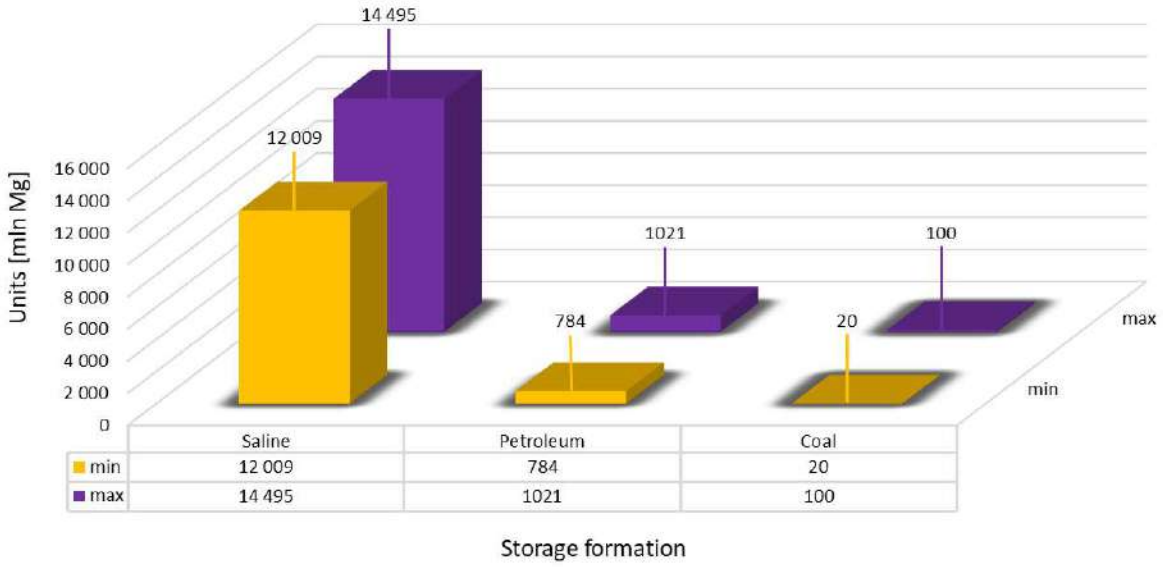


Figure 4 $CO_2$ storage capacity in Poland based on (Wójcicki 2013).

For over the last decade, the Polish Geological and Mining Law had allowed $CO_2$ storage only for demonstration projects (Parliament of the Republic of Poland 2011). Thus, Dubiński et al. 2010; Mika-Brysk and Wróblewska 2015, and Przybojewska 2018, recommended changes, and updates in Polish regulations (Dubiński et al. 2010; Mika-Brysk and Wróblewska 2015; Przybojewska 2018). The latest update of April 25$^{th}$, 2023 to the Polish Mining and Geological Law has amended the Act to, among other things, allow activities involving the underground storage of $CO_2$ to be carried out to a greater scope than under the previous legislation (Ministerstwo Klimatu i Środowiska 2023).

Additionally, as shown in research conducted by Tarkowski and Uliasz-Misiak 2019; Gładysz et al. 2020, and Sowiżdżał et al. 2022, a promising future area of research is the potential for using $CO_2$ to enhance geothermal energy recovery, although its share in Poland's energy supply is lower than 1% (only 1050 TJ in 2019, which account for 0.26% of gross final energy consumption). (Tarkowski and Uliasz-Misiak 2019; Gładysz et al. 2020; Sowiżdżał et al. 2022).

## CCUS in Poland

Nowadays, there were three finalized carbon capture projects Poland. The first was a mobile unit of DR-VPSA (Dual-Reflux Vacuum-Pressure Swing Adsorption) capture pilot plant developed as part of the Strategic Project in the Tauron Wytwarzanie S.A. Łagisza Power Plant in Będzin (Silesia, Poland) (Majchrzak-Kucęba et al. 2021). The second was mobile amine-based carbon capture installation, first applied in Łaziska Power Plant (Tatarczuk et al. 2013), moved further to Jaworzno Power Plant (Stec et al. 2015). The summary of those and other – abandoned projects – are presented in the Table 2.

Table 2 Summary of carbon capture finished and abandoned projects.

| Location | Technology | Comment | Ref. |
|---|---|---|---|
| **Łaziska Power Plant** | Carbon capture, absorption | Mobile pilot amine-based carbon capture installation | (Chwoła et al. 2020) |
| **Jaworzno Power Plant** | Carbon capture, absorption | Mobile pilot amine-based carbon capture installation, previously used in Łaziska Power Plant | (Stec et al. 2015) |
| **Łagisza Power Plant** | Carbon capture, adsorption | Mobile pilot adsorption carbon capture installation | (Majchrzak-Kucęba et al. 2019) |
| **Bełchatów Power Plant** | CCS, absorption | Abandoned in 2013; post-combustion amine-based $CO_2$ capture efficiency approx. 85%, 140 km pipeline; storage site in saline aquifers in Wojszyce | (PGE Systemy S.A) |
| **Kędzierzyn-Koźle Power & Chemical Plant** | CCUS, pre-combustion | Abandoned in 2011; 72% of the captured $CO_2$ was to be stored in saline aquifers and 28% was to be sequestrated in chemical products, including MeOH and urea | (Fabiszewska-Solares et al. 2021) |

Thera are also several projects under different stage of planning and development further detailed by Fabiszewska-Solares et al. 2021 (Fabiszewska-Solares et al. 2021).

# Methodology

## Life Cycle Assessment

To perform an assessment, software OpenLCA™ by GreenDelta in version 1.10.3, with the ecoinvent database version 3.9.1 and EuGeos' 15804+A2_IA version 4.1 were used.

## Goals and Scopes

The primary focus of this paper is to evaluate the environmental impacts of a coal-fired power plant with circulating fluidized boiler unit, located in Poland. Therefore, the following scenarios were selected to analyse: (1) a coal-fired power plant with a CFB unit without CCS, and (2) a coal-fired power plant with a CFB unit with CCS technology. This approach allowed an in-depth environmental impacts comparison with specific Poland's background.

The main scopes of processes developed were set up as follows:

- Poland with its domestic energy market set as a case study;
- gate-to-gate reference power plant scenario, and power plant with CCS scenario analysis are performed, as no impact of acquisition and preparation of raw materials necessary for the operation of power plant unit is considered;
- the capture & purification, is considered to be located all on-situ,
- for underground storage was chosen Upper Silesia Basin (USB) which was located approx. 100 km away from Łagisza power plant.

Limitations of the study:

- the environmental impacts resulting from fuel processing and the power plant and carbon capture unit auxiliary processes (e.g., air for combustion compression energy demand, condenser performance) are negligible at the scale considered in this study;

- heat co-produced within the energy production process is treated as avoided product, therefore heat is treated as a credited burden for the auxiliary substitution process.

According to guidelines provided by Müller et al. 2020; von der Assen et al. 2013; Guinée 2002 and European Commission guideline (2010), to avoid allocation of environmental impacts, system boundaries were expanded with auxiliary processes (Müller et al. 2020b; von der Assen et al. 2013; Guinée 2002; European Commission et al. 2010). Furthermore, where it was suitable, sub-division and substitution were applied. Moreover, noteworthy is that Müller et al. 2020a, 2020b provided specific guidelines, ranking the methods according to the most recommended, for solving multifunctionality for LCA of CCUS technology with solutions for the double role of the $CO_2$ feedstock (Müller et al. 2020a, b).

## Functional Unit

As a functional unit was chosen 1 kWh of net high-voltage electricity produced in a coal-fired power plant with a CFB boiler unit, located in the Silesia region in Poland. This functional unit is set thus its value can be used for straightforward comparison with both conventional and non-conventional approaches to electricity production.

## System Boundaries

Therefore, taking into account the assumed functional unit, and the limitations and assumptions made in the goals and scope section, to perform the calculations, we limited the boundary systems of the model. For this reason, several factors were not taken into consideration in the framework of the model.

The raw material acquisition, energy demand of auxiliary processes, as well as maintenance of the power plants were omitted in this study. In addition, the aspect of the environmental impact of equipment functioning as basic and auxiliary was excluded, to simplify the model to basic processes only. This approach ensured that the model's performance was concentrated within the boundaries that focus on the

environmental issue of the production of electricity with or without carbon capture and storage. A simplified scheme of the entire concept model is shown in Figure 5 below.

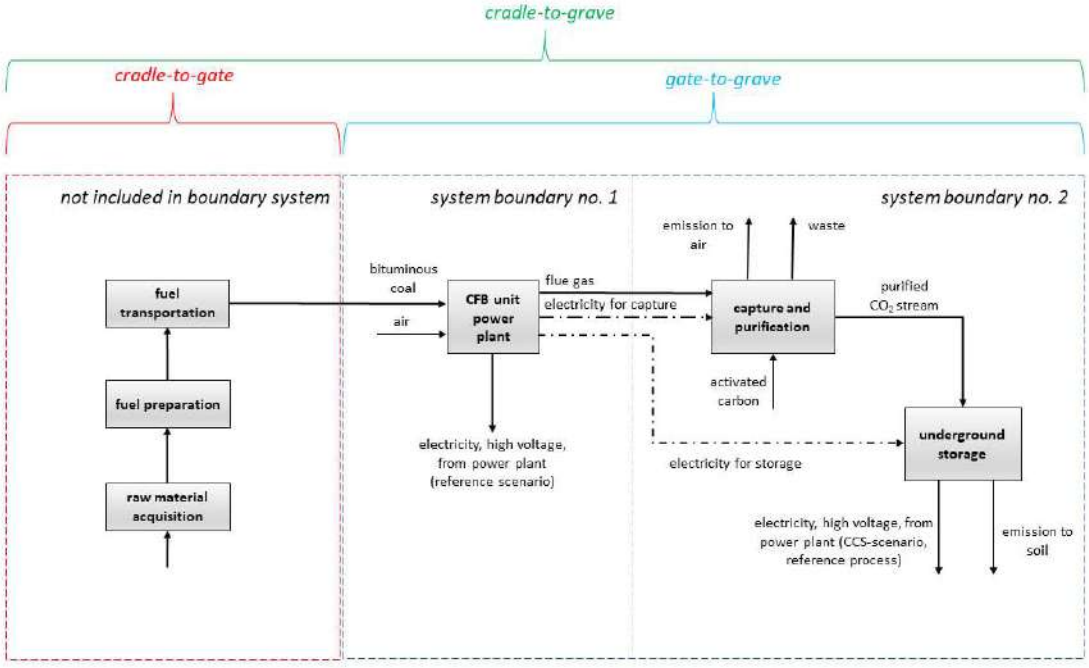


Figure 5 System boundaries for the case study.

Models considering CCS consist of three main processes: (1) the primary processes that is the same as reference the model of a power plant without CCS, (2) the carbon capture and purification unit, and the storage location (3).

## Life Cycle Inventory

### Technology overview

The analysis and model development are carried out based on the collected and elaborated literature information concerning the circulating fluidized bed boiler at Łagisza Power Plant, with carbon capture pilot scale installation of DR-VPSA unit, owned by Tauron Wytwarzanie S.A., located in Będzin, Poland.

### Circulating Fluidized Bed boiler

The Łagisza power plant is the only with a once-through supercritical CFB (CFB OTSC) unit in Poland. The boiler was delivered by Foster Wheeler. The unit achieved full operational status on March 2009. The CFB technology has been seen as an

environmentally friendly way to use fossil fuels as those boilers are considered one of the Best Available Techniques (BAT) for the power sector (Hotta 2010; Nowak and Mirek 2013).

The design capacity of unit is 460 MWe with net electrical efficiency of approx. 44%. Main parameters of stream are: 360 kg per second flow, with 27.5 MPa pressure and 560℃. Reheated stream has flow value of approx. 307 kg per second with 5.5 MPa pressure and 580℃ (Błaszczuk et al. 2012a).

The $SO_2$ emissions are controlled with a limestone feeding system into the boiler furnace (Krzywanski et al. 2015; Cai et al. 2019), while $NO_x$ emissions are controlled with low combustion temperature and air-staging (Błaszczuk et al. 2012b; Saastamoinen and Leino 2019). Those systems allowed to omit additional auxiliary equipment for clean-up flue gases, which makes CFB units require less space to be built (Hotta 2010). Thus, CFB seems to be the perfect solution for repowering and replacing old units with e.g. pulverized coal-fired boilers (PC boilers) (Barisic et al. 2009).

Another major advantage of CFB boilers is the homogenous combustion temperature, both vertically and horizontally. Additionally, CFB boilers are characterized by high bed-to-surface heat transfer coefficients on 100-400 $W/m^2K$ level with a similar footprint to old boilers (Hotta 2010).

Last but not least, high flexibility in quality and range of combusted fuel, as well as the possibility to use mixes of different fuels as feedstock, are also the upper hand for CFB technology (Coda Zabetta et al. 2008; Mirek 2019). Thus, fuel flexibility and the ability to co-fire $CO_2$-neutral fuels with different types of coal, together with high efficiency, can further lead to lower $CO_2$ emissions and reduced ash rates.

The properties and characteristics of bituminous coal used in CFB unit, used as the main design fuel, are the following: Lower Heating Value (LHV) in range of 18-23 MH per kilogram, total moisture from 6 up to 23%, with surface moisture max. 10%, ash content in range of 10-25%. The main chemical components are as follows: carbon 52-60%, hydrogen 3.3-4.2%, oxygen 6.1-8.9%, nitrogen 1.3-1.7%, sulphur 0.7-1.7% (Błaszczuk et al. 2012a).

Lastly, Table 3 resumes the necessary data for LCA analysis, with the inputs and outputs, such: fuel and air quantity and flue gas composition, which were also taken from the literature (Wawrzyńczak et al. 2022a).

Table 3 Power plant inventory, based on (Wawrzyńczak et al. 2022a).

| Parameter | Units | Value |
|---|---|---|
| **Input for power plant** | | |
| **Fuel** | kg/h | 180,000 |
| **Primary air for combustion*** | kg/h | 900,000 |
| **Secondary air for combustion*** | kg/h | 558,000 |
| **Outlet from power plant [wet basis]** | | |
| **Flue gas flow** | kg/h | 1,645,200.00 |
| **$CO_2$** | kg/h | 347,672.41 |
| **$O_2$** | kg/h | 132,615.03 |
| **$N_2$** | kg/h | 1,056,720.79 |
| **$H_2O$** | kg/h | 90,509.76 |
| **Ar** | kg/h | 17,682.00 |
| **Total** | kg/h | 1,645,200.00 |

* (Hotta and Psik Rafał 2013)

DR-VPSA unit

For $CO_2$ capture from the power plant flue gas was selected post-combustion technology Dual-Reflux Vacuum-Pressure Swing Adsorption (DR-VPSA). The assessment of data was derived from a pilot DR-VPSA unit operating on real flue gas from a CFB unit at Łagisza power plant.

DR-VPSA technology is a step forward in carbon capture methods. The two-stage separation process in a single-sectioned adsorber is the result of experience based on single-stage PVSA units, where a single sorption step was not sufficient to achieve sufficient $CO_2$ purity suitable for further treatment (Majchrzak-Kucęba et al. 2019).

The selection of an adsorbent is a crucial step in the DR-VPSA design process. Several parameters should be met by the adsorbent, such as high $CO_2/N_2$ selectivity, significant $CO_2$ sorption capacity, affordable and available in abundance, easy to regenerate, stable during the adsorption-desorption cycle (Ling et al. 2014). Furthermore, the economy of the process is influenced by the lifespan and reusability of adsorbents (Majchrzak-Kucęba et al. 2019).

On the other hand, the major advantages of the adsorption process over absorption are simplicity, lower energy demand, and the possibility of using bio-based adsorbents as an idea of The Closed Circuit Economy (Majchrzak-Kucęba et al. 2019).

The flue gas must be pre-cleaned and dried before it can flow through the carbon capture unit. Thus, it has proceeded throughout the pre-conditioning system made of cooling and heat recovery, desulphurization and $NO_x$ removal section, and drying section (Wawrzyńczak et al. 2018, 2022b; Majchrzak-Kucęba et al. 2019). The DR-VPSA pilot plant was the subject of two patents: PL 231697 (Method of carbon dioxide capture from gas mixtures by vacuum pressure swing adsorption) and PL237180 (Two-stage method of carbon dioxide capture from exhaust gases using the adsorption method) (Wawrzyńczak et al. 2022b). The Table 4 resumes inventory for LCA analysis. The data was elaborated based on the measurements from pilot-scale campaigns in real industrial conditions. Due to the lack of complete data for adsorbent parameters, for instance for modelling purposes, the activated carbon was selected from the existing background inventory of the ecoinvent database. The amount of adsorbent mass was calculated based on literature data (Majchrzak-Kucęba et al. 2019).

Table 4 Carbon capture and purification inventory, based on (Wawrzyńczak et al. 2022a).

| Parameter | Units | Value |
|---|---|---|
| **Recovery** | % | 50.1 |
| **Inlet for capture and purification unit [dry basis]** | | |
| **Energy demand** | kWh/Mg $CO_2$ | 1045* |
| **Flue gas flow** | kg/h | 1,554,696.00 |
| **$CO_2$** | kg/h | 320,656.05 |
| **$O_2$** | kg/h | 124,699.58 |
| **$N_2$** | kg/h | 1,091,121.28 |
| **Ar** | kg/h | 18,219.09 |
| **Total** | kg/h | 1,554,696.00 |
| **Outlet – purified, enriched $CO_2$ stream [dry basis]** | | |
| **Purified $CO_2$ stream flow** | kg/h | 174,954.73 |
| **$CO_2$** | kg/h | 159,484.07 |
| **$O_2$** | kg/h | 6,237.36 |
| **$N_2$** | kg/h | 9,034.22 |
| **Ar** | kg/h | 199.06 |
| **Total** | kg/h | 174,954.73 |
| **Outlet – flue gas from capture and purification unit [dry basis]** | | |
| **$CO_2$** | kg/h | 161,171.98 |
| **$O_2$** | kg/h | 118,462.21 |
| **$N_2$** | kg/h | 1,082,087.06 |
| **Ar** | kg/h | 18,020.03 |
| **Total** | kg/h | 1,379,741.27 |

* process not optimized

$CO_2$ transportation and underground storage

The potential storage site for carbon dioxide captured from the Łagisza power plant may be the unexploited coal beds of the Upper Silesian Basin, situated approx. 100 km distant from the Łagisza power plant and studied under the project of the National Programme "Assessment of formations and structures suitable for safe $CO_2$ geological storage along with their monitoring program" (Wójcicki 2013).

This area has a well-documented geological structure of the USB zone, and the central and southern zone, in particular, is of interest due to its distance from active coal mines, and lack of dense urban area. As previously shown in Figure 4, the potential for unmineable coal layers for $CO_2$-ECBMR technology (Enhanced Coal Bed Methane Recovery) can be estimated at 20 - 100 million tonnes. However, the first volume deals only with selected areas within the Upper Silesia Basin, a total of three regions in the central-southern part of the USB, with capacities of 5-8 million tonnes of $CO_2$ each. The second volume estimates a hypothetical area of the USB where $CO_2$ storage would be possible, although under less favourable reservoir circumstances (Wójcicki 2013, p. 114).

According to Wildbolz 2007 and Volkart et al. 2013, the injection rate per well is assumed to be 125 kg/s, with the number of boreholes determined by the mass flow from the carbon capture installation (Wildbolz 2007; Volkart et al. 2013).

According to Hendriks et al. 2004, $CO_2$ pressure for pipeline transport, must be at least 8 MPa. A higher pressure value requires a higher expenditure of both energy and investment (Hendriks et al. 2004). The same author also provided a simplified solution for calculating the energy requirement for $CO_2$ compression, that were used in this study.

Furthermore, it was assumed that the $CO_2$ storage site is operating as designed, so potential long-term leakage was not analysed. Additionally, scenarios involving the possibility of connecting other $CO_2$ sources to a common storage system have not been considered.

Therefore, Table 5 gathered all calculated and elaborated inventory data for $CO_2$ transportation and underground storage.

Table 5 $CO_2$ transportation and underground storage inventory, based on (Hendriks et al. 2004; Wójcicki 2013; Volkart et al. 2013).

| Parameter | Units | Value |
|---|---|---|
| **Underground storage area** | - | Upper Silesia Basin |
| **Pipeline length** | km | 100 |
| **Injection rate per well** | kg/s | 125 |
| **Energy demand** | $kJ_e/s$ | 17,054.21 |
| **Pressure inlet** | MPa | 0.1 |
| **Pressure outlet** | MPa | 8 |

More information about underground storage, $CO_2$ transportation, and ECBM technology can be found in the literature - (Wakeham et al. 1990; Bachu 2003; Intergovernmental Panel on Climate Change et al. 2005; Coquelet et al. 2017; Sun et al. 2018; Jackson and Brodal 2018; Talapatra 2020; Liu et al. 2022).

## Impact assessment methods

Life Cycle Impact Assessment methods bound together data set in Life Cycle Inventory, within defined model processes, into specific environmental impact categories. The definition of categories is depended on specific impact assessment methodology.

According to Guinée 2002; Corsten et al. 2013; Müller et al. 2020b; Barros et al. 2020, the most novel, updated, and suitable impact assessment method for the process and the localisation where it occurs should be used (Guinée 2002; Corsten et al. 2013; Müller et al. 2020b; Barros et al. 2020). Thus, in a manner that follows the aforementioned literature recommendations, and is commonly used (reviewed by (Corsten et al. 2013; Barros et al. 2020)), the ecoinvent CML v4.8 2016 method was used to conduct the environmental impacts assessment.

This method allows performing calculations for several impact categories: acidification, climate change, ecotoxicity freshwater, ecotoxicity marine, ecotoxicity terrestrial, energy resources, mineral resources, eutrophication, human toxicity, ozone depletion potential, photochemical oxidation.

## Results and discussion

Table 6 summarises the results of the LCA analysis, consistent with the CML methodology, on the selected categories of environmental impacts. Finally, Figure 7 includes a representation of the results in a percentage ratio of the two scenarios.

Table 6 Life Cycle Impact Assessment results.

| Indicator | Unit | Łagisza power plant | Łagisza power plant with CCS | Change in environmental impact |
|---|---|---|---|---|
| **Acidification Potential** | kg $SO_2$-Eq | $1.05x10^{-3}$ | $1.91x10^{-3}$ | Increase |
| **Climate change - $GWP_{100a}$** | kg $CO_2$-Eq | 0.925 | 0.669 | Decrease |
| **Abiotic depletion potential: fossil fuels** | MJ | 13.534 | 24.243 | Increase |
| **Ozone layer depletion** | kg CFC-11-Eq | $9.13x10^{-9}$ | $1.64x10^{-8}$ | Increase |

According to inventory data, current emission from the Łagisza power plant is estimated at 0.756 kg $CO_2$ per kWh, with a slightly increase to 0.925 kg $CO_2$-eq. per kWh in case of $GWP_{100a}$ impact, estimated by LCA analysis. With the CCS scenario the $GWP_{100a}$ impact is reduced by 0.256 kg $CO_2$-eq. per kWh.

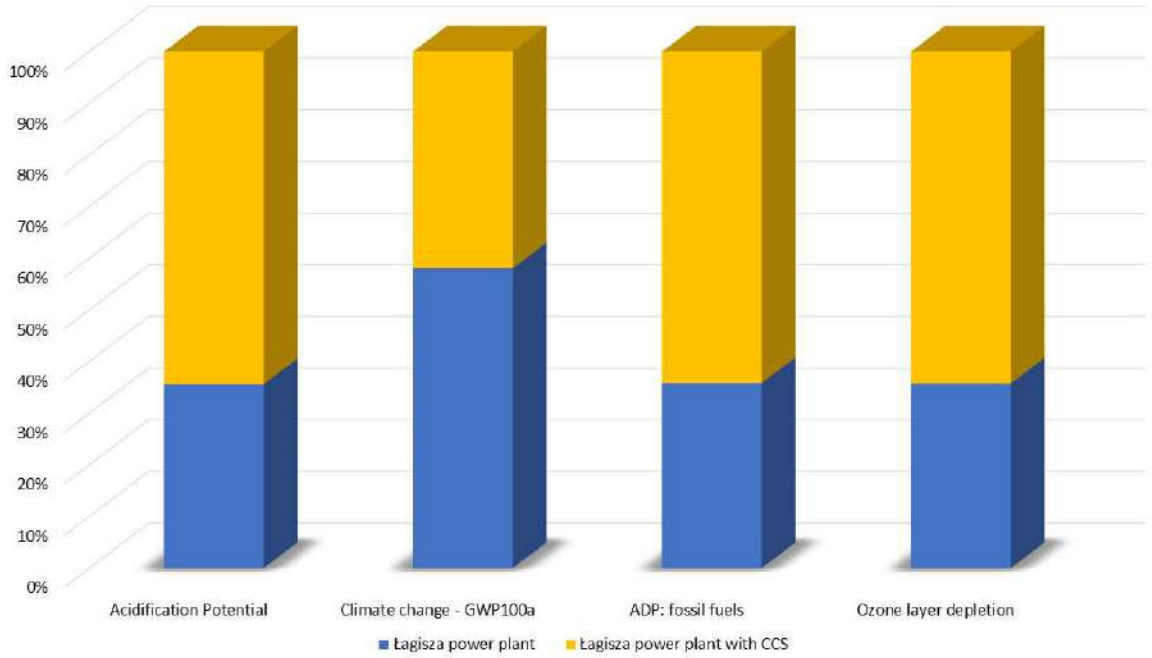


Figure 7 Impact assessment results.

On the other hand, even if the CCS scenario has the possibility to limit $GWP_{100}$ value, the rest of the indicators such as acidification potential, resource depletion, and ozone layer depletion increased. The impact on fossil resource depletion is the most significant with an increase of close to double. The reason for this is the increased demand for electricity, needed for processes such as $CO_2$ capture, and its compression for sequestration. Increase resource and electricity demand is related to higher emissions of other greenhouse gases that are associated with the risk of ozone depletion and enhanced acidification.

It should also not be underestimated that limiting the method and system boundaries, by cutting off the preparation and transport of raw materials needed for the operation of the power plant, can also have a significant impact on the final results of the analysis.

Moreover, it's necessary to point out that implementation to power plant CCS technology will impact unit efficiency. According to Sathre et al. 2011 (Sathre et al. 2011), a drop in efficiency could vary from 8 to 12 percentage points, depending on fuel type (approx. 11% penalty for hard coal).

# Conclusions

Power plants, even with lower environmental impact due to applied boiler technology, still have a high negative impact on the environment. The development of $CO_2$ storage can change that, but it's not the golden solution. Moreover, with current challenges set up by European Union, the polish fossil-fuels based economy comes into a difficult period, demanding rapid transitions. The development of nuclear power plants with RES support could leverage the switch from fossil to green energy, disregarding natural gas as a temporary bridge towards climate neutrality.

As the results of the analysis showed, the application of CCS technology can help to reduce the GWP of a power plant, but other parameters such as ozone depletion potential, resource depletion, or water depletion increase. The rise in other indicators is attributable to the increased energy input for technological processes. This also confirms the need for a holistic evaluation of technologies aimed at addressing climate change to avoid underestimating environmental performance.

Thus, Poland's government to achieve the EPP2040 goals need to strengthen efforts in shifting from fossil fuels to a combination of nuclear energy with RES as a main source of energy, while CCS/CCU should perform as support, especially for industry such as cement industry or iron&steel. With conducted LCA analysis it's clear that CCS can perform its role in carbon neutrality but in cost of efficiency, which is also part of the consideration and aims of EGD.

Further calculations and developments of the model should include a more detailed elaboration of the presented numerical model with, among other things consideration of the environmental impact of raw material acquisition. It also should not be ignored that power plant processes, as well as carbon capture processes, use vast amounts of water, thus specific focus on water depletion should also be taken into consideration in further model development. Additional improvement in the interpretation of the entire process could be the exegetic model of the system and Life Cycle Cost Analysis.

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**CRediT authorship contribution statement**

**Paulina Popielak:** Conceptualization; Data curation; Formal analysis; Methodology; Resources; Visualization; Writing - original draft;

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**Declaration of Competing Interest**

There are no conflicts of interest associated with this article.

**Data availability statement**

All data generated or analyzed during this study are included in this published article.

**Abbreviations**

ADP - Abiotic Depletion Potential

AP - Acidification Potential

CCUS - Carbon Capture Utilization and Storage

CFB - circulating fluidized bed

CRF - Common Reporting Format

ECBM - Enhanced Coal Bed Methane Recovery

EU-ETS - European Union Emission Trading System

LULUCF - Land Use, Land Use Change, and Forestry

NGCC - natural gas combined cycle

OTSC - once through supercritical technology

ODP - Ozone Depletion Potential

BAT - Best Available Technique

CCS - Carbon Capture and Storage

CHP - Combined Heat and Power

DAC - Direct Air Capture

DR-VPSA - Dual-Reflux Vacuum Pressure Swing Adsorption

EPP 2040 - Energy Policy of Poland until 2040

EEA - Environmental Energy Agency

EGD - European Green Deal

EU - European Union

GWP - Global Warming Potential

GHG - Greenhouse Gases

IEA - International Energy Agency

IPCC - International Panel on Climate Change

ISO - International Standards Organization

LCA - Life Cycle Assessment

LCIA - Life Cycle Impact Assessment

LCI - Life Cycle Inventory

LHV - Lower Heating Value

PC - pulverized coal-fired boiler

KOBiZE - the National Centre for Emission Management

TES -Total Energy Supply

USB - Upper Silesia Basin

## References

Anika OC, Nnabuife SG, Bello A, et al (2022) Prospects of low and zero-carbon renewable fuels in 1.5-degree net zero emission actualisation by 2050: A critical review. Carbon Capture Science & Technology 5:100072. https://doi.org/10.1016/j.ccst.2022.100072

Bachu S (2003) Screening and ranking of sedimentary basins for sequestration of CO2 in geological media in response to climate change. Env Geol 44:277–289. https://doi.org/10.1007/s00254-003-0762-9

Barisic V, Coda Zabetta E, Eriksson T, et al (2009) CFB technology provides solutions for reducing CO2 emissions. The Journal of the Southern African Institute of Mining and Metallurgy 108:107–119

Barros MV, Salvador R, Piekarski CM, et al (2020) Life cycle assessment of electricity generation: a review of the characteristics of existing literature. Int J Life Cycle Assess 25:36–54. https://doi.org/10.1007/s11367-019-01652-4

Błaszczuk A, Komorowski M, Nowak W (2012a) Distribution of Solids Concentration and Temperature in the Combustion Chamber of the SC-OTU CFB Boiler. Journal of Power Technologies 92:27–33

Błaszczuk A, Nowak W, Klajny M, et al (2012b) NOx emissions from the 460 MWe supercritical CFB boiler

Bonura G, Todaro S, Frusteri L, et al (2021) Inside the reaction mechanism of direct CO2 conversion to DME over zeolite-based hybrid catalysts. Applied Catalysis B: Environmental 294:120255. https://doi.org/10.1016/j.apcatb.2021.120255

Cai R, Ke X, Huang Y, et al (2019) Applications of Ultrafine Limestone Sorbents for the Desulfurization Process in CFB Boilers. Environ Sci Technol 53:13514–13523. https://doi.org/10.1021/acs.est.9b04747

Catizzone E, Bonura G, Migliori M, et al (2017) CO2 Recycling to Dimethyl Ether: State-of-the-Art and Perspectives. Molecules 23:31. https://doi.org/10.3390/molecules23010031

Chwoła T, Spietz T, Więcław-Solny L, et al (2020) Pilot plant initial results for the methanation process using CO2 from amine scrubbing at the Łaziska power plant in Poland. Fuel 263:116804. https://doi.org/10.1016/j.fuel.2019.116804

Coda Zabetta E, Barisic V, Peltola K, Hotta A (2008) Foster Wheeler Experience with Biomass and Waste in CFBs

Coquelet C, Stringari P, Hajiw M, et al (2017) Transport of CO2: Presentation of New Thermophysical Property Measurements and Phase Diagrams. Energy Procedia 114:6844–6859. https://doi.org/10.1016/j.egypro.2017.03.1822

Corsten M, Ramírez A, Shen L, et al (2013) Environmental impact assessment of CCS chains – Lessons learned and limitations from LCA literature. International Journal of Greenhouse Gas Control 13:59–71. https://doi.org/10.1016/j.ijggc.2012.12.003

Deutz S, Bardow A (2021) Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Nat Energy 6:203–213. https://doi.org/10.1038/s41560-020-00771-9

Dubiński J, Wachowicz J, Koteras A (2010) Podziemne składowanie dwutlenku węgla - możliwości wykorzystania technologii CCS w polskich uwarunkowaniach. Górnictwo i Geologia 5, Zeszyt 1:15

European Commission, Joint Research Centre, Institute for Environment and Sustainability (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance., 1st edn. Publications Office of the European Union, Luxembourg

European Environment Agency (2021) EEA greenhouse gases - data viewer — European Environment Agency. In: European Environment Agency Official Website. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer. Accessed 24 Oct 2022

Fabiszewska-Solares J, Kobyłka K, Laskowski K, et al (2021) Assessment of current state, past experiences and potential for CCS deployment in the CEE region. WiseEuropa, Poland

Gładysz P, Sowiżdżał A, Miecznik M, Pająk L (2020) Carbon dioxide-enhanced geothermal systems for heat and electricity production: Energy and economic analyses

for central Poland. Energy Conversion and Management 220:113142. https://doi.org/10.1016/j.enconman.2020.113142

Guinée JB (2002) Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards. Kluwer Academic Publishers, Netherlands

Hasan MMF, Zantye MS, Kazi M-K (2022) Challenges and opportunities in carbon capture, utilization and storage: A process systems engineering perspective. Computers & Chemical Engineering 166:107925. https://doi.org/10.1016/j.compchemeng.2022.107925

Hendriks C, Crijns-Graus W, Bergen F (2004) Global Carbon Dioxide Storage Potential and Costs

Herold A, Monni S, Erda L, et al (2010) Methodological choice and identification of key categories. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change

Hong WY (2022) A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO2 emissions future. Carbon Capture Science & Technology 3:100044. https://doi.org/10.1016/j.ccst.2022.100044

Hosseini S, Aslani A, Kasaeian A (2023) Life cycle cost and environmental assessment of CO2 utilization in the beverage industry: A natural gas-fired power plant equipped with post-combustion CO2 capture. Energy Reports 9:414–436. https://doi.org/10.1016/j.egyr.2022.11.200

Hotta A (2010) Foster Wheeler's Solutions for Large Scale CFB Boiler Technology: Features and Operational Performance of Łagisza 460 MWe CFB Boiler. In: Yue G, Zhang H, Zhao C, Luo Z (eds) Proceedings of the 20th International Conference on Fluidized Bed Combustion. Springer, Berlin, Heidelberg, pp 59–70

Hotta A, Psik Rafał (2013) Testing and simulation in Turow Unit 3 and the application of the results on the Lagisza 460 MWe OT CFB

Igliński B, Piechota G, Kiełkowska U, et al (2022) The assessment of solar photovoltaic in Poland: the photovoltaics potential, perspectives and development. Clean Techn Environ Policy. https://doi.org/10.1007/s10098-022-02403-0

Intergovernmental Panel on Climate Change, Metz B, Davidson O, et al (eds) (2005) IPCC special report on carbon dioxide capture and storage. Cambridge University Press, for the Intergovernmental Panel on Climate Change, Cambridge

International Energy Agency (2021) Poland. In: IEA. https://www.iea.org/countries/poland. Accessed 17 Apr 2023

Jackson S, Brodal E (2018) A comparison of the energy consumption for CO 2 compression process alternatives. IOP Conf Ser: Earth Environ Sci 167:012031. https://doi.org/10.1088/1755-1315/167/1/012031

Kang Z, Liao Q, Zhang Z, Zhang Y (2022) Carbon neutrality orientates the reform of the steel industry. Nat Mater 21:1094–1098. https://doi.org/10.1038/s41563-022-01370-7

Krzywanski J, Czakiert T, Blaszczuk A, et al (2015) A generalized model of SO2 emissions from large- and small-scale CFB boilers by artificial neural network approach. Fuel Processing Technology 137:66–74. https://doi.org/10.1016/j.fuproc.2015.04.012

Leung DYC, Caramanna G, Maroto-Valer MM (2014) An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews 39:426–443. https://doi.org/10.1016/j.rser.2014.07.093

Ling J, Ntiamoah A, Xiao P, et al (2014) Overview of CO2 capture from flue gas streams by vacuum pressure swing adsorption technology. Austin J Chem Eng 1:1–7

Liu M, Wen H, Fan S, et al (2022) Experimental Study of CO2-ECBM by Injection Liquid CO2. Minerals 12:297. https://doi.org/10.3390/min12030297

Majchrzak-Kucęba I, Wawrzyńczak D, Ściubidło A, et al (2019) Stability and regenerability of acivated carbon used for CO2 removal in pilot DR-VPSA unit in real power plant conditions. Journal of CO2 Utilization 29:1–11. https://doi.org/10.1016/j.jcou.2018.11.003

Majchrzak-Kucęba I, Wawrzyńczak D, Zdeb J, et al (2021) Treatment of Flue Gas in a CO2 Capture Pilot Plant for a Commercial CFB Boiler. Energies 14:2458. https://doi.org/10.3390/en14092458

Marchi B, Zanoni S, Pasetti M (2018) Industrial Symbiosis for Greener Horticulture Practices: The CO2 Enrichment from Energy Intensive Industrial Processes. Procedia CIRP 69:562–567. https://doi.org/10.1016/j.procir.2017.11.117

Marks-Bielska R, Bielski S, Pik K, Kurowska K (2020) The Importance of Renewable Energy Sources in Poland's Energy Mix. Energies 13:4624. https://doi.org/10.3390/en13184624

McQueen N, Gomes KV, McCormick C, et al (2021) A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Prog Energy 3:032001. https://doi.org/10.1088/2516-1083/abf1ce

Mika-Brysk M, Wróblewska E (2015) Polskie podejście do CCS w świetle aktualnego statusu rozwoju tej technologii. Przegląd Geologiczny 63:4

Ministerstwo Klimatu i Środowiska (2023) Projekt ustawy o Prawo geologiczne przyjęty przez Radę Ministrów - Portal Gov.pl. In: Ministerstwo Klimatu i Środowiska. https://www.gov.pl/web/klimat/projekt-ustawy-o-prawo-geologiczne-przyjety-przez-rade-ministrow2. Accessed 16 May 2023

Ministry of Climate and Environment (2021) Energy Policy of Poland until 2040 (EPP2040) - Ministry of Climate and Environment. In: Ministry of Climate and Environment. https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040. Accessed 20 Jan 2023

Mirek P (2019) Experimental investigation of the flow characteristics of low-pressure drop air nozzles working with CFB boilers. E3S Web Conf 82:01013. https://doi.org/10.1051/e3sconf/20198201013

Monitor Polski (2021) Obwieszczenie Ministra Klimatu i Środowiska z dnia 2 marca 2021 r. w sprawie polityki energetycznej państwa do 2040 r.

Monteiro J, Roussanaly S (2022) CCUS scenarios for the cement industry: Is CO2 utilization feasible? Journal of CO2 Utilization 61:102015. https://doi.org/10.1016/j.jcou.2022.102015

Mostafa M, Antonicelli C, Varela C, et al (2022) Capturing CO2 from the atmosphere: Design and analysis of a large-scale DAC facility. Carbon Capture Science & Technology 4:100060. https://doi.org/10.1016/j.ccst.2022.100060

Müller L, Kätelhön A, Bringezu S, et al (2020a) The carbon footprint of the carbon feedstock CO2. Energy & Environmental Science 13:. https://doi.org/10.1039/D0EE01530J

Müller LJ, Kätelhön A, Bachmann M, et al (2020b) A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. Frontiers in Energy Research 8:

Nowak W, Mirek P (2013) Circulating fluidized bed combustion (CFBC). In: Fluidized Bed Technologies for Near-Zero Emission Combustion and Gasification. Elsevier, pp 701–764

Olecka A, Bebkiewicz K, Chłopek Z, et al (2021) Krajowy raport inwentaryzacyjny 2021 Inwentaryzacja gazów cieplarnianych w Polsce dla lat 1988-2019

Parliament of the Republic of Poland (2011) Mining and Geological Law

PGE Systemy S.A Ochrona środowiska - CCS demonstration plant. https://pgegiek.pl/ochrona-srodowiska/ccs/ccs-demonstration-plant2. Accessed 21 Jun 2024

Pietrzak MB, Igliński B, Kujawski W, Iwański P (2021) Energy Transition in Poland—Assessment of the Renewable Energy Sector. Energies 14:2046. https://doi.org/10.3390/en14082046

Przybojewska I (2018) Legal possibilities of carbon capture and storage in Poland. Law and Administration in Post-Soviet Europe 5:18–27. https://doi.org/10.2478/lape-2018-0003

Ray RL, Singh VP, Singh SK, et al (2022) What is the impact of COVID-19 pandemic on global carbon emissions? Science of The Total Environment 816:151503. https://doi.org/10.1016/j.scitotenv.2021.151503

Saastamoinen H, Leino T (2019) Fuel Staging and Air Staging To Reduce Nitrogen Emission in the CFB Combustion of Bark and Coal. Energy Fuels 33:5732–5739. https://doi.org/10.1021/acs.energyfuels.9b00850

Sathre R, Masanet E, Cain J, Chester M (2011) The role of Life Cycle Assessment in identifying and reducing environmental impacts of CCS. Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States)

Sowiżdżał A, Starczewska M, Papiernik B (2022) Future Technology Mix—Enhanced Geothermal System (EGS) and Carbon Capture, Utilization, and Storage (CCUS)—An Overview of Selected Projects as an Example for Future Investments in Poland. Energies 15:3505. https://doi.org/10.3390/en15103505

Stec M, Tatarczuk A, Więcław-Solny L, et al (2015) Pilot plant results for advanced CO2 capture process using amine scrubbing at the Jaworzno II Power Plant in Poland. Fuel 151:. https://doi.org/10.1016/j.fuel.2015.01.014

Sun Y, Zhao Y, Yuan L (2018) CO2-ECBM in coal nanostructure: Modelling and simulation. Journal of Natural Gas Science and Engineering 54:202–215. https://doi.org/10.1016/j.jngse.2018.04.007

Talapatra A (2020) A study on the carbon dioxide injection into coal seam aiming at enhancing coal bed methane (ECBM) recovery. J Petrol Explor Prod Technol 10:1965–1981. https://doi.org/10.1007/s13202-020-00847-y

Tarkowski R, Uliasz-Misiak B (2019) Prospects for the use of carbon dioxide in enhanced geothermal systems in Poland. Journal of Cleaner Production 229:1189–1197. https://doi.org/10.1016/j.jclepro.2019.05.036

Tatarczuk A, Więcław-Solny L, Stec M, et al (2013) First Polish Pilot Plant for CO2 Post Combustion Capture

Turgut O, Bjerketvedt VS, Tomasgard A, Roussanaly S (2021) An integrated analysis of carbon capture and storage strategies for power and industry in Europe. Journal of Cleaner Production 329:129427. https://doi.org/10.1016/j.jclepro.2021.129427

Volkart K, Bauer C, Boulet C (2013) Life cycle assessment of carbon capture and storage in power generation and industry in Europe. International Journal of Greenhouse Gas Control 16:91–106. https://doi.org/10.1016/j.ijggc.2013.03.003

von der Assen N, Jung J, Bardow A (2013) Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls. Energy Environ Sci 6:2721. https://doi.org/10.1039/c3ee41151f

Wakeham VVA, Olchowya GA, Watson JTR (1990) The Transport Properties of Carbon Dioxide. J Phys Chem Ref Data 19:

Wawrzyńczak D, Majchrzak-Kucęba I, Pevida C, et al (eds) (2022a) The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies: A Case Study. CRC Press, Boca Raton

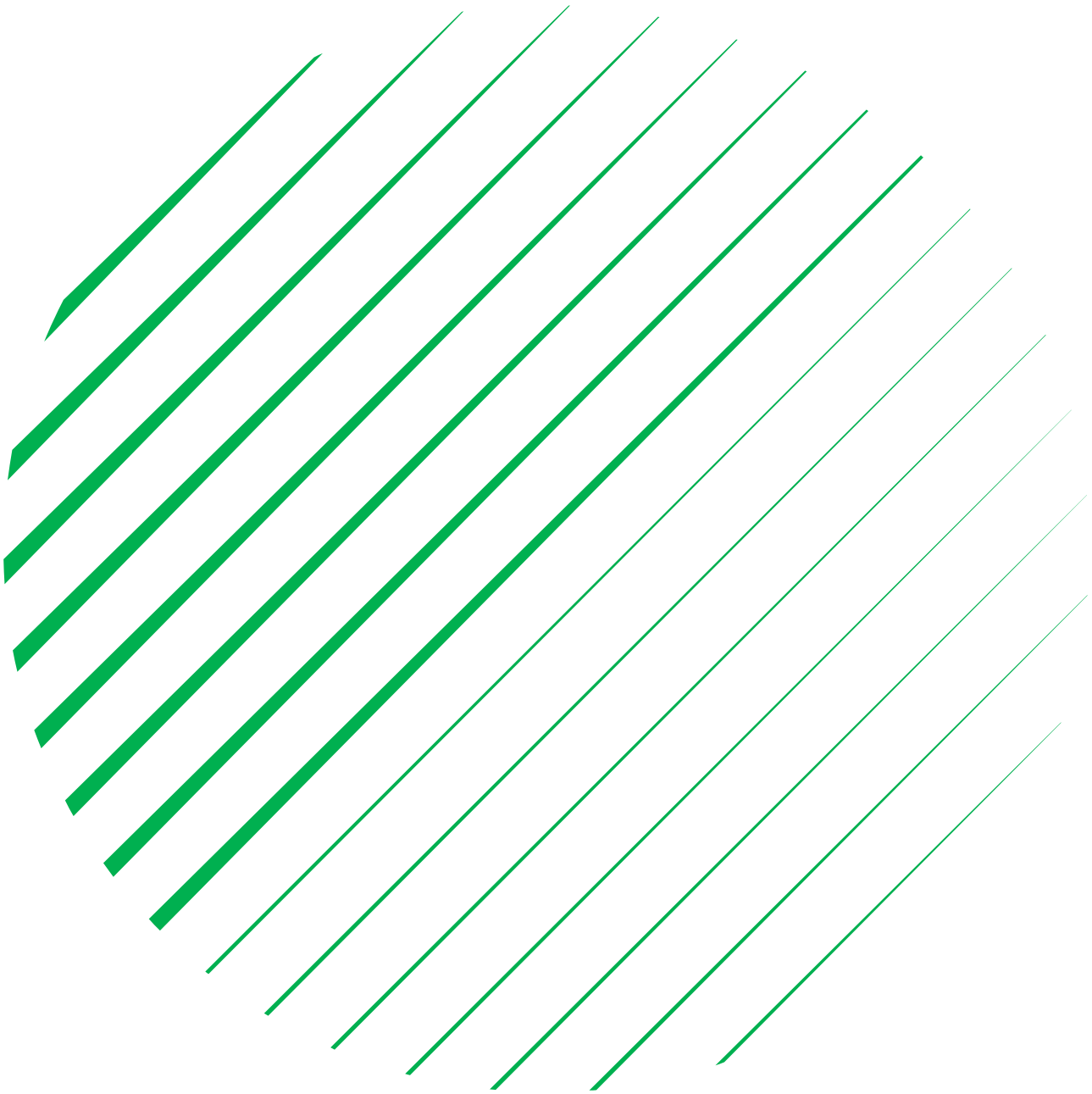
Wawrzyńczak D, Majchrzak-Kucęba I, Pevida C, et al (eds) (2022b) The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies: A Case Study. CRC Press, Boca Raton

Wawrzyńczak D, Majchrzak-Kucęba I, Srokosz K, et al (2018) The pilot dual-reflux vacuum pressure swing adsorption unit for CO 2 capture from flue gas. Separation and Purification Technology 209:. https://doi.org/10.1016/j.seppur.2018.07.079

Wildbolz C (2007) Life Cycle Assessment of Selected Technologies for CO2 Transport and Sequestration. Institute of Environmental Engineering (IfU)

Wójcicki A (2013) Rozpoznanie formacji i struktur do bezpiecznego geologicznego składowania CO2 wraz z ich programem monitorowania. Państwowy Instytut Geologiczny, Warszawa

# Chapter 7 Case study no 2 - Methodologies for CCU technologies environmental analysis



# Methodologies for CCU technologies environmental analysis

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# 7 Methodologies for CCU technologies environmental analysis

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## 7.1 INTRODUCTION

Carbon capture and utilization (CCU) represents a smart solution to re-use $CO_2$ as a reagent for the synthesis of high-end products instead of storing it underground, implementing a "Circular Economy" concept [1]. Many technologies in this field

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are recently attracting attention [2–6], but $CO_2$ is a very stable compound and its utilization as a reagent is energetic intensive. As a consequence, it is unclear whether CCU processes allow for a net reduction of environmental impacts from a life cycle perspective and whether these solutions are sustainable.

In this chapter, we analyze a complete process architecture able to convert $CO_2$ in dimethyl ether (DME, IUPAC name methoxymethane), an organic compound mainly used as a reagent for the synthesis of widely applied products such as dimethyl sulfate (a methylating agent), methyl acetate and light olefins. In addition, a growing interest on DME synthesis is due to its characteristics similar to those of liquefied petroleum gas (LPG) and to the excellent combustion property that make the DME a potential candidate as a fuel in compression-ignition engines [7]. Adding DME to the diesel fuel allows an enhancement of the combustion properties, mainly in terms of reduction of smoke, $NO_x$ and $CO_2$ emissions [8].

However, even if CCU is the best solution to treat $CO_2$ theoretically, in practical terms the need to build a chemical processing plant involves significant energy consumption and additional carbon dioxide emissions (beyond a significant Capital Expenditure). For this reason, there is the need to analyze in detail the pros and cons of these innovative configurations in terms of energy expenditure and environmental impacts.

Some strategies for process analysis, focused on the quantification of the performance, energy and exergy efficiency, carbon footprints, are briefly reported and described. Then, a process scheme for the sustainable production of DME from pure $CO_2$ and green hydrogen (i.e. hydrogen produced through electrolysis using 100% renewable electricity) is described, modeled and simulated.

## 7.2 PROCESS SIMULATION AND ENVIRONMENTAL ANALYSES

There are many tools to evaluate the performance of a process configuration. In this paragraph, we focus the attention on three of them:

- Process simulation by means of process analysis software.
- Exergy balance and efficiency.
- Life Cycle Assessment (LCA).

Each of this allows to evaluate the behavior of a plant from a different point of view:

- The process simulation quantifies the performance of the plant and of each unit composing it, the input/output streams and their physical characteristics (pressure, temperature, flowrate, composition). These tools allow to optimize the performance of a process by means of sensitivity analysis and the implementation of optimization strategies.
- Energy/exergy analysis uses the data achieved in the process simulation to provide a detailed analysis of energy and exergy losses for each unit composing the process, aimed to understand where there are the greatest energy/exergy penalties and how to reduce them.

- LCA is focused on the assessment of environmental footprint in the whole life cycle of the plant, from construction to operation and end-of-life. This impact is calculated by means of a series of indices, such as the Global Warming Potential, the Acidification Potential, the Eutrophication Potential and the Eco-toxicity.

In the following, a brief description of these process analysis approaches is reported.

### 7.2.1 Process simulation

To simulate a process, the following actions have to be made [9]:

1. Design specifications and battery limit selection.
2. Model Development: development of the process flow diagram (PFD), analysis of degrees of freedom, material and energy balances, selection of the thermodynamics model to be implemented.
3. Process Simulation: sensitivity analysis, optimization, basic design.
4. Post-processing activities: techno-economic analysis, dynamic simulations, exergetic analysis, LCA.

Figure 7.1 shows the procedure schematically.

The basis of a proper process modeling and simulation is the application of the material and energy balances. These equations derive from the mass and energy conservation principles and are formulated as follow, after the selection of the control volume where applying them:

*Inlet rate of the quantity (mass or energy) through the control volume surface* − *Outlet rate of the quantity (mass or energy) through the control volume surface* ± *Generation rate of mass or energy inside the control volume* = *Time variation of the quantity (mass or energy) in the control volume*

Mathematical formulation can be expressed as follows:

Mass balance

$$\dot{m}_{in} - \dot{m}_{out} \pm \dot{m}_{gen} = \frac{dM}{dt} \tag{7.1}$$

where $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{m}_{gen}$ are the inlet, outlet and generation flow rates, respectively, and M is the mass inside the control volume.

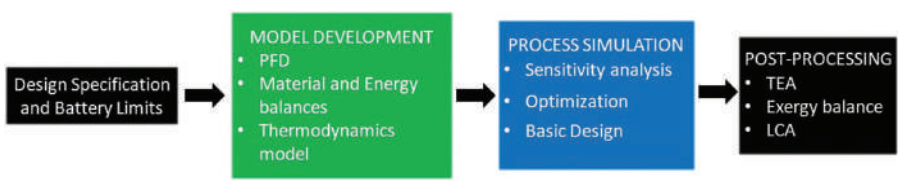



**FIGURE 7.1** Process simulation procedure.

Energy balance

$$\dot{H}_{in} - \dot{H}_{out} \pm \dot{H}_{gen} = \frac{dH}{dt} \tag{7.2}$$

where $\dot{H}_{in}$, $\dot{H}_{out}$ and $\dot{H}_{gen}$ the inlet, outlet and generation enthalpy flow rates, respectively, and H is the enthalpy inside the control volume.

After formulating the mass and energy balances for each unit of the PFD, and for the whole process as well, an appropriate thermodynamic package has to be selected. There is not a single general thermodynamic model suitable in every situation, but rather selecting a model inappropriate for the specific application compromises the entire modeling. Main thermodynamics models are:

- Equations of State
- Activity Models
- Semi-Empirical Models
- Ad-hoc packages

The main Equations of State models and some of their application fields are:

- Peng-Robinson – Gas Dehydration, slightly polar liquids and light gases.
- PRSV – Cryogenic gas processing, vacuum towers.
- Soave Redlich Kwong – polar components at pressure <1 MPa.

Activity models are:

- Wilson and Margules – alcohols, phenols, C4-C6 hydrocarbons, aromatics.
- NRTL – aqueous organics.
- UNIQUAC and UNIFAC – polar components at pressure >1 MPa.

In addition, Semi-Empirical Models and Ad-hoc packages have been developed for specific industrial processes, such as sour gas absorption by means of amine solutions.

Then, after modeling activities, the process can be simulated through the use of simulation tools, such as Aspen Plus, PRO II, ASCEND and many others. First of all, the models should be validated with experimental data, when available. Then, after confirming the reliability of the models, we can perform a sensitivity analysis, by which it is possible to quantify the impact of the main operating conditions (temperature, pressure, composition, flowrates, etc.) on the process performance. The sensitivity analysis gives information for optimizing the operating conditions set, according to selected criteria such as:

- Maximization of process performance.
- Minimization of operating costs.
- Minimization of resource consumption.
- Minimization of environmental impact.

The designers should decide the optimization criteria and then select the optimal operating conditions set coherently with their needs. Then, post-processing activities are performed to verify the most important results achieved in terms of economic, environmental impact and efficiency of the process. In the following, two post-processing actions are described: the Exergy Analysis and the Life Cycle Assessment.

### 7.2.2 Exergy analysis

The exergy of a system is the maximum obtainable work during a process that brings the system into equilibrium with its reference environment through a series of reversible processes in which the system can only interact with such environment [10–12]. In other words, exergy is an "opportunity for doing work" and, in real processes, it is destroyed by entropy generation [12]. Exergy-based analysis is useful to evaluate the thermodynamic inefficiencies of processes, to understand and locate the additional consumption of fuels or primary energy, to provide an instrument for comparison among different process configurations and to detect solution to reduce the energy penalties of a process.

This paragraph is focused on the fundamental definitions at the basis of exergy analysis thanks to the simultaneous invocation of the first and second laws.

Figure 7.2 represents a "black-box separator" (open system) in thermal contact with a number l of heat reservoirs (l = 1…p) at temperatures $T_l$. The mechanical power $\dot{W}$ is considered in this chapter, nevertheless this work transfer rate can be the combination of different effects (e.g. shear, electrical, magnetic) [14, 15]. The control volume is crossed by j feed streams and k product streams and the system is free to transfer work ($p_0$ dV/dt) and heat ($Q_0$) to the environment.

The First and Second Laws of Thermodynamics for the open system of Figure 7.2 result into Eqs. 7.3 and 7.4. The enthalpy is used by neglecting variation of kinetic and potential energy of the streams crossing the control volume.

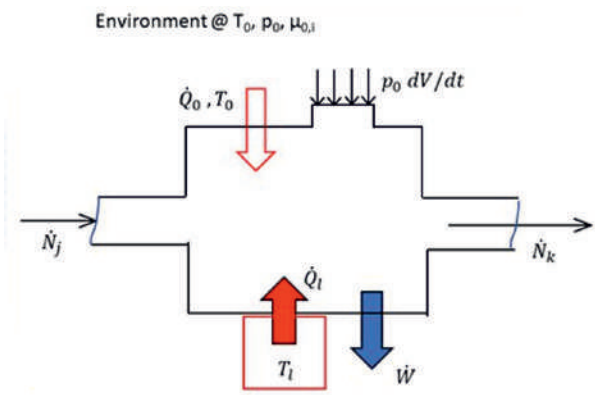



**FIGURE 7.2** Control volume black-box separator adapted from Bejan [13].

$$\frac{dU}{dt} = \dot{W} + \sum_{l=0}^{p} \dot{Q}_l + \sum_{j=1}^{q} \dot{N}_j \overline{h}_j - \sum_{k=1}^{r} \dot{N}_k \overline{h}_k - p_0 \frac{dV}{dt} \tag{7.3}$$

$$\frac{dS}{dt} = \sum_{l=0}^{p} \frac{\dot{Q}_l}{T_l} + \sum_{j=1}^{q} \dot{N}_j \overline{s}_j - \sum_{k=1}^{r} \dot{N}_k \overline{s}_k + \dot{S}_{gen} \tag{7.4}$$

where $N_j$ (with j = 1…q) and $N_k$ (with k = 1…r) are the input and output streams, $p_0$ and $T_0$ are the environmental conditions, $\dot{S}_{gen}$ is the entropy generation. In the case of interest where the atmospheric work is absent, the equations are arranged to obtain the exergy balance for the open system of Eq. 7.5 where the specific exergy of any stream is given by Eq. 7.6.

$$\frac{d\Xi}{dt} = \dot{W} + \sum_{l=0}^{p} \left(1 - \frac{T_0}{T_l}\right)_l \dot{Q}_l + \sum_{j=1}^{q} \dot{N}_j \overline{\xi}_j - \sum_{k=1}^{r} \dot{N}_k \overline{\xi}_k - T_0 \dot{S}_{gen} \tag{7.5}$$

$$\xi_j(T, p, N_i) = h_j - T_o s_j - \sum_i \mu_{0,i} x_i \tag{7.6}$$

where for the j-th stream, $\xi_j$ is the specific exergy, $\mu_{0,i}$ is chemical potential and $x_i$ the molar fraction. In analogy, the terms for the output streams can be defined. The exergy of the system can be seen as the sum of the "available work" composed by the mechanical power and "adjusted" thermal power plus the specific exergy of the process streams multiplied by the stream flowrate. In fact, main interactions though the system boundaries are the work and heat-related exergy fluxes (respectively $\Xi_W$ and $\Xi_Q$) while the exergy destruction term $\Xi_D$ represents the irreversible loss of "work availability", equal to the so-called Gouy–Stodola lost work as reported in the following equation:

$$\Xi_W = \dot{W} \tag{7.7}$$

$$\Xi_Q = \left(1 - \frac{T_0}{T_l}\right) \tag{7.8}$$

$$\Xi_D = T_0 \dot{S}_{gen} \tag{7.9}$$

As often occurs for evaluating systems that includes separation and/or conversion processes, the balance of Eq. 7.5 neglects a portion of the physical exergy, related to the kinetic and potential energy for the sake of simplicity. A more rigorous definition including all terms as depicted in Figure 7.3 is given by Eq. 7.10

$$\xi(T, p, N_i, v, z) = \hat{h} - T_o s - \sum_i \mu_{0,i} x_i = gz + \frac{1}{2} v^2 + h - T_o s - \sum_i \mu_{0,i} x_i \tag{7.10}$$

where the additional first and the second terms are respectively the potential and kinetic energy forms of the stream.

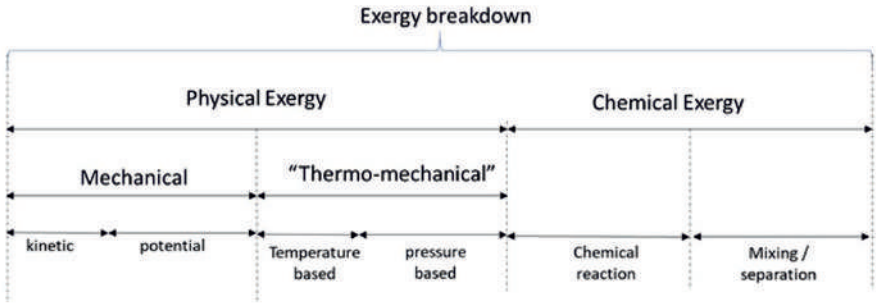



**FIGURE 7.3** Exergy breakdown.

In synthesis, the evaluation of the entropy generation and the consequent destruction of the available work in any part of the process (by applying the exergy balance of Eq. 7.5) is the main goal of the exergy analysis and is implemented in techno-economic evaluations of separation processes in several papers [10–13, 16].

Before performing an exergy analysis it is important to [11, 12]:

- Univocally define the system by selecting the control volume.
- Define an appropriate reference environment.
- Compute mass, energy and entropy balances of the system during the process.
- In case of work-absorbing process (conversion-separation), evaluate the minimum necessary work.

The minimum work of separation can be evaluated from Eq. 7.5 by assuming steady state and reversible behavior and under the hypothesis that the process streams must exit at the "restricted dead state" [15]. In this way, the exergy of the process streams reduces to the Gibbs free energy at atmospheric temperature and pressure (Eq. 7.11).

$$\dot{W}_{least} = \dot{\Xi}_{least} = \sum_{k=1}^{r} \dot{N}_k \bar{g}_k - \sum_{j=1}^{q} \dot{N}_j \bar{g}_j \tag{7.11}$$

where $\dot{\Xi}_{least}$ is the minimum amount of exergy (rate of available energy) necessary to separate the streams $N_j$ into the streams $N_k$ and g is the specific Gibbs free energy of the j-th or k-th component. This minimum amount must be provided to the system by a combination of work and heat (for a stationary process that does not accumulate nonflow exergy, $d\Xi/dt = 0$). For example, with respect to the product "pure" stream obtained through an ideal separation box, the minimum work of separation is around 2 kJ/kg for seawater desalination, 480 kJ/kg to recovery the $CO_2$ from flue gases and 300 kJ/kg to separate the $O_2$ from air. More details can be found in the cited literature [9, 13, 15, 16].

In addition, to identifying the efficiencies, the exergy analysis, starting from the definitions above, allows the calculation of performance indices based on the II Law of Thermodynamics. Two similar definitions are reported below. The first, reported

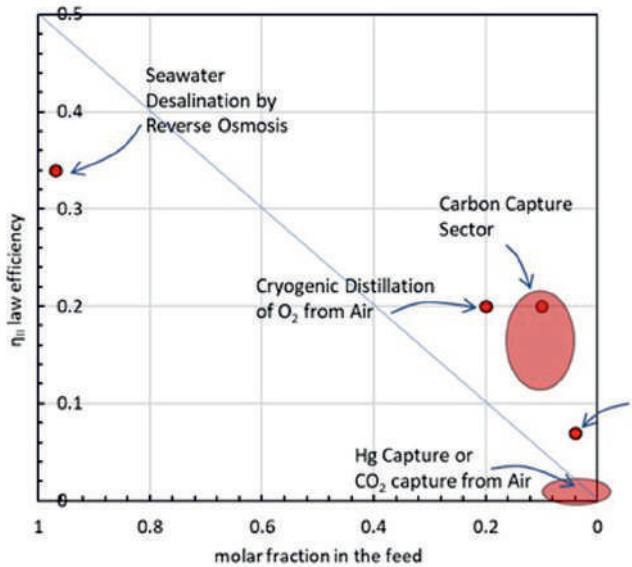



**FIGURE 7.4** Second law efficiency vs. molar fractions in the feed to be separated.

in Eq. 7.12, is specifically designed for separation/conversion processes; the second is appliable to a general process and is defined according to the Fuel–Product paradigm (F–P) in which the fuel represents the primary energy input to the system and the useful exergy of the main product stream (assuming that the others are waste) [10–13]. Figure 7.4 shows the 2-nd law efficiency for reference processes as described by the cited literature [9, 15]. For mature processes, it is of the order of magnitude of 10–20% and it strongly decreases as the concentration of the substance to recover (or to abate in case of pollutants) decreases.

$$\eta_{II}\frac{W_{least}}{W_{real}} = \frac{Q_{least}}{Q_{real}} \tag{7.12}$$

$$\eta_{II} = \frac{\xi_{useful}}{\xi_{in}} = \frac{\xi_{product}}{\xi_{fuel}} = 1 - \frac{\xi_{des} + \xi_{lost}}{\xi_{fuel}} \tag{7.13}$$

## 7.3 LCA ANALYSIS

All products and services have some impact on the environment, different at each stage, determined by various aspects, depending on how the product was created, how long it will be used, how many resources and energy were used in process of its production and how will look final disposal of waste. Each stage has specific impact on the environment and efforts are currently being made to minimize this impact, especially where it is ecologically and economically significant. In this way, it is possible not only to influence the environmental factors positively, but also to decrease the costs of the production as well as services. Life Cycle Assessment is a

reliable tool to evaluate the environmental aspects and impacts that result from the various stages of a product's life, including raw material acquisition (for example: mineral extraction and processing), manufacturing (production process), distribution and transport, usage, reuse, recycling, final disposal of waste.

Life Cycle Assessment can quantify the environmental impact on many different categories of products or services on every life cycle stage.

Because the LCA is a cradle-to-grave study, it allows to evaluate both the overall cycle's impact and the impact of individual process's stage or product. In addition, the LCA makes possible to understanding how entire process works on all stages, establishing complex and extensive relationships between various inputs, such as raw materials or energy and outputs which can be understand as intermediate products (necessary for further processes or technologies analysis) or as final products in their last phase of life, i.e., on disposal. LCA does not only indicate the environmental impact of a product cycle, but also on human health or on the depletion of natural resources. By studying the impacts of a production process or technology at each stage, the LCA can be used as a comparative tool for different scenarios, which can be applied in the decision support process [17].

Figure 7.5 represents a simple example of factors and relations between them that can be estimated in LCA analysis [18].

Fundamental tasks that can be managed with using LCA as a tool are: determine impact assessment on different factors like environment, human health, natural resources depleted, impact of wastes disposal, managing variant scenarios of processes, technologies and services, help in decision-making process and product or process design.

However, like any methodology, LCA analysis also has its limitations. The holistic approach is both a major strength as well as a limitation which may lead to a simplification of the analysis. It is important to define the purpose of the LCA and what simplifications can be applied.

Further limitations that should be taken into consideration for LCA analysis are: linear nature of the model, impossibility to quantify local environmental impacts (only global), limitation of the databases to particular processes in the form of

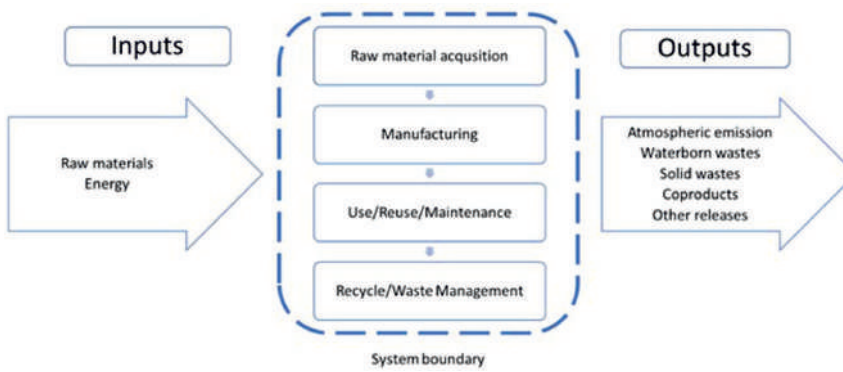



**FIGURE 7.5** LCA analysis simplified scheme.

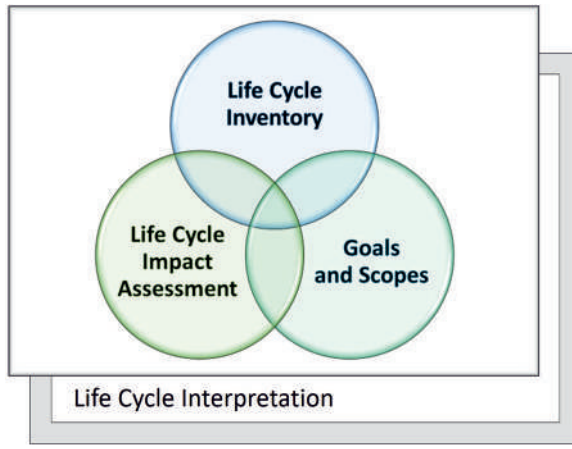



**FIGURE 7.6** LCA steps.

predefined blocks, without the possibility to break them down into individual components (e.g. "electricity production from fossil fuels" as one element), limitation of access to detailed project data [19].

LCA analysis is composed of four major phases of process which are shown in Figure 7.6, including compilation and evaluation of the inputs, outputs and impact assessment with all elements related.

The first part of the LCA process is to define goals and scopes, which can provide data: how the research will be done, what is data assumed to achieved, identification of system boundary and data quality requirement as well as identification of the reasons for undertaking the study and the intended public.

The second phase is Life Cycle Inventory (LCI) which identifies data such as inputs and outputs. At this stage, all data should be collected, from the acquisition of raw materials and energy to the last wastes produced during the entire process. Although, the data obtained for this stage may vary due to pre-defined goals and scopes. Frequently, limited and very case study-specific data is sufficient for a particular instance.

Life Cycle Impact Assessment (LCIA) is the third phase of LCA process, strictly linked with LCI. It presented how particular elements from LCI have certain impacts.

There are three mandatory sub-stages of LCIA. The activities of the first stage are: selection of impact categories, category indicators and characterization models. The next step is a classification which assigned LCI elements to certain impact categories e.g. assigning $CO_2$ emission to global warming category. The third step is the characterization to calculate the contribution of classified LCI elements, within its impact category. To obtain this calculation, the value of each LCI element must be multiplied by the appropriate conversion factor for each considered impact category. The coefficients are specific to the substance or resource and represent the impact intensity of the element which is relative to the reference element, specific for the impact category (e.g. climate change will be estimated in $CO_2$ equivalent).

Then, normalization, which is an optional step, allows to compare obtained results to each other. This can be estimated by multiplying obtained previously results by normalization coefficients. Other optional steps are grouping and weighting, which both support understanding and interpretation of obtained data.

The last stage is not less important compared to previous steps. It is the Life Cycle Interpretation (LCI) and it combines the results from second and third process phases and compare them against goals and scopes from step one. It shows completeness, sensitivity and consistency checks as well as uncertainty and accuracy of obtained results. Additionally, it presents interpretation of environmental impacts [17, 20].

LCA is a crucial tool to quantify the real environmental benefits derived from the application of Carbon Capture Utilization and Storage (CCUS) technologies. The LCA analysis allows to evaluate the environmental impact of the entire processes, from the $CO_2$ separation unit to its compression and storage or its application in chemical processes to synthesize added-value products [21].

The decision to implement CCSU technology should be based on the knowledge provided by the results of in-depth analyses of the overall environmental impact and benefits of the technology, not just its effectiveness in capturing $CO_2$. LCA is an essential tool to provide this knowledge [22].

However, even if LCA analyses have been standardized in ISO 1404x, there is still considerable openness to a number of interpretations, e.g. in the choice of units, boundary conditions, methodology of environmental impact assessment and background processes. Many case study results for $CO_2$ capture and utilization and storage technologies cannot be compared, as all depends on the specification of the case, the complexity of the model developed and the applied environmental impact assessment methods. As a logical conclusion, such analysis should be undertaken on a project-specific issue. According to [19], many case studies in which similar boundary conditions and CCUS technologies were even assumed received different results precisely because of the difference in the choice of e.g. environmental assessment methodology or the choice of the type of input data. Nonetheless, LCA is intended to promote comparable and transparent research on the environmental impacts of CCSU.

## 7.4 CASE STUDY – PROCESS SIMULATION AND LCA OF THE DME SYNTHESIS FROM PURE $CO_2$ AND RENEWABLE ENERGY

Two process schemes are presented here and simulated by means of Aspen Plus. The two process configurations treat a flue gas containing carbon dioxide: the first takes as feed the flue gases coming from a power plant, the second treats the flue gases from a cement plant. In both the schemes, the carbon dioxide is first separated from the flue gas stream and then transformed in a high valuable product such as DME. Currently, the primary usage of DME is as an aerosol propellant in personal care products, such as hair sprays [23, 24]. At ambient condition this substance is a vapor, but it liquefies at 0.6 MPa and room temperature [25], making it very easy to store.

DME is likely to be utilized as a substitute for diesel fuel in diesel engines and gas turbines, as fuel for domestic usage or as intermediate in the production of

hydrocarbon fuels and chemicals [23]. Through the reaction with sulfur trioxide it produces dimethyl sulfate [24]. It represents a key building block in the production of light olefins [26, 27], ethanol [28] and methyl acetate [29].

### 7.4.1 Power plant-based process

The process of conversion of carbon dioxide from the power plant to DME is composed of five macro units which are here listed:

1. $CO_2$ Separation and Purification.
2. Biomass Pyrolysis.
3. Renewable Energy and Green Hydrogen Production.
4. DME Production.
5. Reaction Products Separation.

These units are represented in Figures 7.7–7.12, where all components are reported and tagged in Aspen Plus environment.

#### 7.4.1.1 $CO_2$ separation and purification

The flue gas from the power plant enters the DME production plant at 123°C with the composition reported in Table 1.1 in Chapter 1 [30].

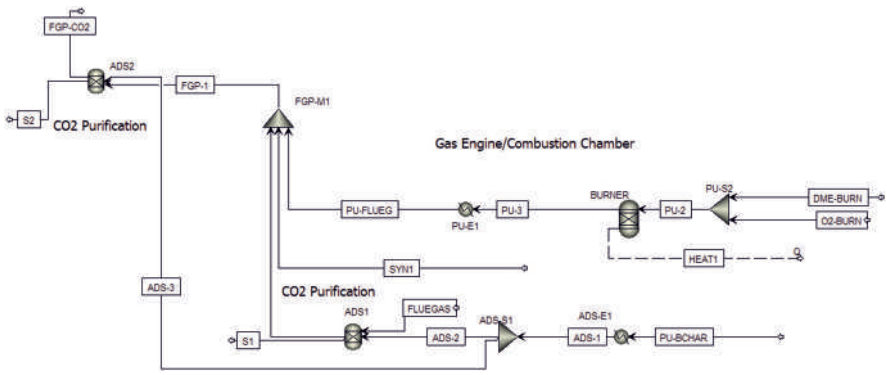



**FIGURE 7.7** $CO_2$ separation and purification unit model in Aspen Plus (power plant).

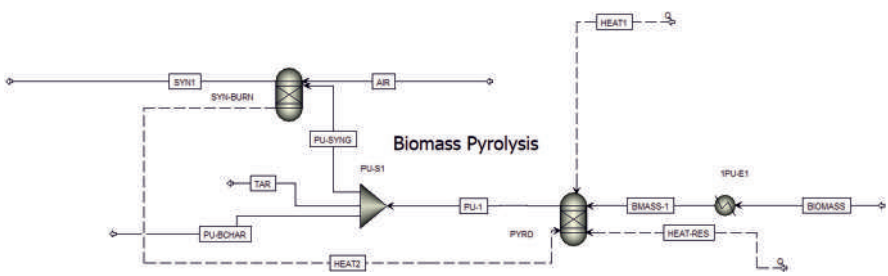



**FIGURE 7.8** Biomass pyrolysis unit model in Aspen Plus.

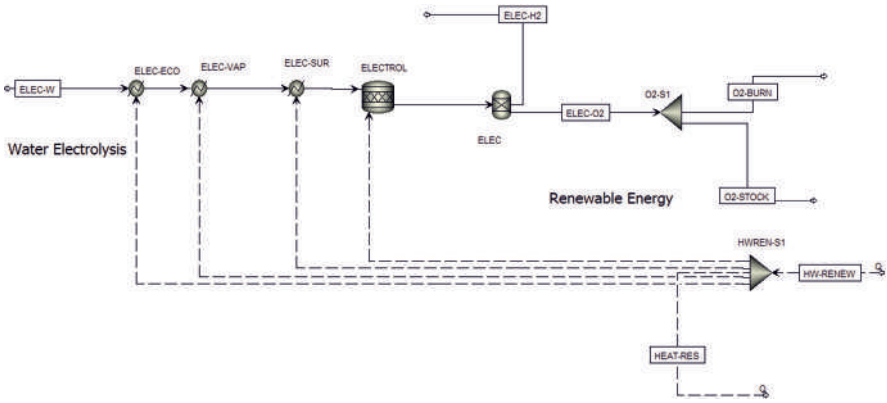



**FIGURE 7.9** Green hydrogen production unit model in Aspen Plus.

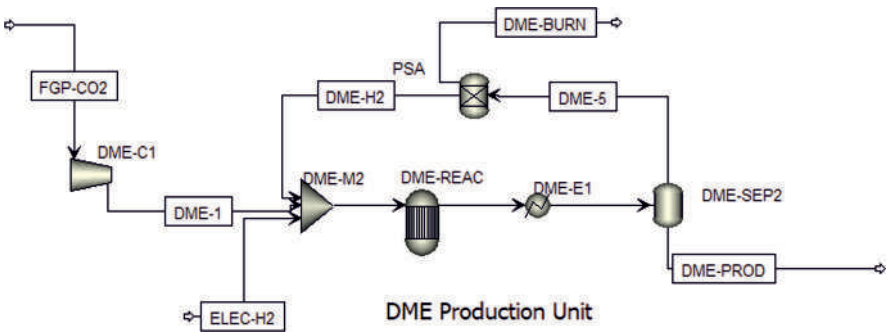



**FIGURE 7.10** DME synthesis reactor model in Aspen Plus (power plant).

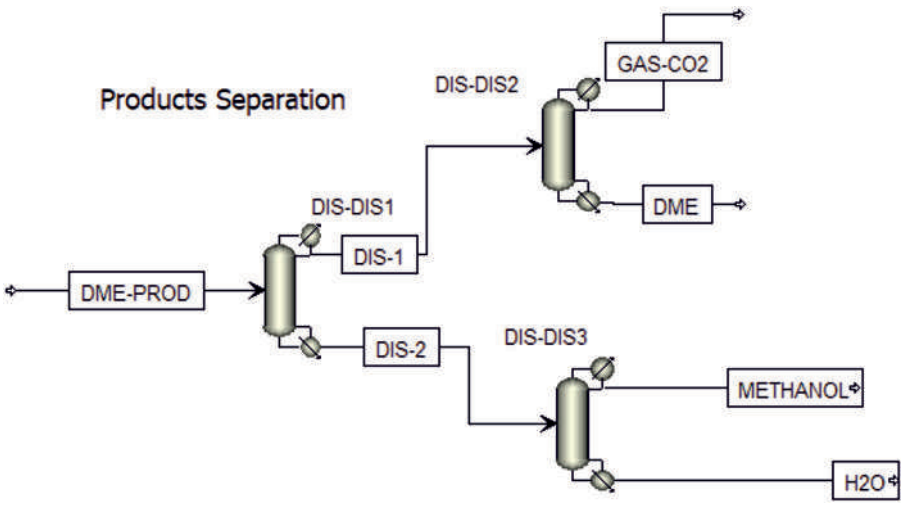



**FIGURE 7.11** Products purification unit in Aspen Plus.

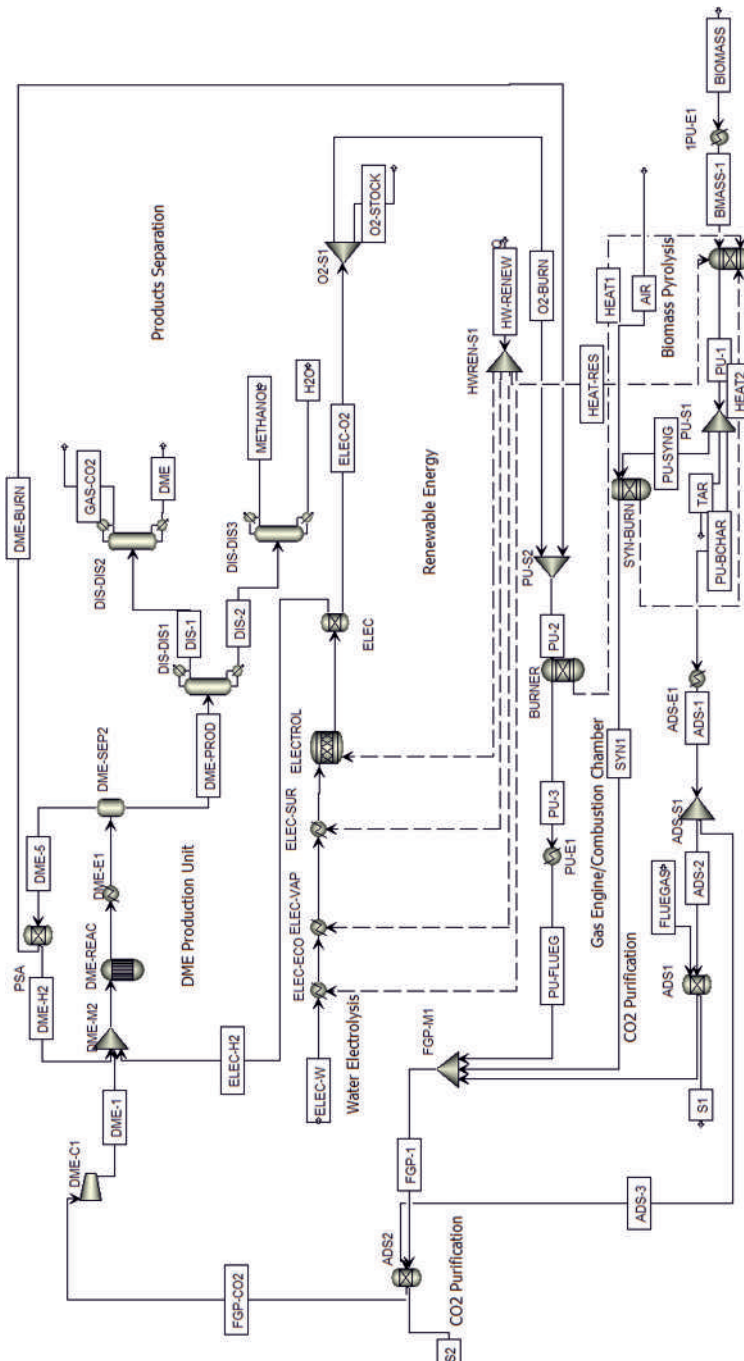



**FIGURE 7.12** Whole process scheme in Aspen Plus (power plant).

Hence the amount of carbon dioxide in the flue gas is 7901 kmol/h (347672.41 kg/h) at 123°C and 130 kPa. The power plant was not simulated since the focus of the project is to use what usually is a waste (carbon dioxide) to produce a valuable product, such as DME.

The flue gas is treated to concentrate the $CO_2$. Another stream containing carbon dioxide is subject to purification as shown in Figure 7.7. This stream consists of the oxyfuel combustion products of the un-reacted gas exiting the DME reactor and contains 3957.57 kmol/h of $CO_2$. As a consequence, the carbon dioxide fed to the reactor is nearly doubled.

The flue gas purification and carbon dioxide adsorption consist of a series of adsorbent columns in which the flue gas is first purified, then carbon dioxide is separated from the other gases and lastly purified by further adsorption. The adsorbent comes from the pyrolysis of the biomass. The process of $CO_2$ isolating and purifying is simulated in Aspen Plus environment with the Aspen Plus block Sep. Sep separates components based on specified flows or split fractions.

#### 7.4.1.2 Biomass pyrolysis

The waste biomass consists of wood, molecular formula $CH_{1.46}O_{0.689}$ [30]. First, the biomass is dried up, as shown in Figure 7.8; the heat is taken from the hot gas exiting the combustion chamber in the DME Production Unit. Then the biomass enters the pyrolysis reactor where the reaction heat is supplied by the hot gas from the combustion chamber in the DME Production Unit and by the combustion of the syngas, obtained as a byproduct of the pyrolysis process itself (the heat supplied by the combustion is not sufficient to thermally treat the biomass). The combusted syngas, as well as the hot gas from the combustion chamber, is fed to the Flue Gas Purification Unit to separate the $CO_2$ contained in it. The biochar leaves the pyrolysis reactor at 800°C [30] and undergoes an activation process; the adsorbent is used in the purification of the flue gas and $CO_2$ adsorption. The pyrolysis is not simulated in Aspen Plus, since data are taken from literature.

The purification is performed by adsorption with the biochar obtained in the waste biomass pyrolysis unit; the biochar has the following molecular formula $CH_{0.153}O_{0.0324}$ [30]. The adsorbent is able to isolate 80% of the carbon dioxide in the remaining flue gas 80%, providing a stream of $CO_2$ at 99% molar purity (the remaining is molecular oxygen). This is simulated in Aspen Plus with the block Sep. The flowrate and purity of the carbon dioxide leaving the block Sep are set according to the values above. The purified $CO_2$ enters the unit of DME production where it is converted into DME and MeOH (methanol, as a byproduct) through reaction with $H_2$.

#### 7.4.1.3 Renewable energy and green hydrogen production

The hydrogen is provided by water electrolysis powered by RES (Renewable Energy Sources), making it the so called "green hydrogen". For a PEMEC (Proton Exchange Membrane Electrolyzer), the power consumption to produce $H_2$ at 3 MPa is around a value of 4.5 kWh/Nm$^3$ $H_2$ [31] with a purity of 99.999% for both $H_2$ and $O_2$ [32]. The water electrolysis is not simulated in Aspen Plus, a stream of $H_2$ and a stream of $O_2$ are added at the flowsheet with a molar ratio of 2:1 ($H_2/O_2$) and an electric power demand is taken into account. The un-reacted gas exiting the DME reactor is

previously sent to a PSA that recovers 86% of the hydrogen in it. The hydrogen recovered at the PSA is fed to the DME reactor; this allows to reduce the quantity of hydrogen produced by the electrolyzer at 12473.12 kg/h. Hence the power consumption at the electrolyzer is 629.04 MW. The PSA unit is simulated with a Sep in Aspen Plus.

The oxygen is consumed in the oxyfuel combustion of the un-reacted gas stream exiting the DME reactor. The combustion of the un-reacted gas provides further carbon dioxide which is previously separated from the other gases and then fed to the DME reactor. Possible overproduction of hydrogen and oxygen is stored.

#### 7.4.1.4 DME production

The carbon dioxide feeding the DME reactor is compressed to 3 MPa and then it is mixed with the hydrogen produced via water electrolysis to obtain a $H_2/CO_2$ ratio of 3 [33] (see Figure 7.10). The resulting gas stream is heated up to 200°C and sent to the DME reactor. $CO_2$ is partially converted into DME and MeOH in a single-step reactor. The reactor was simulated in Aspen Plus with a RGibbs reactor and with REquil reactor. The former provides rigorous reaction and multiphase equilibrium based on Gibbs free energy minimization. The latter allows rigorous equilibrium reactor based on stoichiometric approach. The results of those reactors show absolute symmetry; thus the RGibbs reactor was chosen as easier to manage.

The reaction products are cooled down to 30°C, thus allowing the separation of the desired products, DME and MeOH, from the un-reacted gas via liquid-gas separation. The liquid is an aqueous mixture whose molar composition is 6.25% of DME and 7.31% of MeOH, the gas is a mixture of the un-reacted gases. The gas stream, containing the unreacted gases, is fed to a PSA (pressure swing adsorption unit) to recycle the $H_2$ to the reactor. The remaining gases perform an oxyfuel combustion with $O_2$ produced via water electrolysis, the combustion chamber is simulated with a RGibbs reactor. The liquid products are sent to the Reaction Products Separation Unit.

#### 7.4.1.5 Reaction products separation

As shown in Figure 7.11, the unit is essentially made of three distillation columns. Each of the three distillation columns was simulated in Aspen Plus with the block RadFrac, which provides rigorous 2 or 3-phase fractionation for a single column.

The liquid mixture containing DME and MeOH is sent to the first distillation column operating at 2 MPa. This column performs the separation of DME from MeOH. The former exits from the head of the column in a stream containing the other gases (mostly unreacted carbon dioxide), while the latter exits from the bottom of the column in an aqueous mixture.

The distillate of the first distillation column is sent to the second one operating at 1.9 MPa. The distillate of the second column is composed of unreacted $CO_2$ mostly. DME is collected at the bottom of the column with a flowrate of 203.16 kmol/h (9359.14 kg/h) and a molar purity of 99.98% (mass purity is 99.99%). The impurities in the DME stream are:

- 0.02% MeOH molar;
- ppm $CO_2$.

The bottoms of the first distillation column are sent to a third one operating at a much lower pressure (200 kPa). Here, the aqueous mixture containing MeOH is separated: MeOH is obtained as the distillate product, and the bottoms of the column collect the water with a 0.07 mol% of MeOH (0.13 wt%). The flowrate of the distillate of this column is 173.83 kmol/h (5547 kg/h) and contains MeOH with a molar concentration of 99.06% (mass purity is 99.47%), the remaining share is water (0.94 mol%).

### 7.4.2 Cement plant-based process scheme

In this process, the DME is produced from the carbon dioxide contained in the kiln gas of a cement plant. The scheme process is organized into five units listed below:

1. $CO_2$ Separation and Purification and Concrete Curing Carbonation.
2. Biomass Pyrolysis.
3. Renewable Energy and Green Hydrogen Production.
4. DME Production.
5. Reaction Products Separation.

The main difference between the power plant process scheme and the cement plant process scheme stands in the $CO_2$ Separation and Purification Unit. However, the components of the macro units are the same, as shown in Figures 7.8, 7.9, 7.11, 7.13 and 7.14. Figure 7.15 shows the whole process scheme modeled in Aspen environment.

#### 7.4.2.1 $CO_2$ separation and purification and concrete curing carbonation

The cement plant was not simulated in Aspen Plus for the same reasons the power plant was not too. The flue gas from the cement has the composition and flowrate reported in Table 1.2 in Chapter 1 [35].

Similarly to what happens in the scheme of the power plant, the flue gas is treated in order to be purified and to concentrate the $CO_2$ in it. The same is done to the combusted gas generated by the oxyfuel combustion of the un-reacted gas fed to the DME reactor. The flue gas purification and $CO_2$ separation are performed with the same series of adsorbing step of the power plant scheme; the adsorbent is obtained by the biomass pyrolysis. In this process, a fraction of carbon dioxide is used to perform concrete curing carbonation, an accelerated curing process that injects $CO_2$ gas into the curing vessel and transforms the gaseous $CO_2$ into solid calcium carbonates [34]. The process of concrete curing carbonation is not simulated; in Aspen Plus, a fraction of the purified $CO_2$ obtained by adsorption, representing the feed to the curing processes, is split from the stream that enters the DME Production Unit.

The process of $CO_2$ purification is simulated in Aspen Plus with the block Sep.

#### 7.4.2.2 Biomass pyrolysis

The waste biomass used is the same of the power plant scheme and undergoes the same processes. First, it is dried up using the hot gas from the combustion chamber in the DME Production Unit. Then the biomass enters the pyrolysis reactor and the reaction heat is supplied by the hot gas from the combustion chamber in the

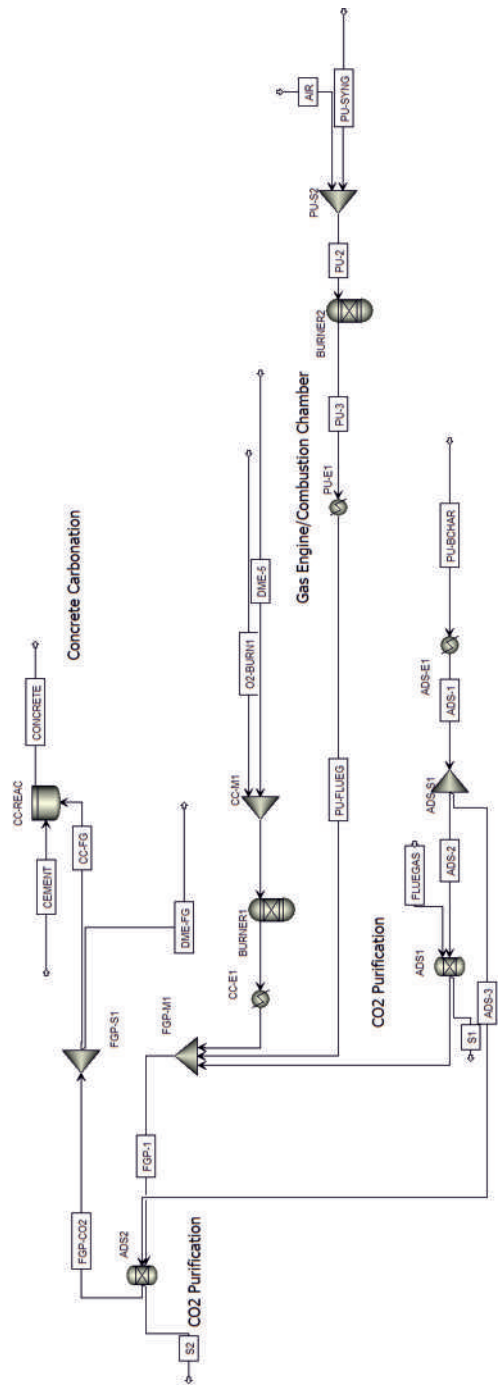



**FIGURE 7.13** $CO_2$ separation and purification and Concrete Curing Carbonation unit model in Aspen Plus (cement plant).

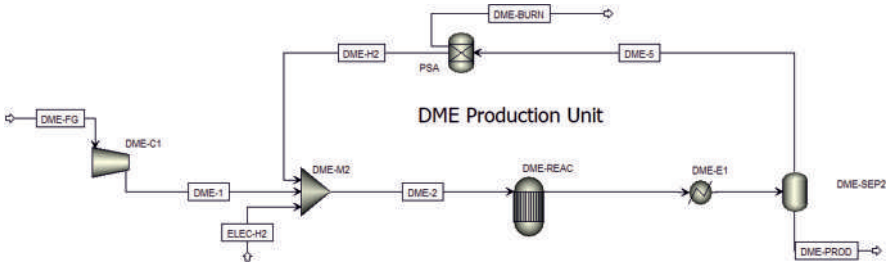



**FIGURE 7.14** DME synthesis reactor model in Aspen Plus (cement plant).

DME Production Unit and by the combustion of the syngas obtained as a byproduct of the pyrolysis process itself, by the way the heat generated is not enough to perform the complete thermal treatment. Those hot gases are both sent to the Flue Gas Purification Unit to isolate the $CO_2$ contained in them. The biochar exits the pyrolysis reactor at 800°C [30] and is activated to be ready to adsorb the carbon dioxide. The pyrolysis is not simulated; data are taken from the literature.

The activated adsorbent is able to extract the 80% of the $CO_2$ in the gas stream with a 99% of molar purity (the remaining share in molar oxygen), this is simulated in Aspen Plus with the block Sep. The purified $CO_2$ enters the unit of DME production where it is converted into DME and MeOH through the reaction with green hydrogen.

#### 7.4.2.3 Renewable energy and green hydrogen production

This unit is the same for the Power Plant-based process and for the Cement Plant-based process, thus it is not described here. The power consumption due to the water electrolysis is 717.92 MW.

#### 7.4.2.4 DME production

$CO_2$, coming from the series of adsorbing steps, hence purified, is compressed to 3 MPa and mixed with the green-$H_2$ from water electrolysis in a molar ratio $H_2/CO_2$ of 3. This gaseous mixture is heated up to 200°C and fed to the DME reactor. Due to the reaction, $CO_2$ is partially converted into DME and MeOH in a single step-reactor simulated in Aspen Plus with a RGibbs reactor. The products exiting the reactor are cooled down to 30°C.

The reaction products are cooled down to 30°C; this allows the separation of the desired products, DME and MeOH, from the un-reacted gas via liquid-gas separation. The liquid is an aqueous mixture with a molar content of DME and MeOH of 7.31% and 6.25%, respectively, the gas is a mixture of the un-reacted gases. The gas stream, containing the unreacted gases, is sent to a PSA (pressure swing adsorption unit) to recycle the $H_2$ to the reactor, simulated with a Sep in Aspen Plus. The remaining gases perform an oxyfuel combustion with $O_2$ from the water electrolysis, combustion chamber is simulated with a RGibbs reactor. The liquid products are sent to the Reaction Products Separation Unit.

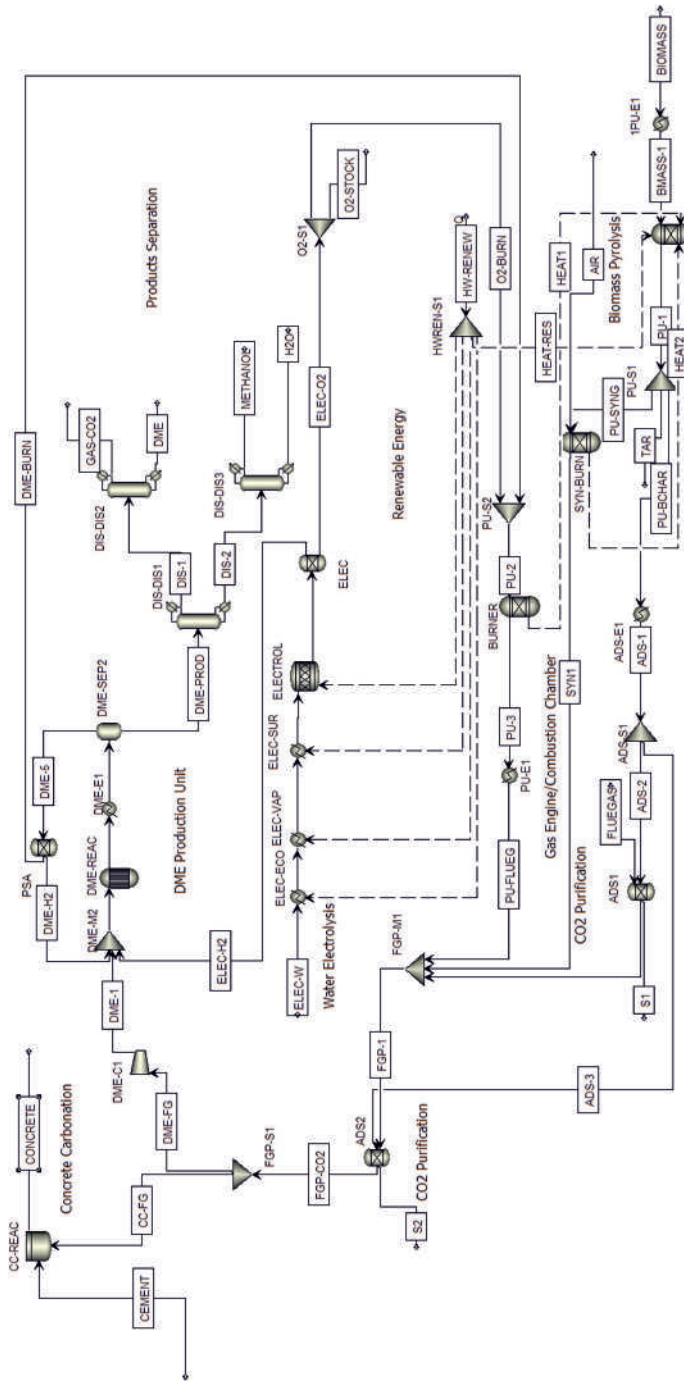



**FIGURE 7.15** Whole process scheme (cement plant).

#### 7.4.2.5 Reaction products separation

This unit is the same in both the Power Plant based process and the Cement Plant based process. Here just the results are listed, the description is not presented. The stream collected at the bottom of the second column has a flowrate of 231.75 kmol/h (10674 kg/h) and carries DME with a molar purity of 99.91% (mass purity is 99.94%). The impurities in the DME stream are due to MeOH and $CO_2$ presence (0.08% and 0.01 mol%, respectively).

The distillate of the third column has a flowrate of 197.96 kmol/h (6316.79 kg/h) and carries MeOH with a molar purity of 99.06% (mass purity is 99.47%). The remaining share is water (0.94 mol%). The stream collected at the bottom of the third column carries dirty water with a flowrate of 2526.88 kmol/h (45548.5 kg/h) in which the molar content of the water is 99.93% (99.87 wt%); the remaining share is MeOH.

Tables 7.1 and 7.2 summarize the main results of the process simulation of the two schemes.

## 7.5 LCA ANALYSIS OF THE PROCESS SCHEMES

A LCA analysis of the process schemes illustrated in Sections 7.4.1 and 7.4.2 are here reported following the methodology described in Section 7.3. The step of normalization and weighting score was not considered in this study. OpenLCA software by Green Delta has been applied for this simulation. Implemented databases are free to download as comes as follows:

- Ecoinvent 3.7 LCIA methods – EULA license – use of the free part of the database.
- ELCD 3.2 – free access.
- OpenLCA LCIA methods v.1.5.7 – Creative Commons Attribution – ShareAlike 4.0 International License.

The main objective of the LCA analysis is to evaluate the environmental impact of DME production with use of $CO_2$ captured from flue gases from power plant and cement plant. The scope of this study is to present a life cycle inventory of DME production, in order to allocate the environmental impact to each stage of its production (power plant/cement plant, capture and purification station, DME and/or carbonate concrete production). Furthermore, in the case of cement plant, the separation of flue gas stream for production of DME and for carbonate concrete is provided. The flue gas stream was split into two individual utilization methods according to Figure 1.4; however, for the purpose of calculating the Impact Assessment, the cement plant model is treated as a single object with implemented allocation for DME/carbonate concrete production.

The system boundaries were set based on Figures 1.3 and 1.4. Additionally, to simplify calculations, we made few cut outs and made a streamlined flowchart of the system, which is shown in Figure 7.16.

**TABLE 7.1**
**Selected parameters of case study process simulation for power plant**

| | | Composition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mass flow | $CO_2$ | $O_2$ | $N_2$ | $H_2$ | CO | DME | $CH_3OH$ | $H_2O$ | Renewable energy in | Heat energy in | Heat energy out |
| Symbol | kg/h | % mol | % mol | % mol | % mol | % mol | % mol | % mol | % mol | kW | MJ/h | MJ/h |
| PU-flueg | 248343 | 51.43 | 1.04 | | 1.16 | 9.38 | | | 36.99 | – | – | 913179 |
| Fluegas | 1645200 | 14.30 | 7.50 | 68.30 | Ar 0.80 | | – | – | 9.10 | – | – | – |
| FGP-$CO_2$/DME-1 | 239362 | 1 | – | – | – | – | – | – | – | – | – | – |
| DME-$H_2$ | 20418.2 | | – | – | 100 | – | – | – | – | – | – | – |
| Elec-$H_2$ | 12473.1 | | | | | | | | | | | – |
| DME-prod | 62961.3 | 6.58 | | | 0.11 | 0.03 | 7.31 | 6.25 | 79.72 | | | – |
| DME-5 | 209282 | 22.56 | | | 73.27 | 1.36 | 2.54 | 0.10 | 0.17 | – | – | – |
| DME-burn | 188864 | 60.98 | | | 27.73 | 3.68 | 6.86 | 0.29 | 0.46 | – | – | – |
| Elec-W | 112257.9 | – | – | – | – | – | – | – | – | 629037 | – | – |
| Elec-$O_2$ | 99784.8 | – | – | – | – | – | – | – | – | – | – | – |
| $O_2$-burn | 59478.8 | – | – | – | – | – | – | – | – | – | – | – |
| $O_2$-stock | 40306 | – | – | – | – | – | – | – | – | – | – | – |
| DME | 9359.14 | – | – | – | – | – | 99.98 | 0.02 | – | | | – |
| Methanol | 5547 | – | – | – | – | – | – | 99.06 | 0.94 | | | – |
| $H_2O$ | 39965.9 | – | – | – | – | – | – | 0.07 | 99.93 | | | – |
| Gas-$CO_2$ | 8089.21 | 97.93 | – | – | 1.59 | 0.45 | 0.03 | – | – | | | – |

**TABLE 7.2**
**Selected parameters of case study process simulation for cement plant with concrete carbonation**

| | | Composition | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mass flow | $CO_2$ | $O_2$ | $N_2$ | $H_2$ | CO | DME | $CH_3OH$ | $H_2O$ | Renewable energy in | Heat energy in | Heat energy out |
| Symbol | kg/h | % mol | % mol | % mol | % mol | % mol | % mol | % mol | % mol | kW | MJ/h | MJ/h |
| PU-Flueg | 283144 | 51.43 | 1.04 | | 1.16 | 9.38 | | | 36.99 | – | – | 1041191 |
| Fluegas | 432000 | 17.80 | 7.50 | 56.50 | – | – | – | – | 18.20 | – | – | – |
| FGP-$CO_2$ | 286142 | 100 | – | – | – | – | – | – | – | – | – | – |
| DME-FG | 272805 | 100 | – | – | – | – | – | – | – | – | – | – |
| DME-$H_2$ | 23279.3 | | | | | | | | | – | – | – |
| Elec-$H_2$ | 14235.6 | | | | | | | | | – | – | – |
| DME-prod | 71783.9 | 6.58 | | | 0.11 | 0.03 | 7.31 | 6.25 | 79.72 | | | – |
| DME-5 | 238608 | 22.56 | | | 73.27 | 1.36 | 2.54 | 0.10 | 0.17 | – | – | – |
| DME-burn | 215329 | 60.98 | | | 27.73 | 3.68 | 6.86 | 0.29 | 0.46 | | – | – |
| Elec-W | 128120 | – | – | – | – | – | – | – | – | 717920 | – | – |
| Elec-$O_2$ | 113884 | – | | – | – | – | – | – | – | | – | – |
| $O_2$-burn | 67815 | – | | – | – | – | – | – | – | – | – | – |
| $O_2$-stock | 46069 | – | | – | – | – | – | – | – | – | – | – |
| DME | 10674 | 0.01 | – | – | – | – | 99.91 | 0.08 | – | | | – |
| Methanol | 6316.79 | | | | | | | 99.06 | 0.94 | | | – |
| $H_2O$ | 45548.5 | | | | | | | 0.07 | 99.93 | | | – |
| Gas-$CO_2$ | 9216.51 | 97.95 | | | 1.59 | 0.45 | 0.01 | | | | | – |
| CC-FG | 13337 | 100 | – | – | – | – | – | – | – | – | – | – |
| Cement | 133370 | | | | | | | | | | | |
| Concrete | 666850 | | | | | | | | | | | |

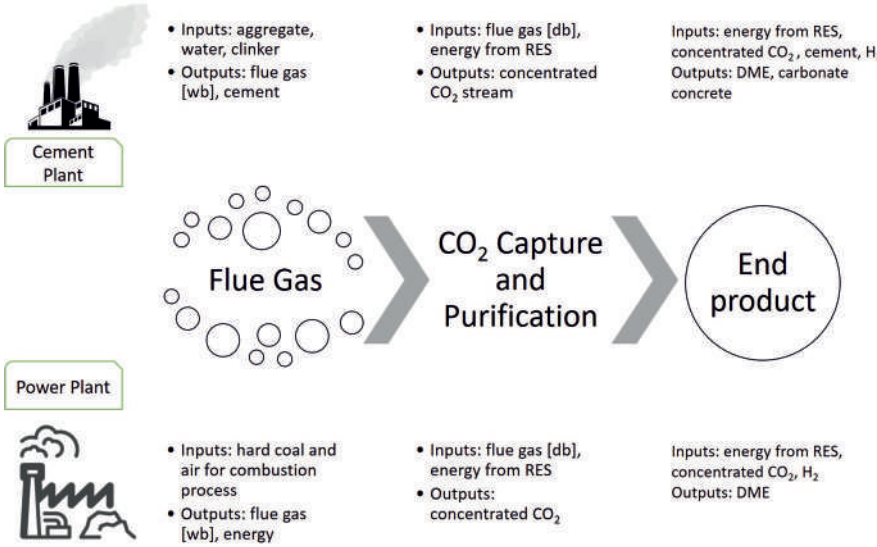



**FIGURE 7.16** Life Cycle Assessment process.

All data necessary to perform the calculations have been collected in this book and refer to the tables: Tables 1.4, 3.4, 5.1 and 6.4. In this case study, all laboratory inputs have been scaled appropriately to industrial scale – for 1 hour of systems operation. The limitations and system boundaries of the model also affected the calculation of the Impact Assessment. The data collected are reported in Table 7.3.

The environmental impact from life cycle inventory is calculated using The International Reference Life Cycle Data System (ILCD) method (ILCD 2011, midpoint [v1.0.10, August 2016]) which determines 16 impacts such as climate change, ozone depletion, human toxicity (non-cancer and cancer effects), particulate matter (PM), ionizing radiation (HH), ionizing radiation E (interim), photochemical ozone formation (POF), acidification, terrestrial eutrophication, freshwater ecotoxicity, land use, water resource depletion, and mineral, fossil and resource depletion [36]. For our case study, we focus and discuss only on few of them as shown in Table 7.4.

The processes comparison is related to 1 hour of operation of the modeled facilities. It has to be noticed that the hourly DME production for the cement plant is almost 25% higher than for the power plant. The difference in the amount of DME produced depends on higher $CO_2$ flow rate from purification unit in case of cement plant. Although we obtain lower hourly DME production in the power plant model case, the impact in terms of carbon dioxide is lower (23.77 kg $CO_2$ eq. per 1 kg DME against 138.54 kg $CO_2$ eq. in the case of the cement plant). However, this is not a sufficiently accurate indicator because of the allocation of the stream for DME and carbonate concrete production, after the $CO_2$ capture and purification unit.

The overall environmental impact of DME production is higher for cement plant than for power plant. This is affected not only by the much larger amount of individual substances making up the outlet stream from DME production, but also due to considerably higher quantities of inputs in the outlet gas stream from the $CO_2$ capture unit (as shown in Table 7.3).

Even if process of carbon capture and utilization from power plant is not zero-emission it is still possible to reduce environmental impact of unit by implementation of CCU technology – and thus obtaining $CO_2$ as a resource in the production for green DME or carbonated concrete or other green technologies.

**TABLE 7.3**
**Life Cycle Inventory – data were obtained from previous chapters and recalculated for industrial scale (in case for modeling purposes)**

| | Power plant | Cement plant |
|---|---|---|
| | **Output from power plant [wb]** | **Output from cement plant [wb]** |
| Parameter | kg/h | kg/h |
| Flue gas flow | 457 | 120 |
| $CO_2$ | 347672.41 | 115364.98 |
| $O_2$ | 132615.03 | 35351.88 |
| $N_2$ | 1056720.79 | 233027.82 |
| $H_2O$ | 90509.76 | 48255.32 |
| Ar | 17682.00 | n/a |
| Total | 1645200.00 | 432000.00 |
| | **Recirculation from oxyfuel combustion** | |
| Flue gas flow | 62.98 | 90.08 |
| $CO_2$ | 174133.29 | 198535.77 |
| $O_2$ | 2561.15 | 2920.87 |
| $H_2O$ | 51260.08 | 58443.15 |
| $H_2$ | 180.12 | 205.35 |
| CO | 20208.20 | 23038.95 |
| Total | 248342.84 | 283144.08 |
| | **$CO_2$ capture and purification** | |
| | **Inlet from power plant [db]** | **Inlet from cement plant [db]** |
| Energy demand [kWh] | 545286.96 | 291927.69 |
| Flue gas flow | 486.60 | 178.08 |
| $CO_2$ | 521805.70 | 313900.74 |
| $O_2$ | 135176.18 | 38272.75 |
| $N_2$ | 1056720.79 | 233027.82 |
| Ar | 17682.00 | 0.00 |
| $H_2$ | 180.12 | 205.35 |
| CO | 20208.20 | 23038.95 |
| Total | 1751772.99 | 608445.61 |

(*Continued*)

**TABLE 7.3 (*Continued*)**
**Life Cycle Inventory – data were obtained from previous chapters and recalculated for industrial scale (in case for modeling purposes)**

| | Outlet [db] | Outlet [db] |
|---|---|---|
| Flue gas flow | 72.94 | 87.95 |
| $CO_2$ | 239362.39 | 286214.07 |
| $O_2$ | 9361.37 | 1273.12 |
| $N_2$ | 13559.06 | 2265.10 |
| Ar | 298.77 | 212.19 |
| Total | 262581.58 | 289964.48 |

| | Production unit | | |
|---|---|---|---|
| | DME | DME | Concrete |
| Production ratio | | 95.73% | 4.27% |
| Energy demand [kWh] | 51202.09 | 639.99 | – |
| $CO_2$ | 239362.39 | 299175.53 | 13336.99 |
| $H_2$ (total) | 32891.28 | 41111.52 | – |
| Electrolyzed | 12473.12 | 15587.70 | – |
| Recirculated from PSA | 20418.16 | 25523.83 | – |
| Total | 272253.67 | 340287.05 | 13336.99 |
| | DME output | DME/carbonate concrete output | |
| DME | 28161.15 | 35199.64 | – |
| MeOH | 6125.54 | 7656.54 | – |
| $CO_2$ | 167624.72 | 209520.23 | – |
| CO | 6155.49 | 7693.97 | – |
| $H_2$ | 23748.04 | 29683.54 | – |
| $H_2O$ | 40428.56 | 50533.13 | – |
| Total | 272243.50 | 340287.05 | 680186.56 |
| Cement production | | – | 133369.91 |
| Concrete production | | – | 666849.57 |

**TABLE 7.4**
**Life Cycle Assessment results**

| Indicator | Power plant | Cement plant | Unit |
|---|---|---|---|
| Climate change | $6.69476 \times 10^{5}$ | $4.87649 \times 10^{6}$ | kg $CO_2$ eq. |
| Human toxicity – carcinogenics | $3.06559 \times 10^{-4}$ | $7.69674 \times 10^{-3}$ | CTUh |
| Human toxicity – non-carcinogenics | $1.14970 \times 10^{-2}$ | $1.92157 \times 10^{-1}$ | CTUh |
| Ozone depletion | $7.32560 \times 10^{-3}$ | $2.79747 \times 10^{-1}$ | kg CFC-11 eq. |
| Resource depletion – mineral, fossils and renewables | $1.64542 \times 10^{3}$ | $2.31399 \times 10^{3}$ | kg Sb eq. |
| Resource depletion – water | $7.49116 \times 10$ | $8.42254 \times 10^{2}$ | $m^3$ |

## NOMENCLATURE

### Symbols

| | |
|---|---|
| $g$ | Specific Gibbs free energy [kJ/kg] |
| $\overline{g}$ | Molar Gibbs free energy [kJ/kmol] |
| $h$ | Specific enthalpy [kJ/kg] |
| $\dot{H}$ | Enthalpy flow rate [kJ/s] |
| $\overline{h}$ | Molar enthalpy [kJ/kmol] |
| $\dot{m}$ | Mass flow rate [kg/s] |
| $N$ | Molar flow rate [kmol/s] |
| $p$ | Pressure [kPa] |
| $\dot{Q}$ | Heat flux [kW] |
| $s$ | Specific entropy [kJ/kg K] |
| $S_{gen}$ | Specific entropy generation per unit water produced [kJ/kg K] |
| $\dot{S}_{gen}$ | Entropy generation rate [kW/K] |
| $\mathbf{T}$ | Temperature [°C] |
| $\dot{W}$ | Work [kW] |

#### Greek

| | |
|---|---|
| $\eta pp$ | Power plant intrinsic efficiency [–] |
| $\eta II$ | Second Law/exergetic efficiency [–] |
| $\mu$ | Chemical potential [kJ/mol] |
| $\xi$ | Specific exergy [kJ/kg] |
| $\dot{\Xi}$ | Exergy flow rate [kW] |

#### Subscripts & acronyms

| | |
|---|---|
| 0 | Ambient |
| gen | Generated |
| in | Inlet |
| min | Minimum |
| out | Outlet |

## REFERENCES

[1] Centi, G.; De Falco, M.; Iaquaniello, G.; Perathoner, S. Strategy and drivers for $CO_2$ (re)use. In *$CO_2$: A valuable source of carbon, green energy and technology*; De Falco, M., Iaquaniello, G., Centi, G. Eds. Springer-Verlag, 2013, 1–26.

[2] Guo, J.; Lou, H.; Zhao, H.; Chai, D.; Zheng, X. Dry reforming of methane over nickel catalysts supported on magnesium aluminate spinels, *Applied Catalysis A: General* **2004**, *273, 75–82*, https://doi.org/10.1016/j.apcata.2004.06.014.

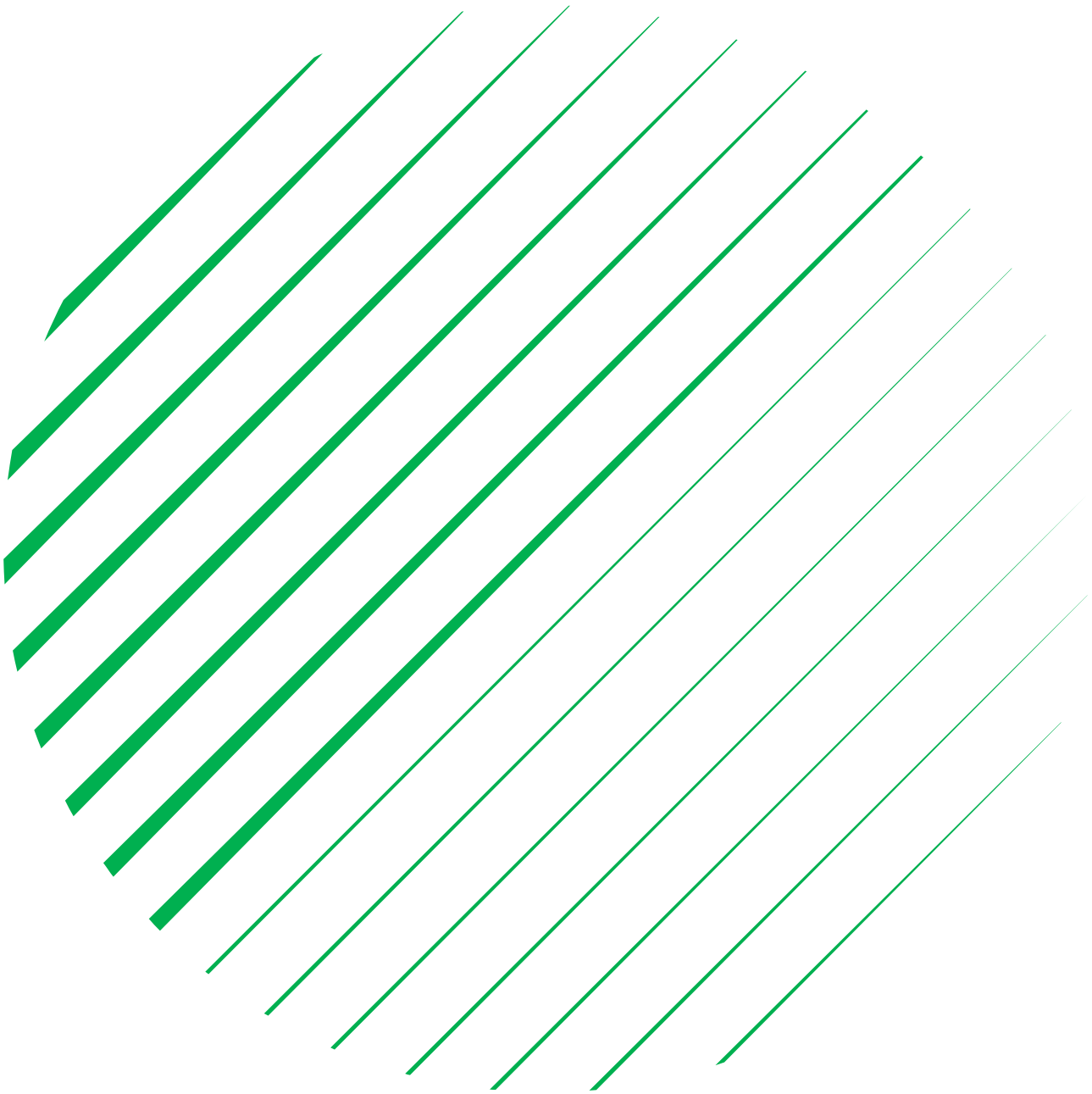
[3] Xin-Mei, L.; Lu, G. Q.; Zi-Feng, Y.; Beltramini, J. Recent advances in catalysts for methanol synthesis via hydrogenation of CO and $CO_2$, *Industrial & Engineering Chemistry Research* **2003**, *42*, *6518–6530*, https://doi.org/10.1021/ie020979s.

[4] Haiduc, A. G.; Brandenberger, M.; Suquet, S.; Vogel, F.; Bernier-Latmani, R.; Ludwig, C. SunCHem: An integrated process for the hydrothermal production of methane from microalgae and $CO_2$ mitigation, *Journal of Applied Psychology* **2009**, *21, 529–541*, https://doi.org/10.1007/s10811-009-9403-3.

[5] Barbarossa, V.; Bassano, C.; Deiana, P.; Vanga, G. $CO_2$ Conversion to $CH_4$. In *$CO_2$: A valuable source of carbon, green energy and technology*; De Falco, M., Iaquaniello, G., Centi, G., Eds. Springer-Verlag, 2013, 123–146.
[6] Mennicken, L.; Janz, A.; Roth, S. The German R&D program for $CO_2$ utilization—Innovations for a green economy, *Environmental Science and Pollution Research* **2016**, *23*, *11386–11392*, https://doi.org/10.1007/s11356-016-6641-1.
[7] Arcoumanis, C.; Bae, C.; Crookes, R.; Kinoshita, E. The potential of di-methyl ether (DME) as an alternative fuel for compression-ignition engines: A review, *Fuel* **2008**, *87*, *1014–1030*, https://doi.org/10.1016/j.fuel.2007.06.007.
[8] Ying, W.; Longbao, Z.; Hewu, W. Diesel emission improvements by the use of oxygenated DME/diesel blend fuels, *Atmospheric Environment* **2006**, *40, 2313–2320*, https://doi.org/10.1016/j.atmosenv.2005.12.016.
[9] De Falco M.; Capocelli, M. Process analysis and plant simulation in a sustainable economy, *Studies in Surface Science and Catalysis* **2019**, *179, 121–140*, https://doi.org/10.1016/B978-0-444–64337-7.00008-2.
[10] Moran, M. J.; Shapiro, H. N.; Boettner, D. D.; Bailey, M. *Fundamentals of engineering thermodynamics*. John Wiley & Sons; 2010.
[11] Kotas, T. J. *The exergy method of thermal plant analysis*. Paragon Publishing, 2012.
[12] Rocco, M. V.; Colombo, E.; Sciubba, E. Advances in exergy analysis: A novel assessment of the Extended Exergy Accounting method, *Applied Energy* **2014**, *113*, *1405–1420*, https://doi.org/10.1016/j.apenergy.2013.08.080.
[13] Bejan, A. *Advanced engineering thermodynamics*, 4th ed. John Wiley & Sons, Inc., 2016.
[14] Olaleye, A. K.; Wang, M. Conventional and advanced exergy analysis of post-combustion $CO_2$ capture based on chemical absorption integrated with supercritical coal-fired power plant, *International Journal of Greenhouse Gas Control* **2017**, *64*, *246–256*. ISSN 1750-5836, https://doi.org/10.1016/j.ijggc.2017.08.002.
[15] Wilcox, J. *Carbon capture*. Springer, 2012, ISBN 978-1-4614-2214-3.
[16] Mistry, K. H.; Lienhard, J. H. V. Generalized least energy of separation for desalination and other chemical separation processes, *Entropy* **2013**, *15*, *2046–2080*, https://doi.org/10.3390/e15062046.
[17] Deska, M.; Kruczek, M.; Zawartka, P.; Burchart, D. Zastosowanie metody LCA do wspomagania decyzji środowiskowych w gospodarce wodno-ściekowej, *Scientific Papers of Silesian University of Technology. Organization and Management Series* **2018**, *11*, *91–107*, https://doi.org/10.29119/1641-3466.2018.117.6.
[18] Environmental Protection Agency. *Life cycle assessment: Inventory guidelines and principles. EPA/600/R-92/245*. Office of Research and Development, Cincinnati, OH, USA, 1993.
[19] Müller, L. J.; Kätelhön, A.; Bachmann, M.; Zimmermann, A.; Sternberg, A.; Bardow, A. A guideline for life cycle assessment of carbon capture and utilization, *Frontiers in Energy Research* **2020**, *8*, https://doi.org/10.3389/fenrg.2020.00015.
[20] Guinée, J. B. *Handbook on life cycle assessment. Operational guide to the ISO standards*. Springer Netherlands Eco-Efficiency in Industry and Science Ser, v.7, 2002.
[21] De Falco, M.; Iaquaniello, G.; Centi, G. *$CO_2$: A valuable source of carbon*. Springer, 2013, https://doi.org/10.1007/978-1-4471-5119-7.
[22] Sathre, R.; Masanet, E.; Cain, J.; Chester, M. The role of Life Cycle Assessment in identifying and reducing environmental impacts of CCS, LBNL Report.
[23] Jeon, J.; Bae, C.; Johansson, B. *Effect of hydrogen and DME injection in homogeneous charge compression ignition engine with DME second injection strategy, Institution of Mechanical Engineers – Internal combustion engines: Improving performance, fuel economy and emissions*. Woodhead Publishing, 2011, 157–166, https://doi.org/10.1533/9780857095060.5.157.
[24] International Energy Agency Home Page. Assessed January 24, 2022. https://www.iea.org/news/a-multi-source-multi-purpose-fuel-for-the-future.

[25] Gas Encyclopedia Air Liquide Home Page. Assessed January 24, 2022. https://encyclopedia.airliquide.com/dimethylether.
[26] Pérez-Uriarte, P.; Ateka, A.; Aguayo, A. T.; Gayubo, A. G.; Bilbao, J. Kinetic model for the reaction of DME to olefins over a HZSM-5 zeolite catalyst, *Chemical Engineering Journal* **2016**, *302*, https://doi.org/10.1016/j.cej.2016.05.096.
[27] Pérez-Uriarte, P.; Ateka, A.; Gayubo, A. G.; Cordero-Lanzac, T.; Aguayo, A. T.; Bilbao, J. Deactivation kinetics for the conversion of dimethyl ether to olefins over a HZSM-5 zeolite catalyst, *Chemical Engineering Journal* **2017**, *311*, https://doi.org/10.1016/j.cej.2016.11.104.
[28] Yang, G.; San, X.; Jiang, N.; Tanaka, Y.; Li, X.; Jin, Q.; Tao, K.; Meng, F.; Tsubaki, N. A new method of ethanol synthesis from dimethyl ether and syngas in a sequential dual bed reactor with the modified zeolite and Cu/ZnO catalysts, *Catalysis Today* **2011**, *164(1)*, https://doi.org/10.1016/j.cattod.2010.10.027.
[29] Zhou, H.; Zhu, W.; Shi, L.; Liu, H.; Liu, S.; Ni, Y.; Liu, Y.; He, Y.; Xu, S.; Li, L.; Liu, Z. In situ DRIFT study of dimethyl ether carbonylation to methyl acetate on H-mordenite, *Journal of Molecular Catalysis A: Chemical* **2016**, *417*, https://doi.org/10.1016/j.molcata.2016.02.032.
[30] Kodera, Y.; Kaiho M. Model calculation of heat balance of wood pyrolysis, *Journal of The Japan Institute of Energy* **2016**, *95*, *881–889.*
[31] Koponen, J.; Kosonen, A.; Huoman, K.; Ahola, J.; Ahonen, T.; Ruuskanen, V. *Specific energy consumption of PEM water electrolysers in atmospheric and pressurised conditions*. In 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), 2016, 1–10.
[32] Shiva Kumar, S.; Himabindu, V. Hydrogen production by PEM water electrolysis – A review, *Materials Science for Energy Technologies* **2019**, *2*(*3)*, https://doi.org/10.1016/j.mset.2019.03.002.
[33] De Falco, M.; Capocelli, M.; Centi, G. Dimethyl ether production from $CO_2$ rich feedstocks in a one-step process: Thermodynamic evaluation and reactor simulation, *Chemical Engineering Journal* **2016**, *294*, https://doi.org/10.1016/j.cej.2016.03.009.
[34] Khan, M.; Saud, K.; Ashraf, K.; Irfan, M.; Ibrahim, S. Curing of concrete by carbon dioxide, *IRJET*, **2018**, *4410–4414*.
[35] Jones, J.; Barton, C.; Clayton, M.; Yablonsky, A.; Legere, D. SkyMine carbon mineralization pilot project, Final Phase 1 Topical Report, September 2011. Accessed June 1, 2021. https://digital.library.unt.edu/ark:/67531/metadc845150/m2/1/high_res_d/1027801.pdf.
[36] Zampori, L.; Saouter, E.; Schau, E.; Cristobal, J.; Castellani, V.; Sala, S. *Guide for interpreting life cycle assessment result*, JRC Technical Reports, European Commission, 2016, ISBN 979-92-79-64114-5.

# Chapter 8 Case study no 3 -The Environmental Impacts of Carbon Capture Utilization and Storage on the Electricity Sector: A Life Cycle Assessment Comparison between Italy and Poland



# The Environmental Impacts of Carbon Capture Utilization and Storage on the Electricity Sector: A Life Cycle Assessment Comparison between Italy and Poland

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# The Environmental Impacts of Carbon Capture Utilization and Storage on the Electricity Sector: A Life Cycle Assessment Comparison between Italy and Poland

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**Abstract:** Carbon Capture Utilization and Storage (CCUS) is a set of technologies aimed at capturing carbon dioxide ($CO_2$) emissions from point-source emitters to either store permanently or use as a feedstock to produce chemicals and fuels. In this paper, the potential benefits of CCUS integration into the energy supply sector are evaluated from a Life Cycle Assessment (LCA) perspective by comparing two different routes for the $CO_2$ captured from a natural gas combined cycle (NGCC). Both the complete storage of the captured $CO_2$ and its partial utilization to produce dimethyl ether are investigated. Moreover, the assessment is performed considering the region-specific features of two of the largest $CO_2$ emitters in Europe, namely Italy and Poland. Results shows that the complete storage of the captured $CO_2$ reduces Global Warming Potential (GWP) by ~89% in Italy and ~97%, in Poland. On the other hand, the partial utilization of $CO_2$ to produce dimethyl ether leads to a decrease of ~58% in Italy and ~68% in Poland with respect to a comparable reference entailing conventional dimethyl ether production. A series of environmental trade-offs was determined, with all the investigated categories apart from GWP showing an increase, mainly connected with the higher energy requirements of CCUS processes. These outcomes highlight the need for a holistic-oriented approach in the design of novel implemented configurations to avoid burden shifts throughout the value chain.

**Keywords:** CCS; CCU; dimethyl ether; life cycle assessment

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## 1. Introduction

Climate neutrality is one of the main objectives of the European Union's (EU) environmental policies. The goals set out within the European Green Deal [1] and the implemented legislative framework amended by the European Commission [2] make the EU a frontrunner in climate mitigation. Climate action is foreseen within the purposes of European environmental policies, strongly based on the principles of precaution, prevention and rectifying pollution at source. Mitigation strategies are indeed intended to prevent or reduce the emissions of greenhouse gases (GHGs) to ease the impacts of climate change.

The strong commitment of the EU dates back to 2015, when 195 countries signed the Paris Agreement, agreeing "to keep the increase in global mean surface temperature to well below 2 °C, and to limit the increase to 1.5 °C" in order to lessen the negative outcomes of climate change [3]. Signing the agreement, the EU set a binding target to cut emissions in the EU territory by 2030 to levels at least 40% below those in 1990 [4]. Nonetheless, according to a report published by the European Environment Agency in

2021, the strategies implemented by the EU lead to a decrease in GHGs as high as 31% with respect to 1990 levels [5], thus supporting the new targets adopted in 2021 under the European Climate Law increasing the reduction target to 55% [2].

However, in 2020, $CO_2$ emissions in the 27 Member States of the EU exceeded 2.6 Gt (also considering the other GHGs, the value rose to around 3.3 Gt of $CO_2$), with the energy supply sector being the main source (~31%), followed by the transport sector (~28%), manufacturing industries (~24%), and residential and commercial activities (~16%) [6]. It is therefore evident that the energy sector is the largest contributor to GHG emissions, and that the achievement of the aforementioned goals requires the combined action of a series of climate mitigation strategies.

Among them, the European Commission called for the improvement of energy efficiency, a deeper electrification of fossil fuel–supplied sectors, and a growing share of renewable energy production (in 2020, the share of energy consumed from renewable sources reached 22.1%, whereas the 2030 target was set at 40%) [5]. According to Gelien et al. [7], energy efficiency and renewable energy technologies are the core elements of energy transition, having the potential to meet ~70% of the global energy demand. Nonetheless, without favorable policies at national and international levels, there is no possibility to fully exploit that potential. Though recognizing the high level of maturity and economic competitiveness of solar photovoltaic power generation, Jäger-Waldau et al. [8] underlined that to reach a 55% emission reduction, the solar photovoltaic installed capacity should be brought to 455–605 GW, thus making mandatory a drastic growth of the photovoltaic market volume in the EU due to the increase of the average annual growth rate. Nonetheless, the intrinsic intermittency of these sources requires proper integration with other energy systems. For instance, Rashidi et al. [9] proposed to utilize wind energy to supply power to desalination systems. This resulted in improvements of the overall reliability of the systems, lower GHG emissions, and a proper balance of power fluctuations.

In addition to wind and solar photovoltaics, natural gas can be considered as a bridge towards a cleaner energy system. Natural gas indeed represents a cleaner energy source option compared to other fossil fuels (such as coal, bitumen, and diesel) [10], with the potential to take advantage of the well-developed dedicated infrastructure and having strong economic competitiveness. Within the EU, the inland demand for natural gas in 2020 exceeded 360 Mtoe [11], representing 21.5% of the EU's primary energy consumption, with the residential sector accounting for most EU gas demand (40%), followed by industry and gas use for power generation [12]. Worldwide, natural gas–fired power plants supplied ~6300 TWh, accounting for about 24% of total global power generation, in 2020 [13]; this technology is seemingly the only one among fossil resources that is capable of providing flexibility for the power system in the coming years [14], enabling the integration of intermittent renewable energy sources [10].

In order to continue using natural gas, the implementation of technologies to avoid $CO_2$ emissions into the atmosphere is essential. Within this context, Carbon Capture Utilization and Storage (CCUS) can be seen as a viable tool to enable industrial decarbonization while curbing $CO_2$ emissions. CCUS refers to a set of technologies aiming at capturing $CO_2$ emitted from a wide variety of sources (i.e., power plants, cements plants, etc.) in order to store in different forms. The captured $CO_2$ can be either stored underground or employed as a feedstock to other industrial processes for the production of fuels, chemicals, or building materials.

As for the storage pathway, Carbon Capture and Storage (CCS) involves different operations, mainly consisting of three major processes: $CO_2$ capture, transportation, and injection underground [15,16]. The technical aspects of carbon sequestration depend on the specific industrial application; it can be performed by adopting different physico-chemical processes, with the main distinction being among pre-combustion, post-combustion, and oxy-fuel combustion [17]. On the other hand, both transportation and storage phases are deeply site-dependent, thus requiring an extended investigation of the

local and geological characteristics [18]. The main hinderance to widespread CCS, in addition to the high costs, is the low social acceptance [19]. Concerns of $CO_2$ being leaked from the storage sites are mainly related to both climate change issues and ecosystem damage at a local level. Therefore, in order for CCS to be considered as a safe technology, the storage site must be properly selected according to strict safety, geological, and technical standards [18].

On the other hand, Carbon Capture and Utilization (CCU) uses the same process schemes of CCS for $CO_2$ capturing, with the main difference lying in $CO_2$ being used as a raw material for the production of synthetic fuels or chemical compounds. $CO_2$ is commonly perceived as an industrial waste, but its hydrogenation leads to the generation of several valuable products (such as methane, methanol, dimethyl ether, formic acid, etc.) [20]. The required hydrogen could be produced by water electrolysis fueled by renewable energies, therefore creating a network connecting the renewable energy supply system and the industrial value chain according to a concept known as Power-to-Gas (PtG). PtG is described as a chemical energy storage technology aiming at transforming electric energy through water electrolysis into combustible gases with high energy density [21]. Among CCU technologies, however, great attention has been paid to $CO_2$ conversion into fuels, with both methanol [22] and dimethyl ether [23] produced within this context being credited as potential alternative fuels in the future energy scenarios.

Nonetheless, the spread of these technologies is still limited. According to the latest estimates [24], the current capacity of CCUS facilities allow the capturing of ~40 $MtCO_2$ each year. At first, these plants were constructed to supply $CO_2$ to local oil producers for enhanced oil recovery operation (this is still one of the main utilization pathways for $CO_2$, covering more than 30% of the overall demand), being connected to natural gas processing facilities. However, in the 1980s, CCUS facilities barely managed to handle 0.5 Mt of $CO_2$; a major expansion has taken place during the last decade, with the majority of plants still operating in the natural gas processing sector (~28.5 Mt of $CO_2$) and some related to the power generation sector (~2.4 Mt of $CO_2$). Though the largest deployment of CCUS has been seen in China, European countries are also committed to the implementation of these kinds of technologies. The North Sea is currently the center of CCUS deployment in Europe, with the first projects being implemented in 1996. Indeed, to date, the main large-scale CCUS projects operating in Europe (namely, Sleipner and Snøhvit), with a combined storage capacity of 1.7 Mt of $CO_2$ per year, are both located in Norway and both capture $CO_2$ from natural gas processing and reinject it into dedicated storage sites. Nonetheless, other small pilot and demonstration projects are currently operating in Europe, with a capacity of nearly 30 Mt of $CO_2$ per year, which is projected to rise to around 35 Mt in 2030. CCUS technologies should thus be coupled with existing facilities belonging to the three main $CO_2$ emission contributors (namely, power generation, transport, and manufacturing), considering that most of Europe's energy sector emissions come from sources located in relatively close proximity to potential storage sites (for instance, ~68% of all the emissions from power plants and factories in Europe are located within 100 km of a potential storage site) [16].

A deeper understanding of the environmental outcomes related to the implementation of this kind of system could be obtained by means of Life Cycle Assessment (LCA). Holistic LCA, dealing with performance improvement of industrial processes, is recognized as a valid tool for governments in aiding decision-making processes [25]. This tool is crucial, since implementing $CO_2$ emission–mitigating technologies and shifting the energy supply towards more sustainable technologies could lead to significant environmental trade-offs, thus leading to further negative outcomes.

LCA methodology has been widely adopted to evaluate and compare the environmental profile of systems and products [26]. During the last decades, many assessments were performed to investigate the outcomes deriving from changing the energy scenarios at national or regional levels [27–30]. Through a wider perspective, Carvalho et al. [30] carried out an environmental assessment to gain insights into the

environmental profile of the electricity system of seven European countries in 2030. The authors found out that the implementation of the policies promoted by the European Commission would eventually lead to an average reduction of 42% in the impacts of climate change, with the best result coming from the reduction of acidification (impact category closely linked to the first). In addition, assessments have been performed to evaluate the feasibility of implementing both CCUS units [14,31,32]. Singh et al. [31] proposed a hybrid life cycle assessment to evaluate the consequence of coupling a natural gas combined cycle (NGCC) power plant with CCS, showing that a $CO_2$ capture efficiency of 90% could result in the avoidance of 70% of $CO_2$ emissions per kWh, reducing global warming potential (GWP) by 64%. The authors also identified some relevant trade-offs related to acidification, eutrophication, and toxicity, whose increase is due to the use and degradation of monoethanolamine (MEA) and on some process wastes. Similarly, Barbera et al. [14] investigated the effects of the introduction of the most promising CCS configurations in series to a gas-fired combined cycle power plant, employing either MEA or potassium carbonate as solvents. The authors also considered electricity generation from a photovoltaic plant and a wind turbine to identify the technology with the higher environmental performance, assuming Germany as a reference site. The environmental impacts of renewable energy sources were found to be very low when compared with those of fossil fuel–based technologies, but a burden shifting among environmental compartments was also found, with detrimental effects towards human health and freshwater. A more holistic perspective was instead proposed by Volkart et al. [32], who performed an assessment to evaluate the environmental consequences of integrating a carbon capture and storage (CCS) unit in both power generation and the cement industry, assuming Europe as a reference geographical region. The authors assessed the impacts on power generation assuming 2050 as a reference year, considering the time required for large-scale implementation of the CCS technology and the future potential technology development. They found a significant reduction of the life cycle GHG emissions from power generation thanks to CCS unit implementation for all the investigated power generation technologies, while the benefits of integrating CCS in cement plants was found to be highly dependent on the source of heat and power for the capturing process. Studies related to CCU technologies, on the contrary, have been mostly focused on the potential environmental benefits of the process itself rather than their integration into the energy sector [33,34]. However, the evaluation of the environmental impacts of these technologies are also intimately related to territorial features and to production–consumption patterns [35]; this relationship should be taken into account in order to understand which technology best suits the needs of a specific territory.

With this aim, a systematic analysis focused on the effect of storing or utilizing the $CO_2$ emitted from a power plant could be useful in order to address national environmental policies. Therefore, the present study aims at evaluating the potential environmental benefits of a NCGC power plant coupled with either a CCS or CCUS unit in two different European countries. The analyzed plant configurations are the same as those reported in a parallel work by De Falco et al. [36], within which an energetic and exergetic comparison between CCS and CCUS was made. Two possible routes for the $CO_2$ captured from a NGCC power plants are considered: (1) feeding 25% of the captured $CO_2$ to a methanol and dimethyl ether production plant while storing the remaining 75% underground under supercritical conditions, and (2) storing 100% of the captured $CO_2$ underground. An LCA-based comparison, relying on an extensive evaluation of the country's environmental profile, was thus performed to identify whether CCUS technologies could actually play a beneficial role within the climate-mitigating efforts of those countries, and which processes could potentially hinder their deployment.

The paper is organized as follows: Section 2 describes the current environmental profile of the selected countries, with a brief insight into the potential for CCUS spread; Section 3 outlines the methodology adopted to run the assessment, with an in-depth description of the process units; Section 4 shows the results from the two analyzed routes in Italy

and Poland, identifying the major drawbacks coming from their development; lastly, some final considerations are reported in Section 5.

## 2. Potential for CCUS Implementation in Italy and Poland

According to the European Environment Agency [6], in 2020, Germany, Poland, and Italy were the three major contributors to $CO_2$ total emissions, with released amounts accounting for 639.381 Mt, 303.523 Mt, and 302.279 Mt of $CO_2$ emitted throughout the reference year, respectively. It is worth noting that the overall emissions of Poland and Italy considered together were lower than the total emissions of Europe's largest contributor. Nevertheless, considering the per capita emissions of $CO_2$, only Italy is below the European mean average (5.885 kt of $CO_2$ per capita), with an emission footprint of 5.086 kt of $CO_2$ per capita. On the other hand, though having a smaller footprint than Poland (8.009 kt of $CO_2$ per capita), Germany (7.688 kt of $CO_2$ per capita) exceeds the European mean average of total emissions per capita.

As shown in Figure 1, the shares of $CO_2$ emissions per sector in Italy are similar to the ones previously detailed for the EU, with the major contribution given by transport (~28%), energy supply (~28%), and residential and commercial activities (~22%). On the contrary, regarding Poland, the contribution of individual sectors to total emissions differs significantly, with energy supply accounting for near half of the total $CO_2$ emissions (~47%), followed by the transport sector (~21%), and industrial activities (~16%).

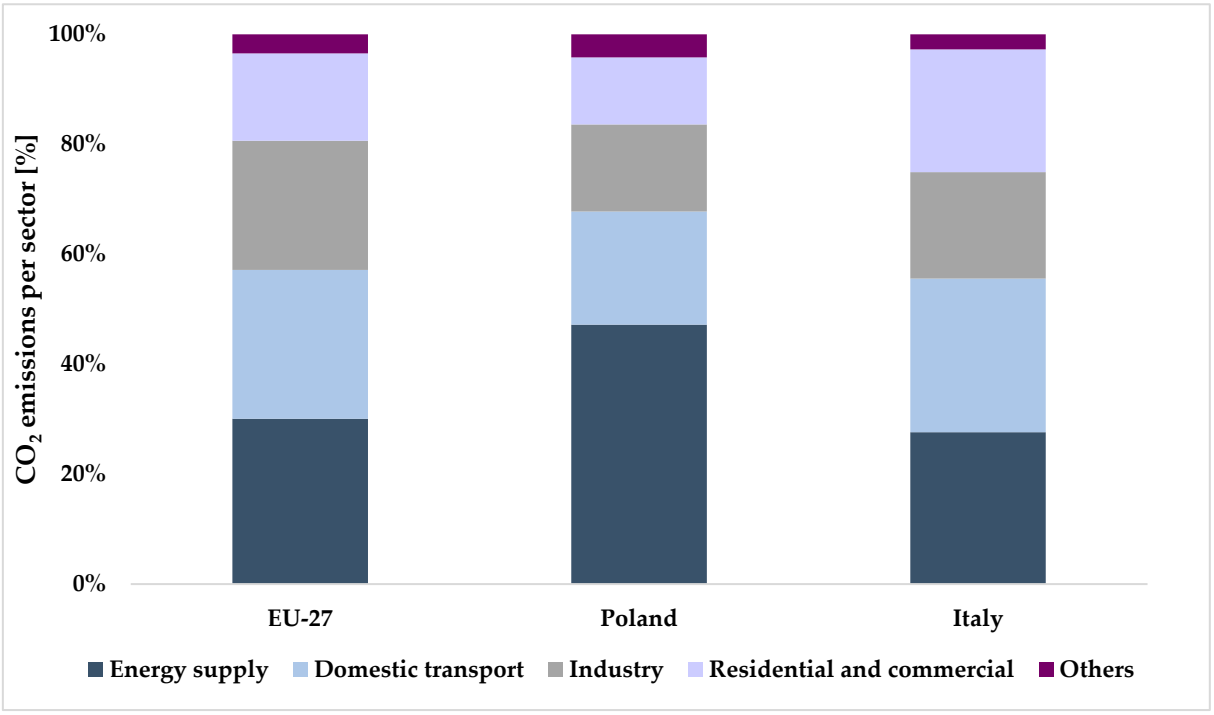


**Figure 1.** $CO_2$ emissions by sector in EU-27, Poland, and Italy. Data elaborated from [6].

Due to their role as large $CO_2$ emitters within the EU, Italy and Poland were selected for the present investigation. The choice of this pair of countries is also related to the significant difference among the specific energy supply sectors. Indeed, as will be further detailed in the following paragraphs, the internal energy demand of Italy and Poland is satisfied by a different set of energy supply sources, with Poland still majorly relying on fossil fuels. Therefore, this section deals with a brief description of the current environmental and energy scenarios of the countries covered by the present analysis, with a focus on the potential for the implementation of CCUS systems. For the data to be comparable, we refer to European institutions or to the International Energy Agency (IEA) as main sources.

### *2.1. Italian Case*

Energy and climate are at the top of the Italian political agenda. Within the Integrated National Plan for Energy and Climate (PNIEC), ambitious targets were set for renewables by 2030, aiming at reaching 30% in total energy consumption and 22% in transport sector consumption [37]. In 2020, Italy reached the target set by the EU for the share of energy from renewable sources, with 20.4% of energy supplied by renewables [38]. Nonetheless, the main energy supply source for Italy in 2020 was still natural gas, accounting for ~43% of the total energy supply (TES), being also the second-most natural gas–demanding country in Europe after Germany [11].

With reference to CCUS technologies, some investigations on their feasibility in the country have already been made [18,39]. Desideri et al. [18] presented their solution for a $CO_2$ capture and storage network in Italy, performing a case study located in Northern Italy, acknowledged as the Italian industrial district. The authors underlined the complex geological characteristics of the country, suggesting depleted or in-use hydrocarbon reservoirs as the most convenient storage site, provided that the safety standards were satisfied. The authors found that it would have been possible to store up to 8 Mt of $CO_2$ by implementing a 122 km long pipeline for storage and trading of $CO_2$. On the other hand, Bellocchi et al. [39] evaluated the impacts of PtG and Power-to-Liquid (PtL) systems on future $CO_2$-reduced scenarios, featured by a high renewable energy penetration. The authors found that PtG and PtL could allow the exploitation of renewable energy surplus in other sectors apart from electricity generation, with the production of synthetic natural gas ultimately leading to $CO_2$ emission reduction in the heavy transport sector.

### *2.2. Polish Case*

Poland's economy is largely based on non-renewable energy sources, with its energy supply dominated by fossil fuels (85% of TES in 2020), and the largest share coming from coal (40%), followed by oil (28%) and natural gas (17%). Poland had the highest shares of coal in energy production, and the second-highest share in heat production among all IEA member countries, though this massive dependence has declined in the last decade [40]. As for renewables, Poland failed the 2020 target set by the EU, reaching a share of ~16% [38], although the country was recognized as one of the fastest growing photovoltaic markets in the EU [40].

As a result of the introduction of the European Green Deal, the Polish government amended Poland's Energy Policy 2040 [41]. The document led the way to decarbonization based on three main pillars—i.e., (1) a fair transition, (2) a zero-carbon energy system, and (3) good air quality—and eight Strategic Objectives describing the actions to be taken while aiming to spread cleaner technology. One of the objectives was also to reduce the share of coal and lignite in electricity generation to less than 60% by 2030, also by means of natural gas, which has been targeted as a viable transition fuel to severely abate the national dependence on coal. As for CCUS, Poland does not have a clear strategy, and these technologies do not have a role within Poland's Energy Policy 2040. Nonetheless, the Polish Geological Institute documented 87 oil fields in Poland, estimating a storage potential in Poland for brine levels ranging from 12,009 Mt to 14,495 Mt for a total of 45 structures [42,43]. However, regardless of the large-scale research on the possibility of storing carbon dioxide, social factors need to be considered in the case of CCS implementation. According to Kaiser et al. [44], a large part of the Polish public has a positive outlook on CCS technology, although there are expectations from the public, such as clear benefits of CCS installations for the region or the country, among others.

## 3. Methodology

### *3.1. Life Cycle Assessment*

Life Cycle Assessment (LCA) is a methodology dealing with the holistic evaluation of environmental impacts of a product or service throughout its entire life cycle. To date,

LCA is regarded as a valuable supporting tool both for process design and policymakers. Despite having been adopted since the 1970s [26], the International Standardization Organization (ISO) standardized LCA methodology only a few decades ago, through ISO 14040 [45] and ISO 14044 [46], which are still regularly updated. According to the developed framework, the procedure for the calculation and preparation of LCA modelling is carried out in four interdependent and iterative steps:

1. **Goal and Scope Definition**, related to defining the intended application of the analysis alongside the basic issues determining the following evaluation (that is, functional unit, system boundaries, and level of details);
2. **Life Cycle Inventory Analysis**, consisting of gathering data on the inputs and outputs featured in each analyzed process, deriving from the interaction among each stage of the product's life cycle with the environment;
3. **Life Cycle Impact Assessment**, dealing with the actual computation of the environmental pressure consequent to both resource consumption and emissions into the different environmental compartments;
4. **Life Cycle Interpretation**, during which conclusions are drawn, identifying the most significant issues to provide feasible recommendations.

Due to its holistic approach, LCA provides the possibility of consistently evaluating CCUS technologies and avoiding problem shifting between both environmental impact categories and life cycle stages. Furthermore, the main issue in conducting LCA studies on CCUS technology lies in the double role of $CO_2$ as both emission (from a point-source emitter) and feedstock (to produce chemicals and fuels) [47]. Dealing with a product system producing multiple outputs is known as multifunctionality, which is a common problem for other processes [25]. Several methodological approaches can be used to address multifunctionality, depending on the goal of the study and the available information. However, ISO [46] defined a hierarchy among the possible options, with system expansion being the most recommended [47,48]. Through this approach, the system can either maintain each function by creating a joint functional unit to include other functions of the product systems or subtract the burdens related to the co-products that are not part of the functional unit [49]. Substitution and expansion are mathematically equivalent in comparative LCA, though the former can lead to negative environmental impacts that could be misinterpreted [47,48].

### *3.2. Goal and Scope Definition*

The main objective of the present LCA investigation was to evaluate the environmental consequences of coupling a CCS and/or a CCU unit with a gas-fired combined cycle power plant. The assessment was performed considering the current features of the energy supply sector of two different countries to run a comparison and obtain country-specific results able to guide future decision-making processes. For this analysis, the carbon capture unit was modelled according to a post-combustion capture process involving methyl diethanolamine (MDEA) as a solvent. As for the $CO_2$ enriched stream flowing for the carbon capture unit, according to the different routes proposed and following the existing guidelines [47,48], two scenarios were modelled:

1. **CCS scenario**: Assessing the environmental performance of CCS at a NGCC power plant located either in Poland or in Italy, compared to a reference system without CCS.
2. **CCUS scenario**: Assessing the environmental performance of a CCUS system implemented at a NGCC power plant located either in Poland or in Italy, compared to a reference system without CCUS. As mentioned, within this investigation, CCU was intended to produce dimethyl ether using the captured $CO_2$ as feedstock for its production. Therefore, with dimethyl ether being a product of the CCUS scenario, the reference scenario must also provide the same production function. Consequently, the system was expanded to include not only conventional production of dimethyl

ether but also the amount of renewable electricity used to produce it through the Power-to-Liquid (PtL) concept. Eventually, to obtain a fair comparison between CCS and CCU, the CCS scenario was expanded to include the additional functions.

Accordingly, the functional unit was defined in conformity to the specific goal of each scenario:

1. **CCS scenario**: "1 kWh of high-voltage electricity generated through a natural gas combined cycle power plant" with or without carbon capture and storage.
2. **CCUS scenario**: "1 kWh of high-voltage electricity generated through a natural gas combined cycle power plant" with or without carbon capture and storage; "production of 0.55 kg of dimethyl ether"; renewable electricity used to satisfy the internal demand or for substitution.

Performing calculations, the boundaries of the systems were restricted, focusing only on plant operation, due to the lack of reliable data related to plant construction and operating activities such as the transport and storage of $CO_2$. The present study can be therefore be regarded as a gate-to-gate analysis, focused on the issues of combustion of natural gas, capture, utilization, and storage of $CO_2$, in addition to its twofold nature in CCUS processes. Following the guidelines of Müller et al. [47] and von der Assen [48], allocation was avoided by dividing the process into sub-processes and extending the boundaries with additional auxiliary sub-processes.

As shown in Figure 2, the largest system boundary of the CCU scenario is defined by a total of five processes and sub-processes that were implemented for each country, as follows: (1) a state-of-the-art NGCC power plant; (2) a NGCC power plant integrated with a CCS unit; (3) a green hydrogen production plant; (4) a green dimethyl ether production facility; and (5) a NGCC power plant coupled with both a CCS and a CCU unit.

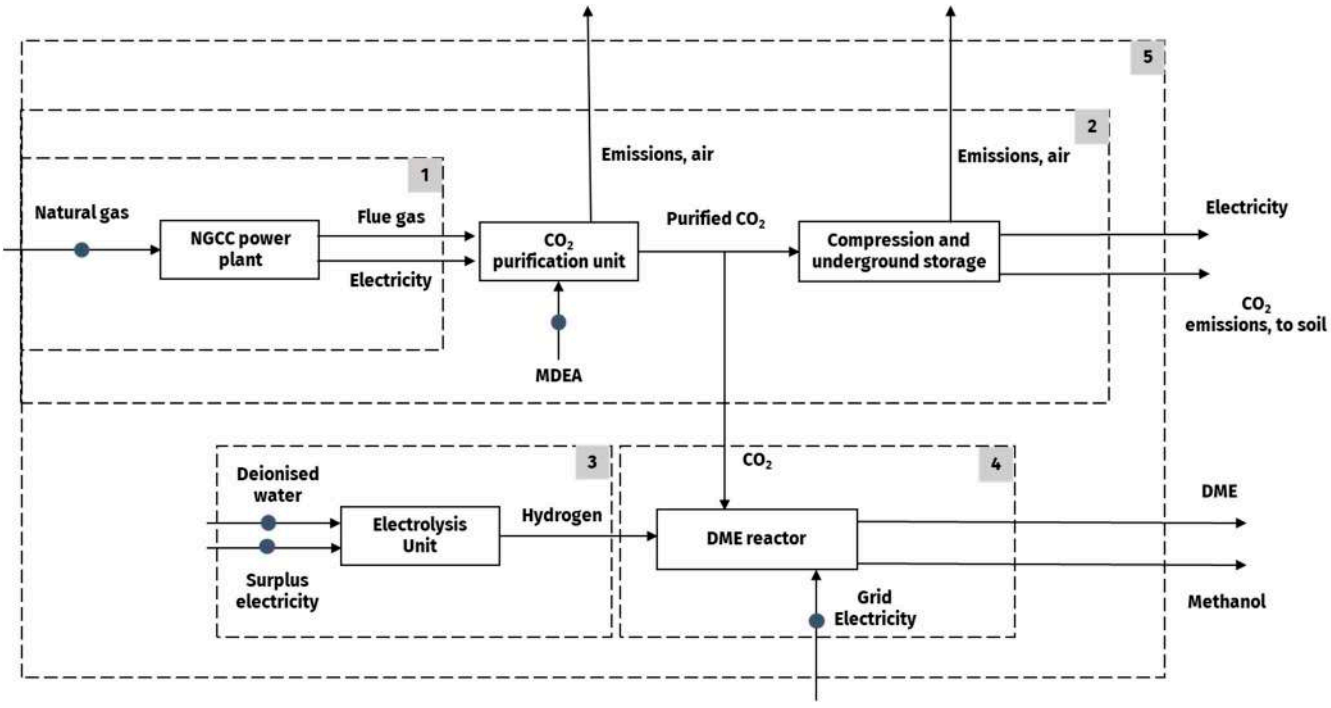


**Figure 2.** System boundaries.

The assessment was performed using openLCA™ 1.10.3 (©GreenDelta, Berlin, Germany), and the background data were mainly retrieved within ecoinvent v3.8 (ecoinvent, Zurich, Switzerland) [50].

### *3.3. Life Cycle Inventory*

The inventory was compiled according to the outcomes of a process simulation carried out by means of Aspen Plus™ (AspenTech®, Bedford, MA, USA). The following paragraphs will detail the main inputs and outputs of the processes featuring the investigated product system.

Data about the energy supply chain and the natural gas market are provided as background processes. Nonetheless, due to their significant contribution to the cumulative LCA results [32], country-specific markets for both electricity and natural gas are adjusted according to the 2020 scenario.

#### 3.3.1. Natural Gas Combined Cycle Power Plant

A 188.5 MW NGCC power plant was modelled as the reference process of the present investigation. The functioning principle of a NGCC power plant basically consists of the use of the high-temperature exhaust gases deriving from the combustion of natural gas to generate steam that is then exploited to drive a steam turbine generator [14]. By coupling these generation cycles, several advantages in terms of efficiency, operating flexibility, and emission reduction can be achieved. Table 1 includes the inventory related to the electricity production process. The coproduced heat is actually the amount needed from the reboiler of the carbon capture unit, but it was chosen to consider it as a co-product within the reference case scenario, expanding the base case system through substitution. This assumption is coherent with the heat recovery process implemented when the carbon capture unit is added, though different from the approach of Barbera et al. [14], which converted heat into power by means of an efficiency factor.

**Table 1.** Inventory for the NGCC power plant operation.

| Parameter | Value | Unit |
|---|---|---|
| **Inputs** | | |
| Natural gas | 50,000 | kg $h^{-1}$ |
| Air | 2,572,035 | kg $h^{-1}$ |
| Make-up water | 9502 | kg $h^{-1}$ |
| Cooling water | 7066 | $m^3$ $h^{-1}$ |
| **Outputs** | | |
| Electricity | 188.5 | MWh |
| Coproduced Heat | 143.8 | MWh |
| **Emissions** | | |
| $CO_2$ | 132,327 | kg $h^{-1}$ |
| Flue gas (without $CO_2$) | 2,489,707 | kg $h^{-1}$ |

Natural gas composition for each investigated case and for each natural gas demanding application is based on that reported by the National Energy Technology Laboratory (NETL) [51], and its characteristics are listed in Table 2.

**Table 2.** Natural gas composition and characteristics.

| Component | Volume Percentage |
|---|---|
| Methane, $CH_4$ | 93.10% |
| Ethane, $C_2H_6$ | 3.20% |
| Propane, $C_3H_8$ | 0.70% |
| Butane, $C_4H_{10}$ | 0.40% |
| Carbon dioxide, $CO_2$ | 1.00% |
| Nitrogen, $N_2$ | 1.60% |
| **Calorific Value** | Value |
| Higher Heating Value (HHV) in kJ $kg^{-1}$ | 52,581 |

| | |
|---|---|
| Gross Calorific Value in MJ $m^{-3}$ | 38.46 |

However, the natural gas market was adjusted for each country according to the market data for 2020. Due to the crucial role of natural gas as an energy supply source in Italy, the country developed a branched infrastructure to allow multiple access points for the imports and a wide distribution across the country [52]. On the other hand, the historical dependence of Poland from coal hindered the spread of natural gas as an energy supply source in the country [40]. Despite the small role in the energy system, the natural gas network is well-developed and extremely interconnected, apart from also representing a bridge between the Russian Federation and Western Europe through the Yamal–Europe gas pipeline [53].

In 2020, both Italy and Poland were net importers of natural gas, with the highest share of import coming from the Russian Federation. The gas balance for both countries is reported in Table 3, according to data provided by Eurostat [11]. Furthermore, information about the natural gas import market for Italy [54] and Poland [53] is given in Table 4, outlining the market share by origin country and considering the major exporters. These data were used to adjust the background process related to the market for the natural gas feeding the plant, considering only the import processes available in the adopted dataset. For this reason, only imports from the Russian Federation, Algeria, Norway, and the Netherlands were considered for Italy, while the Polish market comprised imports from the Russian Federation, Germany, and the Netherlands.

**Table 3.** Natural gas balance in Italy and Poland in 2020. Values are expressed in terajoules (gross calorific value).

| Natural Gas Balance | Italy | Poland |
|---|---|---|
| Primary production | 149,810 | 157,151 |
| Imports (entries) | 2,523,249 | 1,582,568 |
| Resources | 2,673,059 | 1,739,720 |
| Stock change | −41,034 | −18,444 |
| Exports (exits) | 12,027 | 966,209 |
| Inland demand | 2,702,066 | 791,955 |
| Energy dependency (from import) | 92.94% | 77.83% |
| **Share on EU inland demand** | 17.80% | 5.22% |
| **Natural gas share in the overall energy mix** | 40.47% | 16.89% |

**Table 4.** Natural gas import shares by origin country for Italy and Poland in 2020.

| Country | Italy | Poland |
|---|---|---|
| Russian Federation | 43.37% | 55.81% |
| Algeria | 22.83% | - |
| Netherlands | 1.38% | - |
| Libya | 6.74% | - |
| Norway | 11.17% | 1.74% |
| Qatar | 10.49% | 13.37% |
| United States | 2.65% | 5.81% |
| France | 0.93% | - |
| Germany | - | 20.93% |
| Czech Republic | - | 1.74% |
| Others | 0.43% | 0.58% |

3.3.2. Carbon Capture and Storage Units

As mentioned, the technology selected for $CO_2$ capture was post-combustion. Post-combustion capture is regarded as one of the most mature and feasible processes to

separate $CO_2$ from flue gas streams, with the capturing being typically performed through absorption into a suitable solvent (commonly MEA in power plants). The process simulation for the present investigation adopted a 40 wt% MDEA aqueous solution to achieve a 90% removal of $CO_2$ from the gaseous stream. The inventory of the unit is outlined in Table 5.

**Table 5.** Inventory of the carbon capture unit.

| Parameter | Value | Unit |
|---|---|---|
| **Inputs** | | |
| $CO_2$ | 132,327 | kg $h^{-1}$ |
| Flue gas (without $CO_2$) | 2,489,707 | kg $h^{-1}$ |
| Water make-up | 3415 | kg $h^{-1}$ |
| MDEA make-up | 249 | kg $h^{-1}$ |
| Required power | 123.5 | MWh |
| Heat | 143.8 | MWh |
| Cooling water | 46,914.27 | $m^3$ $h^{-1}$ |
| **Outputs** | | |
| $CO_2$ enriched stream | 125,014 | kg $h^{-1}$ |
| **Emissions** | | |
| Clean gas | 2,410,824 | kg $h^{-1}$ |

As for the storage unit, the process included the purification and pressurization of the captured $CO_2$ stream from the top of the carbon capture unit stripper, as well as the amount of cooling water needed to refrigerate and liquefy the stream. Table 6 shows the inventory of the storage process.

**Table 6.** Inventory of the underground storage unit.

| Parameter | Value | Unit |
|---|---|---|
| **Inputs** | | |
| $CO_2$ enriched stream | 125,014 | kg $h^{-1}$ |
| Required power | 11.5 | MWh |
| Cooling water | 1867.50 | $m^3$ $h^{-1}$ |
| **Outputs** | | |
| $CO_2$ underground | 119,067.55 | |
| **Emissions** | | kg $h^{-1}$ |
| Losses | 5947 | kg $h^{-1}$ |

3.3.3. Hydrogen Production Unit

To produce chemicals and fuels using the captured CO2 as feedstock, another reactant is needed. Most of CCU processes mainly consist of the hydrogenation of the CO2, thus involving a certain amount of hydrogen for the process. To date, hydrogen can be produced through several industrial processes, though most of it is still produced from steam methane reformation [55–57].

However, even though economically convenient, these processes feature the highest environmental burden among the available technologies [55]. Therefore, hydrogen should be produced by water electrolysis, a more environmentally friendly strategy, enabling the production of a high-purity hydrogen stream without releasing harmful GHGs to the atmosphere [57]. Currently, there exists different water electrolysis technologies featuring different levels of maturity and operating conditions [58]. Among them, for the purpose of the present study, an alkaline electrolyzer was chosen for the production of the required

hydrogen stream. Alkaline electrolysis is actually the oldest and most widespread technology, being characterized by an extremely simple functioning mechanism [57,59].

As mentioned, a sub-process was modelled for hydrogen production, assuming as a functional unit "1 kg of hydrogen" according to a gate-to-gate approach. Table 7 outlines the inventory related to the operating phase of an alkaline electrolyzer, as reported by Koj et al. [59], whose data refer to a 6 MW electrolyzer producing hydrogen at ~30 bar and 40 °C.

**Table 7.** Inventory of the hydrogen production unit.

| Parameter | Value | Unit |
|---|---|---|
| **Inputs** | | |
| Water, deionized | 10 | kg per kg of hydrogen |
| Electricity | 50 | kWh per kg of hydrogen |
| Potassium hydroxide | 0.11 | g per kg of hydrogen |
| Steam | 1.9 | per kg of hydrogen |
| **Outputs** | | |
| Hydrogen | 1 | kg |

It is commonly recognized that the operating phase for water electrolysis is the one associated with the highest environmental impacts [60]. Therefore, with the energy supply source as the major contributor for most of the impact categories investigated through LCA studies, the required electricity was assumed as deriving only from intermittent renewable sources—i.e., solar and wind plants. A costumed market entailing these sources was therefore implemented according to each country electricity mix and is further detailed in the following section.

3.3.4. Dimethyl Ether Production Unit

In the implemented CCU scenario, a part of the captured $CO_2$ is sent to a dimethyl ether production unit. While there exist different pathways and reactor configurations, the process considered within the present study is a one-step synthesis process [61], where the reactor is equipped with a bifunctional catalyst [62,63]. Table 8 specifies the main inputs and outputs of the process as obtained from process simulations, with the amount of required power and cooling water given by the contribution of the various equipment constituting the entire $CO_2$ conversion unit.

**Table 8.** Inventory of the dimethyl ether production unit.

| Parameter | Value | Unit |
|---|---|---|
| **Inputs** | | |
| $CO_2$ | 29,766 | kg $h^{-1}$ |
| Hydrogen | 3751 | kg $h^{-1}$ |
| Required power | 4.66 | MWh |
| Cooling water | 6,482,752 | $m^3$ $h^{-1}$ |
| **Outputs** | | |
| Dimethyl Ether | 10,444 | kg $h^{-1}$ |
| Methanol | 3293 | kg $h^{-1}$ |
| Water | 16,199 | kg $h^{-1}$ |
| **Emissions** | | |
| $CO_2$ | 2964 | kg $h^{-1}$ |

Differently from the compression and storage unit, the dimethyl ether production plant was intended to be fed by grid electricity. This assumption allows us to consider the

production facility as a separate production facility, improving the comparability with the currently adopted processes. The latter actually involve a different production scheme, consisting of an indirect production process. Conventional production plants are equipped with reforming unit producing syngas to be converted into methanol, which is in turn dehydrated to produce dimethyl ether [33]. Therefore, the process implemented within the reference case scenario to expand the system was taken from the inventory of Ecoinvent. The selected process was related to the production of 1 kg of dimethyl ether from methanol with a process yield of 95%. Nonetheless, since the already present process unit was for the average European market, both the electricity and heat requirement were changed to account for the country-specific case.

#### 3.3.5. Electricity

Data related to each country's electricity mix are taken from Eurostat [64] in order to be comparable. Eurostat structures the electricity production mix, splitting it according to the energy source and classifying it in classes and sub-classes. Despite the high level of detail offered by these datasets, the adopted ecoinvent 3.8 database (ecoinvent, Zurich, Switzerland) is not based on the same set of assumptions as Eurostat. For this reason, the electricity production mix was redesigned to be in compliance with the employed database, assuming as valid the assumptions related to plant technologies (type of installation, technology, and size) while adapting the shares to the 2020 electricity mix reported in Table 9. Moreover, in order to redesign the market for electricity consumption at the different voltage levels, electricity import shares were adjusted according to 2020 data. As for Italy, data from Terna [65] were used, and the imports from Switzerland (49.68%), France (36.80%), Slovenia (10.15%), and Austria (3.37%) were included in the implemented process in Ecoinvent. On the other hand, data for Poland were retrieved from IEA [40], considering Germany (53.53%), Sweden (23.52%), Lithuania (12.26%), and Ukraine (10.70%) as the main exporters.

**Table 9.** Electricity mix in Italy and Poland in 2020. Values are reported in TWh.

| | **Italy** | **Poland** |
|---|---|---|
| **Gross Electricity Production** | 280.03 | 157.95 |
| Solid Fossil Fuels | 13.38 | 107.40 |
| Natural Gas | 133.68 | 17.29 |
| Oil and petroleum products | 3.17 | 1.75 |
| Manufactured Gas [(1)] | 1.66 | 1.97 |
| Other Solid Fuels [(2)] | 20.74 | 7.61 |
| Other Gaseous Fuels [(3)] | 8.17 | 1.23 |
| Hydro Power | 49.49 | 2.94 |
| Geothermal Power | 6.03 | - |
| Wind Power | 18.76 | 15.80 |
| Photovoltaic Power | 24.94 | 1.96 |
| **Net Imports** | 32.20 | 13.3 |

[(1)] Comprising blast furnace gases and coke oven gases. [(2)] Comprising biofuels, municipal waste, and other oils. [(3)] Biogas.

Eventually, the above-mentioned market for intermittent renewable electricity was designed considering only wind and solar photovoltaic production to obtain the shares of the two sources within the fictional market. This process resulted in an Italian market in which the shares were quite similar (42.93% solar photovoltaic and 47.07% wind), while for Poland there was a predominance of electricity produced from wind farms (11.03% solar photovoltaic and 88.97% wind).

### *3.4. Impact Assessment Methods*

The evaluation of the environmental impacts of technologies was performed by means of a selected impact assessment method. Although the main aim of CCUS technologies is the reduction of GHG emissions [66,67], their introduction into the energy sector might lead to adverse effects on other environmental compartments and impact categories. According to Müller et al. [47], it is important to include other impact categories apart from Global Warming Potential (GWP) to avoid misinformed decision making, especially if these categories are considered relevant and assessable. Since numerous impact categories and assessment methods are available in the market, the choice of the impact categories to be treated as relevant was made according to both the existing literature [66,67] and guidelines [34,47]. As for the latter, the European Joint Research Centre (JRC) drew up an Impact Assessment guideline [68], providing a set of recommendations about the impact categories and related methods to be used, while Rosental et al. [34] provided the six most relevant categories representing commonly affected environmental impacts, where conflicts of interest could occur in terms of environmental protection goals. These categories are reported in Table 10, together with a brief description and the recommendation level set by the JRC (level I stands for "recommended and satisfactory", while level II indicates categories that are "recommended but in need of some improvements").

**Table 10.** Suggested impact categories for CCUS. Adapted from [34].

| Impact Category | Indicator | Unit | Recommendation Level |
|---|---|---|---|
| Global Warming Potential (GWP) | Potential global warming in a 100-year time horizon due to emissions of greenhouse gases to air | kg $CO_2$-eq | I |
| Cumulated Energy Demand (CED) | Total energy content of all fossil, nuclear, and renewable energies consumed | GJ | Not listed |
| Acidification Potential (AP) | Potential acidification of soils and water due to the increased concentration of hydrogen ions in a local environment | kg $SO_2$-eq | II |
| Eutrophication Potential (EP) | Nutritional element enrichment within aquatic and terrestrial ecosystem caused by the release of nitrogen or phosphor containing compounds | kg $PO_4$-eq | II |
| Ozone Depletion Potential (ODP) | Deterioration of the stratospheric ozone layer caused by the emission of halogenated hydrocarbons | g CFC-11-eq | I |
| Particulate Matter Formation ($PM_{2.5}$) | Particulate matter emissions to air that cause damage to human health | g $PM_{2.5}$-eq | I |

Of the above-mentioned categories, particulate matter formation was excluded from the present assessment, while due to the adoption of CML (Institute of Environmental Sciences, University of Leiden) as an impact assessment method, as suggested by Müller et al. [47], abiotic depletion (AD) (fossil fuels) was considered in place of cumulated energy demand. The two categories are indeed similar since AD (fossil fuels) is an index of the fossil energy exploited to satisfy the energy demand of the value chain under investigation [66].

## 4. Results and Discussion

In the case of CCS and CCUS, the modified environmental profile was compared to the reference case of each scenario. In this section, the environmental consequences of implementing CCS and CCUS technologies will be therefore discussed for both Italy and Poland, with each process and sub-process modelled considering the country's market for natural gas and the national market for electricity supply. Results are reported normalized to the highest computed value.

### *4.1. Carbon Capture and Storage*

The addition of a CCS unit to the NGCC power plant mainly aims at reducing the emitted $CO_2$ during plant operation. Results from the impact assessment, as shown in Figures 3 and 4, confirm a drastic reduction of $CO_2$-equivalent emissions both in Italy and Poland.

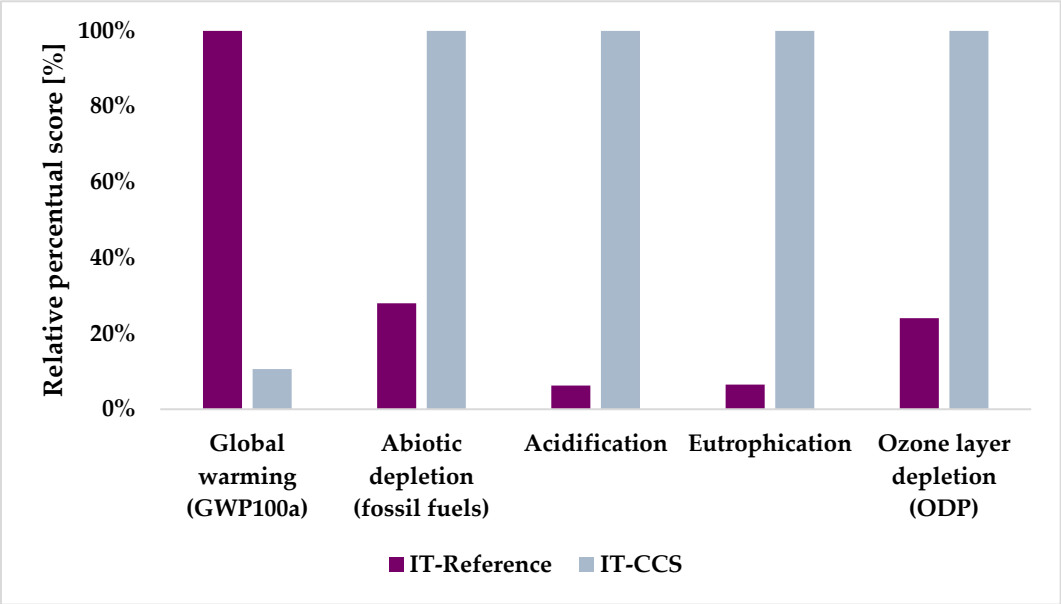


**Figure 3.** Impact category scores for the Italian case study in the CCS scenario.

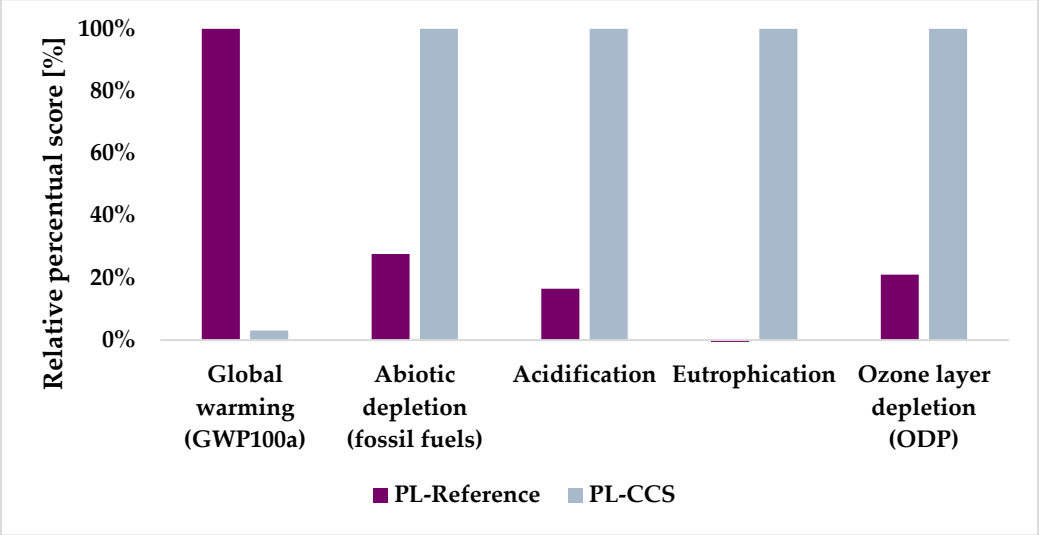


**Figure 4.** Impact category scores for the Polish case study in the CCS scenario.

While current emissions are estimated to be 0.715 kg $CO_2$-eq $kWh^{-1}$ and 0.695 kg $CO_2$-eq $kWh^{-1}$ in Italy and Poland, in the CCS scenario the GWP is reduced to 0.076 kg $CO_2$-eq $kWh^{-1}$ and 0.021 kg $CO_2$-eq $kWh^{-1}$, respectively. Results for the reference case also reflect the choice of considering the heat coproduced from the plant (which is actually used in the carbon capture unit) as an avoided product for the sake of comparability between the case studies. Without this assumption, the gap would have been even higher. Moreover, it must be noted that the large decrease in GWP (~89% and ~97%, for Italy and Poland, respectively), is also attributable to the gate-to-gate approach. Indeed, if considering also the emissions associated with the carbon capture infrastructure development and the $CO_2$ network (requiring further energy for the compressors and covering large distances), the total reduction of $CO_2$ emissions would be limited.

However, since data on GHG emissions mainly refer to the operating phase, assuming as valid the obtained emission rates and considering the energetic scenario of the two countries, the implementation of CCS would lead to an overall $CO_2$ emission reduction of 9.64% and 1.16% in Italy and Poland, respectively. As previously outlined, the main difference in the percentual decrease can be attributed to the different amount of electricity generated from NGCC power plants in the two countries.

On the other hand, in addition to $CO_2$ emissions, various other impact categories were analyzed, resulting in significant environmental trade-offs that must be properly treated, as also identified by similar earlier studies [14,31]. The significant increase of the other impact categories is mostly driven by natural gas utilization, in terms of extraction, processing, and transportation, especially as regards the increase in AP (+94% and +84% for Italy and Poland, respectively), EP (+93% and +101% for Italy and Poland, respectively), and ODP (+76% and +79% for Italy and Poland, respectively), with the difference between Italy and Poland mainly due to the amount of Russian natural gas imported. Moreover, neglecting the sulfur content within the natural gas feed and the amount of release of nitrogen oxides from the plant, the three impact categories are underestimated in the reference case, while the gap between the compared cases could have been also reduced from considering the beneficial effect of ammine scrubbing for nitrogen oxide and sulfur component removal.

The higher AD of fossil fuels (+72% for both Italy and Poland) can be attributed to the large energy consumption of both carbon capture and underground storage. Indeed, the energy required for the compression of the flow rate of flue gas resulting from the process simulation exceeds 60% of the net power produced from the plant, with severe consequences in terms of efficiency. This outcome is mainly due to the process not being optimized in terms of air excess and operating pressure of the absorber.

Even though impact categories related to toxicity have not been regarded as fitting the purpose of the present study, previous investigations have underlined the possible increase in toxicity-related issues due to the production and use of ammine-based solvents during the absorption process, most of which are toxic compounds whose emission during the process (to atmosphere, water, and soil) is unavoidable [32,66]. Therefore, further attention in process design must be paid both to efficiency losses and solvent selection if post-combustion processes are chosen for cleaning the flue gas stream.

### *4.2. Carbon Capture Utilization and Storage*

Differently from the CCS scenario, CCUS processes represent multifunctional systems, and the reference case is provided with the equal amounts of renewable energy to substitute background processes, apart from being expanded to account for the conventional production of the equal amount of dimethyl ether. Figures 5 and 6 provide the scores of each impact category for the Italian and Polish case study, respectively.

Regarding GWP, the reduction in $CO_2$ emissions is less marked. Indeed, the reduction of $CO_2$ emissions has been estimated to account for ~58% and ~68% in Italy and Poland, respectively. In the reference scenario, the production of electricity and dimethyl ether accounts for 0.723 kg $CO_2$-eq and 0.745 kg $CO_2$-eq for the two countries, with the substitute electricity coming from renewables, contributing to a decrease of 0.053 kg $CO_2$-eq in Italy and 0.024 kg $CO_2$-eq in Poland. In both cases, the burden of conventional dimethyl ether production on GWP was less than 9%, mainly because of the small amount produced. The implementation of CCUS processes, however, lowers the emission to 0.303 kg $CO_2$-eq and 0.236 kg $CO_2$-eq in Italy and Poland, respectively. In the investigated case, the production of dimethyl ether from $CO_2$ hydrogenation accounts for 26.95% in Italy and 28.32% in Poland, with differences related to the Polish country electricity mix used to satisfy the energy demand of the synthesis process being more $CO_2$ intensive than the Italian one. However, adopting the same perspective as for the CCS scenario, CCUS technologies could lead to an overall emission reduction of 3.85% in Italy and 0.68% in Poland.

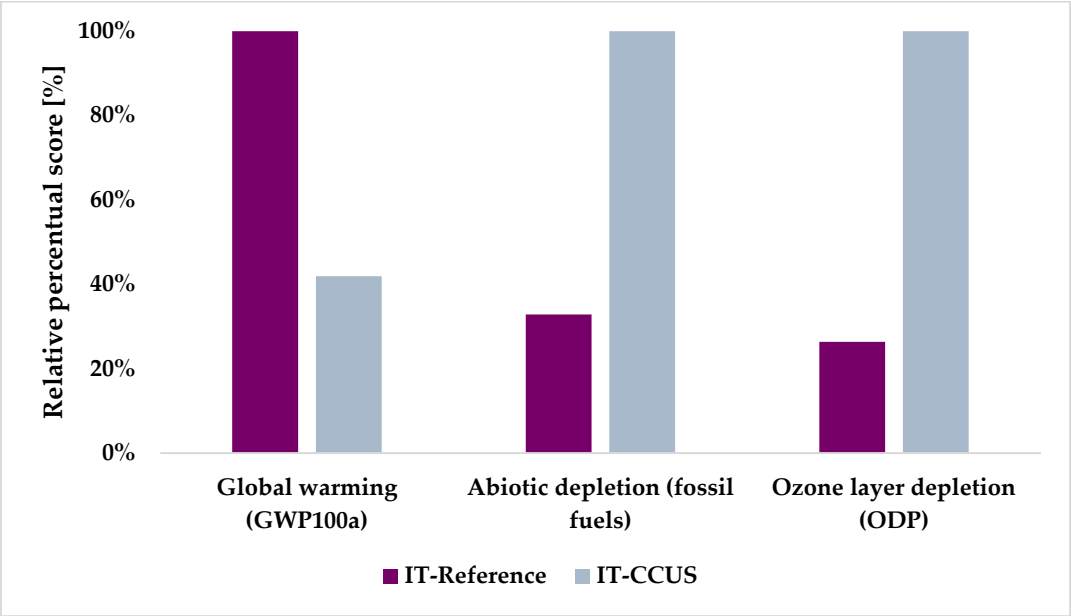


**Figure 5.** Impact category scores for the Italian case study in the CCUS scenario.

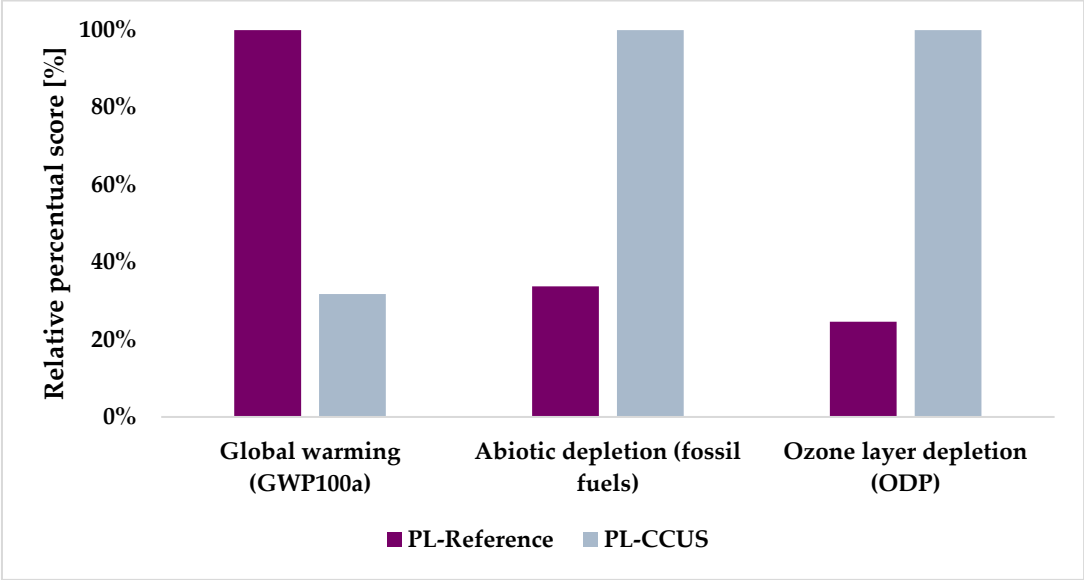


**Figure 6.** Impact category scores for the Polish case study in the CCUS scenario.

As in the CCS scenario, all the other investigated categories showed an increase. Considerations related to AD (fossil fuels)—whose increase was 67% for Italy and 66% for Poland—and ODP—whose increase was 74% for Italy and 75% for Poland—are the same as for the CCS scenario. On the other hand, little confidence is given to the results related to AP and EP; therefore, they are not shown within the graphs. Nonetheless, it must be underlined that both wind and solar power generation technologies are featured by a high impact in terms of AP and EP, and the implementation of CCUS processes fed with hydrogen produced by renewable electricity is therefore likely to be featured by a marked worsening of performance with respect to these categories [66].

Lastly, Figures 7 and 8 provide a wider comparison of the CCS scenario, properly modified to account for the production of dimethyl ether and the use of renewable electricity. As for the previous case, only impacts related to GWP, AD, and ODP are shown to avoid misinterpretation issues related to the substitution approach.

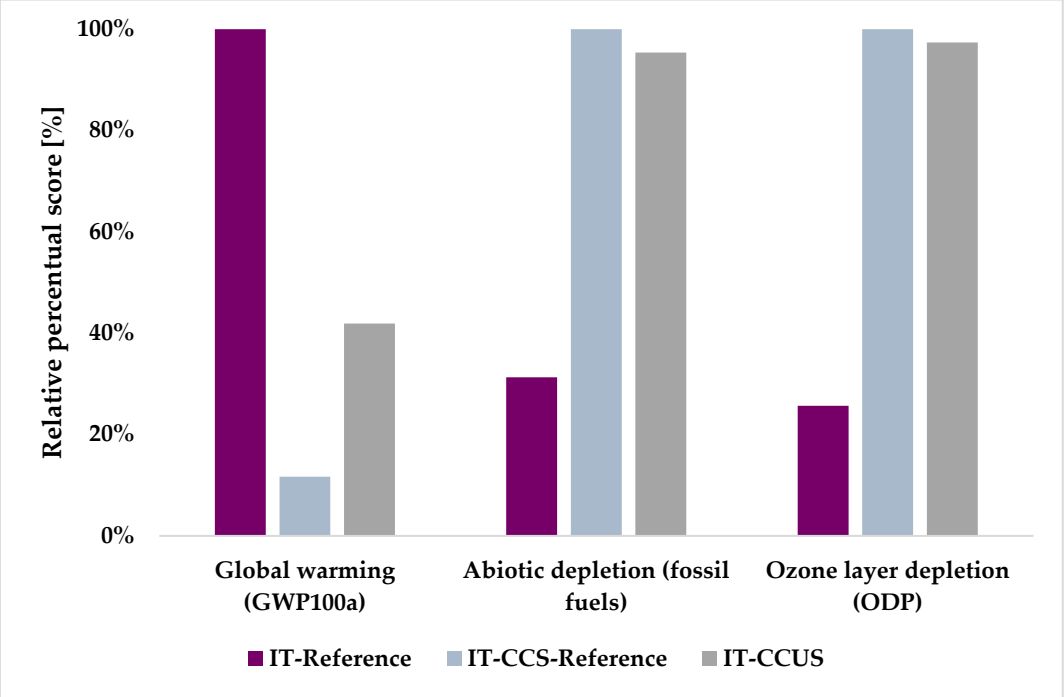


**Figure 7.** Impact category scores for the Italian case study in the CCUS scenario considering a comparable CCS reference scenario.

Considering the CCS comparable reference case, it is clear that, from a GWP perspective, it is the option to be implemented. Indeed, though entailing a conventional dimethyl ether production process, the CCS comparable scenario has a lower GWP (0.085 kg $CO_2$-eq for Italy and 0.071 kg $CO_2$-eq for Poland) than in the CCUS scenario (0.303 kg $CO_2$-eq and 0.236 kg $CO_2$-eq for Italy and Poland, respectively). This marked difference is mostly ascribable to renewable electricity replacing conventional fossil energy supply within the background processes. These results therefore suggest that, in terms of GWP, the considered amount of renewable electricity would perform better if employed within other processes rather than in CCUS.

As for the other categories, results from AD (45.16 MJ and 43.07 MJ for CCS and CCUS, respectively, in Italy, and 43.52 MJ and 40.98 MJ for CCS and CCUS, respectively, in Poland) are similar due to the small faction of the captured $CO_2$ used as feedstock in the CCUS scenario. AD is mostly driven by the increased amount of natural gas required when multiple energy-demanding units are added to the NGCC power plant, though dimethyl ether production contributes 5.9% and 6.39% in Italy and Poland within the CCS scenario and 1.68% and 1.34%, respectively, in the CCUS scenario. Similarly, ODP levels do not significantly differ between the CCS ($5.58 \times 10^{-7}$ kg CFC-11-eq for the Italian case and $4.46 \times 10^{-7}$ kg CFC-11-eq for the Polish case) and the CCUS ($5.58 \times 10^{-7}$ kg CFC-11-eq for the Italian case and $4.46 \times 10^{-7}$ kg CFC-11-eq for the Polish case) scenarios, being majorly influenced by the modified power plant configurations. The higher ODP in the CCS reference scenario with respect to CCUS scenarios is partially attributable to conventional dimethyl ether production, contributing 3.02% and 3.70% in Italy and Poland, respectively, in the former case. However, in the CCUS scenario, the burden of green dimethyl ether production is decreased to 1.2% and 0.6% in Italy and Poland, respectively. Though not extremely significant in absolute terms, ODP caused by green dimethyl ether production in the Italian case ($6.51 \times 10^{-9}$ kg CFC-11-eq) is more than doubled with respect to its counterpart in Poland ($2.57 \times 10^{-9}$ kg CFC-11-eq), mainly due to the higher share of photovoltaics in the Italian renewable electricity market.

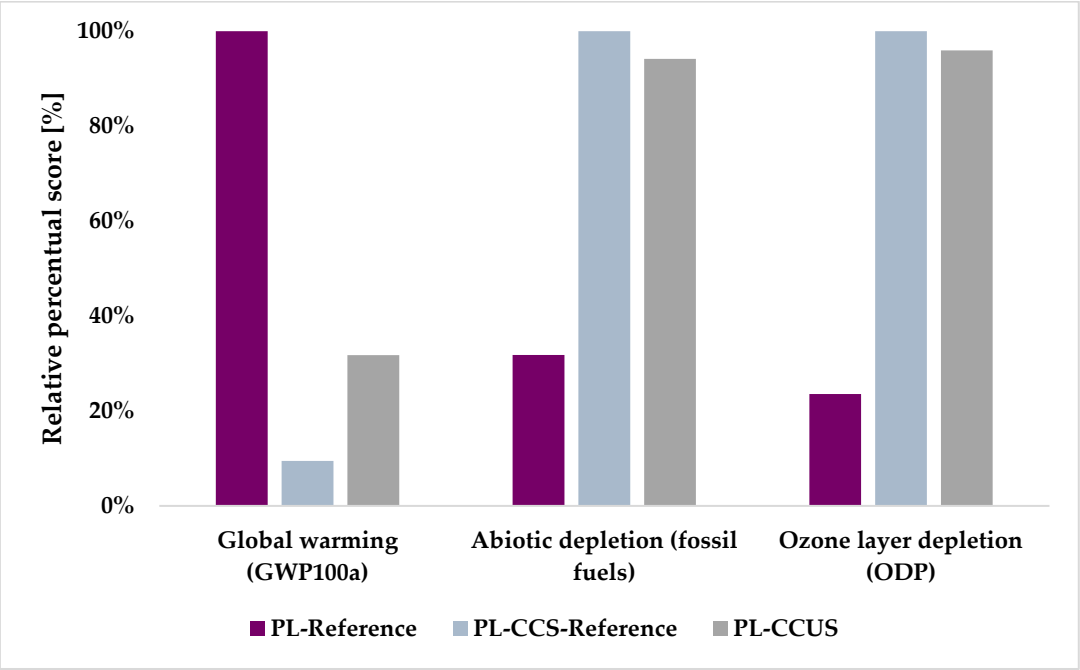


**Figure 8.** Impact category scores for the Polish case study in the CCUS scenario considering a comparable CCS reference scenario.

## 5. Conclusions

The implementation of both carbon capture and storage and carbon capture and utilization processes coupled with a natural gas combined cycle power plant was evaluated by means of life cycle assessment methodology. Due to the twofold nature of carbon dioxide as emission and feedstock within the carbon capture and utilization scenario, the system boundary of the reference case was expanded by creating a joint functional unit comprising both the produced electricity and the synthetized chemical (i.e., dimethyl ether). Each analysis was performed accounting for the characteristics of both Italy and Poland to obtain region-specific outcomes. Results from both scenarios confirm the crucial importance of evaluating climate-mitigating technologies from a wider perspective, thus avoiding the issue of burden shift. Indeed, though the Global Warming Potential drastically decreased in each investigated scenario, all the other categories showed an increase. The increase in abiotic depletion, eutrophication potential, acidification potential, and ozone depletion can be attributable to the higher requirement of natural gas to produce the same amount of electricity with and without carbon capture utilization and storage units. Therefore, an in-depth analysis aimed at optimizing the investigated configurations is required to evaluate the trade-offs between process requirements and environmental impacts. Moreover, results revealed the crucial role of the electricity produced from renewable sources as substituted within background processes, suggesting its spread could play a major role with respect to carbon capture and utilization processes. Nonetheless, further calculations and developments of the model should include a more detailed elaboration of the presented numerical model, entailing estimates of plant construction and transportation and storage issues.

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## Nomenclature

| | |
|---|---|
| AP | Acidification Potential |
| AD | Abiotic Depletion |
| CCS | Carbon Capture and Storage |
| CCU | Carbon Capture and Utilization |
| CCUS | Carbon Capture Utilization and Storage |
| GWP | Global Warming Potential |
| MDEA | Methyl Diethanolamine |
| MEA | Monoethanolamine |
| LCA | Life Cycle Assessment |
| NGCC | Natural Gas Combined Cycle |
| ODP | Ozone Depletion Potential |

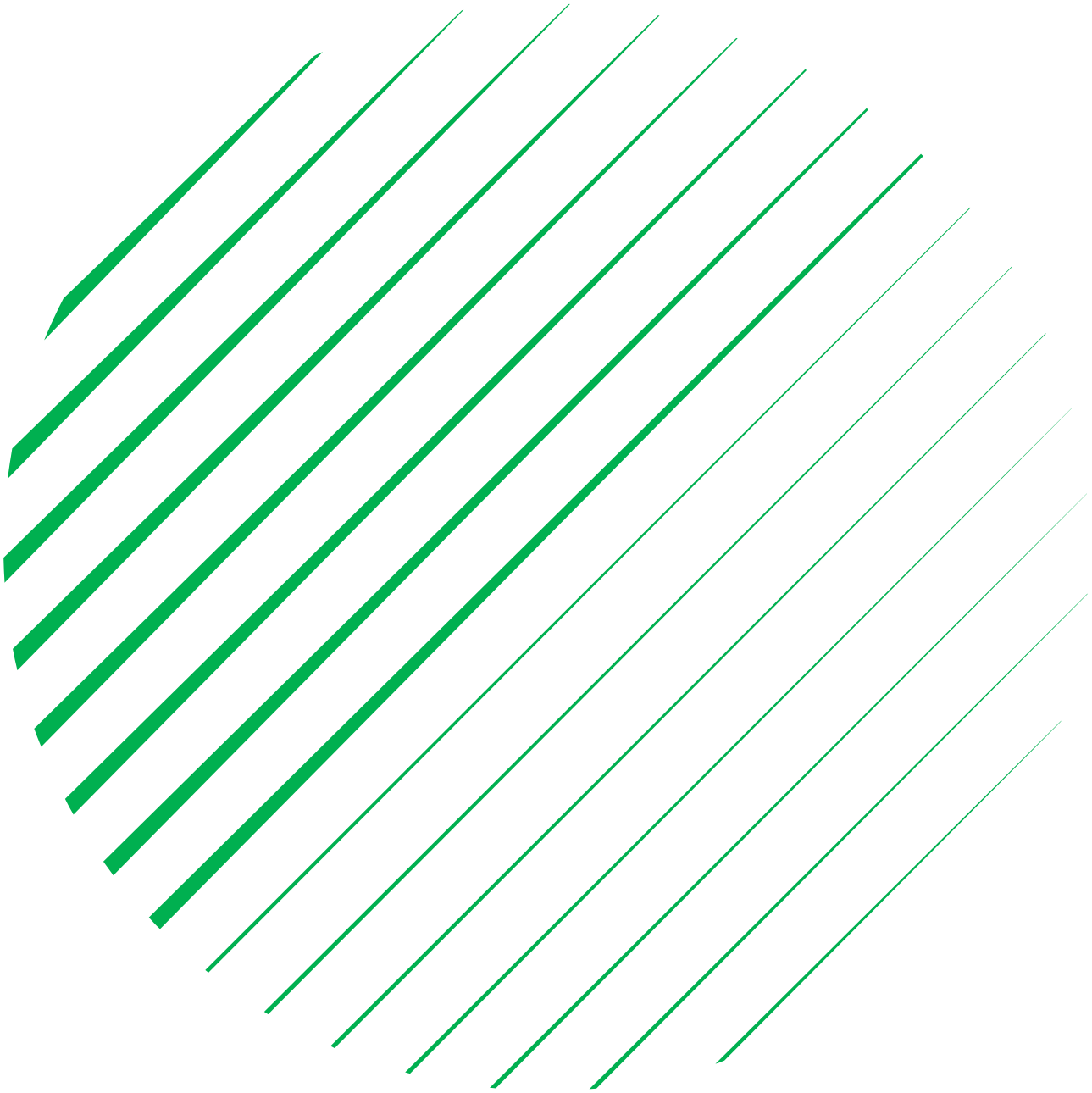
## References

1. European Commission. *Communication from the Commission to the European Parliament, the European Counclin, the Council, the European Economic and Social Committe and the Committe of the Regions 'European Green Deal'*; European Commission: Brussels, Belgium, 2019.
2. European Commission. *Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending REGULATIONS (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')*; European Commission: Brussels, Belgium, 2021.
3. United Nations Framework Convention on Climate Change (UNFCCC). The Paris Agreement. 2016. Available online: https://unfccc.int/documents/184656 (accessed on 5 August 2022).
4. European Commission. *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast)*; European Commission: Brussels, Belgium, 2018.
5. Dael, S.; Renders, N.; Nissen, C.; Förster, H.; Siemons, A.; Tomescu, M.; Sporer, M.; European Environment Agency. *Trends and Projections in Europe 2021*; EU Publications: Luxembourg, 2021. https://doi.org/10.2800/80374.
6. European Environment Agency. EEA Greenhouse Gases—Data Viewer, 13 April 2021. Available online: https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (accessed on 1 August 2022).
7. Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. https://doi.org/10.1016/J.ESR.2019.01.006.
8. Jäger-Waldau, A.; Kougias, I.; Taylor, N.; Thiel, C. How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030. *Renew. Sustain. Energy Rev.* **2020**, *126*, 109836. https://doi.org/10.1016/j.rser.2020.109836.
9. Rashidi, M.M.; Mahariq, I.; Murshid, N.; Wongwises, S.; Mahian, O.; Nazari, M.A. Applying wind energy as a clean source for reverse osmosis desalination: A comprehensive review. *Alex. Eng. J.* **2022**, *61*, 12977–12989. https://doi.org/10.1016/j.aej.2022.06.056.
10. Mohammad, N.; Ishak, W.W.M.; Mustapa, S.I.; Ayodele, B.V. Natural Gas as a Key Alternative Energy Source in Sustainable Renewable Energy Transition: A Mini Review. *Front. Energy Res*. **2021**, *9*, 625023. https://doi.org/10.3389/fenrg.2021.625023.
11. Eurostat. Natural Gas Supply Statistics. April 2022. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics#Consumption_trends (accessed on 23 July 2022).
12. Gas Factsheet. ACER. Available online: https://www.acer.europa.eu/gas-factsheet (accessed on 23 July 2022).
13. Greenfield, C. *Natural Gas-Fired Power*; IEA: Paris, France, 2021. Available online: https://www.iea.org/reports/natural-gas-fired-power (accessed on 23 July 2022).
14. Barbera, E.; Mio, A.; Pavan, A.M.; Bertucco, A.; Fermeglia, M. Fuelling power plants by natural gas: An analysis of energy efficiency, economical aspects and environmental footprint based on detailed process simulation of the whole carbon capture and storage system. *Energy Convers. Manag.* **2022**, *252*, 115072. https://doi.org/10.1016/j.enconman.2021.115072.
15. Bandilla, K.W. 31—Carbon Capture and Storage. In *Future Energy*, 3rd ed.; Letcher, T.M., Ed.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 669–692. https://doi.org/10.1016/B978-0-08-102886-5.00031-1.
16. International Energy Agency (IEA). CCUS in Clean Energy Transitions, Paris, 2021. Available online: www.iea.org/t&c/ (accessed on 20 July 2022).
17. Capocelli, M.; de Falco, M. Generalized penalties and standard efficiencies of carbon capture and storage processes. *Int. J. Energy Res.* **2022**, *46*, 4808–4824. https://doi.org/10.1002/er.7474.
18. Desideri, U.; Arcioni, L.; Tozzi, M. Feasibility study for a carbon capture and storage project in northern Italy. *Int. J. Energy Res.* **2008**, *32*, 1175–1183. https://doi.org/10.1002/er.1454.

19. Majchrzak-Kucęba, I.; Szymanek, P. CCU Technologies in the Green Economy. *Eng. Prot. Environ.* **2018**, *21*, 261–271. https://doi.org/10.17512/ios.2018.3.5.
20. Leonzio, G. State of art and perspectives about the production of methanol, dimethyl ether and syngas by carbon dioxide hydrogenation. *J. CO2 Util.* **2018**, *27*, 326–354. https://doi.org/10.1016/J.JCOU.2018.08.005.
21. Ma, J.; Li, Q.; Kühn, M.; Nakaten, N. Power-to-gas based subsurface energy storage: A review. *Renew. Sustain. Energy Rev.* **2018**, *97*, 478–496. https://doi.org/10.1016/J.RSER.2018.08.056.
22. Matzen, M.; Demirel, Y. Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life-cycle assessment. *J. Clean. Prod.* **2016**, *139*, 1068–1077. https://doi.org/10.1016/J.JCLEPRO.2016.08.163.
23. Catizzone, E.; Bonura, G.; Migliori, M.; Frusteri, F.; Giordano, G. $CO_2$ recycling to dimethyl ether: State-of-the-art and perspectives. *Molecules* **2018**, *23*, 31. https://doi.org/10.3390/MOLECULES23010031.
24. International Energy Agency (IEA). *About CCUS*; IEA: Paris, France, 2021. Available online: https://www.iea.org/reports/about-ccus (accessed on 5 August 2022).
25. Joint Research Centre (JRC). *International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment: Provisions and Action Steps*; Publication Office of the European Union: Luxembourg, 2013. https://doi.org/doi/10.2788/33030.
26. Guinée, J.B.; Heijungs, R.; Huppes, G.; Zamagni, A.; Masoni, P.; Buonamici, R.; Ekvall, T.; Rydberg, T. Life Cycle Assessment: Past, Present, and Future. *Environ. Sci. Technol.* **2011**, *45*, 90–96. https://doi.org/10.1021/es101316v.
27. Gargiulo, A.; Carvalho, M.L.; Girardi, P. Life Cycle Assessment of Italian Electricity Scenarios to 2030. *Energies* **2020**, *13*, 3852. https://doi.org/10.3390/en13153852.
28. Lelek, L.; Kulczycka, J.; Lewandowska, A.; Zarebska, J. Life cycle assessment of energy generation in Poland. *Int. J. Life Cycle Assess.* **2016**, *21*, 1–14. https://doi.org/10.1007/s11367-015-0979-3.
29. Barros, M.V.; Salvador, R.; Piekarski, C.M.; de Francisco, A.C.; Freire, F.M.C.S. Life cycle assessment of electricity generation: a review of the characteristics of existing literature. *Int. J. Life Cycle Assess.* **2020**, *25*, 36–54. https://doi.org/10.1007/s11367-019-01652-4.
30. Carvalho, M.L.; Marmiroli, B.; Girardi, P. Life cycle assessment of Italian electricity production and comparison with the European context. *Energy Rep.* **2022**, *8*, 561–568. https://doi.org/10.1016/j.egyr.2022.02.252.
31. Singh, B.; Strømman, A.H.; Hertwich, E. Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage. *Int. J. Greenh. Gas Control.* **2011**, *5*, 457–466. https://doi.org/10.1016/J.IJGGC.2010.03.006.
32. Volkart, K.; Bauer, C.; Boulet, C. Life cycle assessment of carbon capture and storage in power generation and industry in Europe. *Int. J. Greenh. Gas Control.* **2013**, *16*, 91–106. https://doi.org/10.1016/J.IJGGC.2013.03.003.
33. Lerner, A.; Brear, M.J.; Lacey, J.S.; Gordon, R.L.; Webley, P.A. Life cycle analysis (LCA) of low emission methanol and di-methyl ether (DME) derived from natural gas. *Fuel* **2018**, *220*, 871–878. https://doi.org/10.1016/j.fuel.2018.02.066.
34. Rosental, M.; Fröhlich, T.; Liebich, A. Life Cycle Assessment of Carbon Capture and Utilization for the Production of Large Volume Organic Chemicals. *Front. Clim.* **2020**, *2*, 586199. https://doi.org/10.3389/fclim.2020.586199.
35. Loiseau, E.; Aissani, L.; le Féon, S.; Laurent, F.; Cerceau, J.; Sala, S.; Roux, P. Territorial Life Cycle Assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. *J. Clean. Prod.* **2018**, *176*, 474–485. https://doi.org/10.1016/J.JCLEPRO.2017.12.169.
36. De Falco, M.; Natrella, G.; Capocelli, M.; Popielak, P.; Sołtysik, M.; Wawrzyńczak, D.; Majchrzak-Kucęba, I. Exergetic Analysis of DME Synthesis from $CO_2$ and Renewable Hydrogen. *Energies* **2022**, *15*, 3516. https://doi.org/10.3390/en15103516.
37. Ministeri dello Sviluppo Economico dell'Ambiente e della Tutela del Territorio e del Mare delle Infrastrutture e dei Trasporti. Piano Nazionale Integrato per l'Energia e il Clima. December 2019. Available online: https://www.mise.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf (accessed on 24 July 2022).
38. Eurostat. Renewable Energy Statistics. January 2022. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Share_of_renewable_energy_more_than_doubled_between_2004_and_2020 (accessed on 4 August 2022).
39. Bellocchi, S.; de Falco, M.; Gambini, M.; Manno, M.; Stilo, T.; Vellini, M. Opportunities for power-to-Gas and Power-to-liquid in $CO_2$-reduced energy scenarios: The Italian case. *Energy* **2019**, *175*, 847–861. https://doi.org/10.1016/J.ENERGY.2019.03.116.
40. International Energy Agency (IEA). *Poland 2022—Energy Policy Review*; IEA: Paris, France, May 2022. Available online: www.iea.org (accessed on 24 July 2022).
41. Ministry of Climate and Environment. Energy Policy of Poland until 2040, Warsaw, 2021. Available online: https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040 (accessed on 5 August 2022).
42. Polish Geological Institute. Mineral Resources of Poland, 2020. Available online: http://geoportal.pgi.gov.pl/surowce/energetyczne/ropa_naftowa/2020 (accessed on 5 August 2022).
43. Mathisen, A.; Skagestad, R. Utilization of $CO_2$ from Emitters in Poland for $CO_2$-EOR. *Energy Procedia* **2017**, *114*, 6721–6729. https://doi.org/10.1016/J.EGYPRO.2017.03.1802.
44. Kaiser, M.; Zimmer, R.; Brunsting, S.; Mastop, J.; Pol, M. Development of CCS Projects in Poland. How to Communicate with the Local Public? *Energy Procedia* **2014**, *51*, 267–273. https://doi.org/10.1016/J.EGYPRO.2014.07.031.
45. *ISO 14040:2006(en)*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO—The International Organization for Standardization: Geneva, Switzerland, 2006.
46. *ISO 14044:2006(en)*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO—The International Organization for Standardization: Geneva, Switzerland, 2006.

47. Müller, L.J.; Kätelhön, A.; Bachmann, M.; Zimmermann, A.; Sternberg, A.; Bardow, A. A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. *Front. Energy Res.* **2020**, *8*, 15. https://doi.org/10.3389/fenrg.2020.00015.
48. Von der Assen, N.; Jung, J.; Bardow, A. Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls. *Energy Environ. Sci.* **2013**, *6*, 2721–2734. https://doi.org/10.1039/C3EE41151F.
49. Heijungs, R.; Allacker, K.; Benetto, E.; Brandão, M.; Guinée, J.; Schaubroeck, S.; Schaubroeck, T.; Zamagni, A. System Expansion and Substitution in LCA: A Lost Opportunity of ISO 14044 Amendment 2. *Front. Sustain.* **2021**, *2*, 692055. https://doi.org/10.3389/frsus.2021.692055.
50. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
51. Zoelle, A.; Keairns, D.; Pinkerton, L.L.; Turner, M.J.; Woods, M.; Kuehn, N.; Shah, V.; Chou, V. *Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3*; Technical Report DOE/NETL-2015/1723; Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2015. https://doi.org/10.2172/1480987.
52. Snam. Transportation Network. 2022. Available online: https://www.snam.it/en/about-us/snam-infrastructures/the-transportation-network/ (accessed on 5 August 2022).
53. International Energy Agency (IEA). Poland Natural Gas Security Policy. 30 June 2022. Available online: https://www.iea.org/articles/poland-natural-gas-security-policy (accessed on 4 August 2022).
54. Ministero della Transizione Ecologica. Analisi e Statistiche Energetiche e Minerarie. Gas Naturale. 2022. Available online: https://dgsaie.mise.gov.it/importazioni-gas-naturale (accessed on 4 August 2022).
55. Cetinkaya, E.; Dincer, I.; Naterer, G.F. Life cycle assessment of various hydrogen production methods. *Int. J. Hydrogen Energy* **2012**, *37*, 2071–2080. https://doi.org/10.1016/j.ijhydene.2011.10.064.
56. Simons, A.; Bauer, C. Life cycle assessment of hydrogen production. In *Transition to Hydrogen: Pathways toward Clean Transportation*; Wokaun, A., Wilhelm, E., Eds.; Cambridge University Press: Cambridge, UK, 2011; pp. 13–57. https://doi.org/10.1017/CBO9781139018036.006.
57. Vidas, L.; Castro, R. Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis. *Appl. Sci.* **2021**, *11*, 1363. https://doi.org/10.3390/app112311363.
58. International Renewable Energy Agency. Green Hydrogen Cost Reduction: Scaling Up Electrolyseres to Meet The 1.5 °C Climate Goal. 2020. Available online: www.irena.org/publications (accessed on 25 July 2022).
59. Koj, J.C.; Wulf, C.; Schreiber, A.; Zapp, P. Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis. *Energies* **2017**, *10*, 860. https://doi.org/10.3390/en10070860.
60. Kanz, O.; Bittkau, K.; Ding, K.; Rau, U.; Reinders, A. Review and Harmonization of the Life-Cycle Global Warming Impact of PV-Powered Hydrogen Production by Electrolysis. *Front. Electron.* **2021**, *2*, 711103. https://doi.org/10.3389/felec.2021.711103.
61. de Falco, M.; Capocelli, M.; Giannattasio, A. Membrane Reactor for one-step DME synthesis process: Industrial plant simulation and optimization. *J. CO2 Util.* **2017**, *22*, 33–43. https://doi.org/10.1016/J.JCOU.2017.09.008.
62. Mota, N.; Ordoñez, E.M.; Pawelec, B.; Fierro, J.L.G.; Navarro, R.M. Direct Synthesis of Dimethyl Ether from $CO_2$: Recent Advances in Bifunctional/Hybrid Catalytic Systems. *Catalysts* **2021**, *11*, 411. https://doi.org/10.3390/catal11040411.
63. Bonura, G.; Todaro, S.; Frusteri, L.; Majchrzak-Kucęba, I.; Wawrzyńczak, D.; Pászti, Z.; Tálas, E.; Tompos, A.; Ferenc, L.; Solt, H.; et al. Inside the reaction mechanism of direct $CO_2$ conversion to DME over zeolite-based hybrid catalysts. *Appl. Catal. B* **2021**, *294*, 120255. https://doi.org/10.1016/J.APCATB.2021.120255.
64. Eurostat. Energy Balances April 2022 Edition, April 2022. Available online: https://ec.europa.eu/eurostat/web/energy/data/energy-balances/ (accessed on 4 August 2022).
65. Terna. Dati Statistici Sull'energia Elettrica in Italia, 2020. Available online: https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche (accessed on 18 July 2022).
66. Raadal, H.L.; Modahl, I.S. *Life Cycle Assessment of CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilization)*; NORSUS: Kråkerøy, Norway, 2021.
67. Skone, T.J.; Schivley, G.; Jamieson, M.; Marriott, J.; Cooney, G.; Littlefield, J.; Mutchek, M.; Krynock, M.; Shih, C.Y. *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power* Plants; Technical Report DOE/NETL-2018/1890; Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2018. https://doi.org/10.2172/1562914.
68. EC-JRC. ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European Context. 2011. Available online: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-Recommendations-for-Life-Cycle-Impact-Assessment-in-the-European-context.pdf (accessed on 25 July 2022).

# Chapter 9 General conclusions



The power sector is one of the main industry sectors under enormous pressure of change. Worldwide agreements on environmental protection (i.e. Kyoto Agreement, Paris Agreement, Montreal Agreement) as well as regional (i.e. European Green Deal for the European Union, EPP2040 for Poland, Energiewende for Germany, Carbon Budget for the United Kingdom) forcing the industry to turn into environmental-friendly technologies, to reduce their environmental footprint, to become less and less pollutant and take more share in the circular economy idea. However the question is – **are we able to measure and benchmark CCUS technologies – and if yes, then how?** How industry and policymakers can prove environmentally friendly technologies and at the same time avoid greenwashing? Can state-of-the-art CCUS technologies leverage emissions reduction to desirable levels?

There is a possibility to tackle those questions and provide measurable results with the Life Cycle Assessment analysis. This analysis, as was proved in this doctoral thesis (**Chapter 6-8, P2 – P4**), is a valuable tool to resolve issue of evaluating and benchmarking environmental impacts of any process, product or technology i.e., CCUS supply chain. Several analyses have been conducted using the LCA analysis for carbon capture utilization and storage of carbon dioxide - the most important greenhouse gas - **and the results in P2-P4 demonstrate the numerous environmental benefits of CCUS technology in the power generation (P1-P4) and cement industry (P3).**

Furthermore, **it was proved in P2-P4, that industry, represented by power and cement sector, can have environmental benefits from applying CCUS supply chain by lowering their environmental impact, meaning steps towards decarbonization process**.

Additionally, Poland as the EU's state member and a signatory of the European Green Deal, is obliged to make every effort to achieve climate neutrality by 2050. The CCUS technology assumptions are part of the energy transition and the deep decarbonization not only of the energy sector but also of the industrial sector, which has a smaller range of low-carbon technologies than the energy sector. The performed research fulfilled a missing area of knowledge focused on the transformation possibilities of the specific Polish energy market.

Nevertheless, the conducted research will contribute to the development of the knowledge base on CCUS technologies and their potential as a tool for reducing GHG emissions. This research will be valuable for policymakers, regulators, and other stakeholders involved in the development and deployment of CCUS technologies, as well as for researchers working on related topics.

Additionally, it is important to make CCUS technology attractive to the technology market. It is estimated that more than 26% of CCS projects have been abandoned or delayed for economic reasons (Global CCS Institute 2016). There are numerous fields in industry where CCUS can be applied, but the price of the technology is a bottleneck to its extensive implementation (**P1**).

The main goals of the CCUS technology is to reduce environmental impacts, re-use captured $CO_2$ as a feedstock (while in non-CCUS scenario $CO_2$ will be emitted to the environment) and leverage the decarbonization process for industries that are difficult to decarbonize i.e., cement industry. Cement industry is also very specific case, as CCUS seems to be the last opportunity for decarbonization for this branch of industry sectors.

In the case study no 1 (**P2**) it was investigated and proved, that according to CML v4.8 2016 midpoint the GWP100 indicator for power plant with CCS supply chain can be reduced by around 28.6% in comparison to facility without CCS applied. On the other hand, even if GWP100 was reduced, that was the only one indicator affected by this, as other of chosen indicators increased in CCS scenario (Acidification Potential: +81%, Abiotic Depletion Potential for fossil fuels: +79%, Ozone Layer Depletion: +80%). This situation can occur due to: (1) increased amount of resources needed for make-up efficiency losses in power plant with carbon capture unit, (2) increased amount of resources needed for carbon capture process itself, (3) additional energy needed for compression of $CO_2$ to transport and underground storage.

In the second case study (**P3**) the main goal was to compare two different facilities: power plant and cement plant – both with applied CCUS supply chain, to evaluate possible environmental benefits in both scenarios. To make comparison possible an atypical functional unit was selected and it was one hour of operation of each unit. According to selected LCIA method: ILCD 2011, midpoint [v1.0.10, August 2016], the

hourly production of DME from cement plant was almost 25% higher than from power plant, as the carbon capture unit applied in cement plant has higher efficiency of 45 percentage points. Nonetheless, the calculations indicated that the amount of $CO_2$ emitted into the atmosphere in the chain for the power plant fell by 51.7% and for the cement plant by 36.1%. This $CO_2$ that was converted at the end of the CCUS chain into DME or carbonated concrete can be treated as avoided emissions. Therefore, there are measurable environmental benefits from applying CCUS supply chain in cement plant and power plant. Lastly, the atypical functional unit used in this case study made it possible to compare the two facilities. Although to make a full environmental comprehensive analysis, it would be advisable to undertake a further analysis, using system expansion, substitution or allocation (as subdivision is inapplicable to CCUS models) to create different CCUS scenarios as it had place in third case study (**P4**).

In the third case study, a comparative analysis showed that the use of CCS technology for natural gas power plants has a significantly more favourable environmental impact than the use of CCUS technology. In the first considered scenario of the power plant with and without CCS supply chain, the reduction in GWP100 was 89% for Italy (from 0.715 kg $CO_2$-eq kWh-1 reduced to 0.076 kg $CO_2$-eq kWh-1) and was 97% for Poland (from 0.695 kg $CO_2$-eq kWh-1 to 0.021 kg $CO_2$-eq kWh-1). However, as discussed in **Chapter 2** and **Chapter 5**, as well as in publications **P2-P4**, the environmental benefits of CCS technologies should not be assessed by one indicator alone. Thus, for the other indicators, there was an increase in: AP (Italy: +94%, Poland: +84%), EP (Italy: +93%, Poland: +101%), and ODP (Italy: +76%, Poland: +79%).

On the other hand, for the second scenario, where the CCUS supply chain was considered, the GWP100 reduction is lower compared to the CCS scenario and is ~58% and ~68% in Italy and Poland, respectively. In the reference scenario, electricity and DME production account for 0.723 kg $CO_2$-eq (Italy) and 0.745 kg $CO_2$-eq (Poland); in addition, in both countries, renewable electricity contributes 0.053 kg $CO_2$-eq in Italy and 0.024 kg $CO_2$-eq in Poland. Although, for the CCUS supply chain implemented, the GWP100 are reduced to 0.303 kg $CO_2$-eq. for Italy and 0.236 kg $CO_2$-eq. for Poland. Additionally, in the case studied, dimethyl ether production from $CO_2$ hydrogenation accounts for 26.95% of GWP100 indicator for Italy and 28.32% of

GWP100 indicator for Poland. In parallel to the CCS scenario, all the other investigated impact categories showed increase: AD +67% for Italy, +66% for Poland, ODP +74% for Italy and +75% for Poland. Overall, the increase in the AD rate is mainly due to the increased amount of natural gas required following the addition of many energy-intensive units to NGCC power plants. Although it should be mentioned that in the CCS scenario, DME production contributes 5.9% to AD in Italy and 6.39% in Poland, and for the CCUS scenario these values are 1.68% and 1.34% for Italy and Poland respectively. Similarly, the ODP levels do not differ significantly between the CCS (5.58E-07 kg CFC-11-eq for the Italian case and 4.46E-07 kg CFC-11-eq for the Polish case) and CCUS (5.58E-07 kg CFC-11-eq for the Italian case and 4.46E-07 kg CFC-11-eq for the Polish case) scenarios, mainly influenced by the modified power plant configurations. The higher ODP indicator in the CCS reference scenario in comparison to the CCUS scenarios can be partly attributed to conventional DME production, accounting for 3.02% in Italy and 3.70% in Poland. On the other hand, for CCUS scenario this indicator for production of green DME decreases to 1.2% and 0.6% in Italy and Poland, respectively. Although in quantitative terms, the ODP indicator for green DME production in Italy (6.51E-09 kg CFC-11-eq) is more than twice as high as in Poland (2.57E-09 kg CFC-11-eq), mainly due to the higher share of photovoltaics in the Italian renewable electricity market. Lastly, a variety of environmental trade-offs have also been identified in (**P4**), with all examined categories except GWP showing an increase. Admittedly, the high energy demand of CCUS processes severely affects overall plant efficiency, with increased demand for fossil fuels leading to various load shifts across the value chain studied.

Indeed, as the research (**P2-P4**) has shown, there is potential to decarbonise the power and cement industries (by reducing the GWP100 indicator), although this comes at the expense of environmental trade-offs. Additionally, from LCA perspective there might be some visible in numbers benefits, however from methodology point of view, the $CO_2$ sequestrated in products such as a fuel or chemicals, makes very little difference for environment as it will not be stored permanently, only temporary. Furthermore, carbon capture part of supply chain is very high energy demanding process, which generates additional burden for resource use (as proved in **Chapter 6-8, P2-P4**). Therefore, CCS might have slight upper hand over CCU technology from LCA perspective.

# Abbreviations

ADP - Abiotic Depletion Potential

AP - Acidification Potential

CCUS - Carbon Capture Utilization and Storage

CFB - circulating fluidized bed

CRF - Common Reporting Format

ECBM - Enhanced Coal Bed Methane Recovery

EU-ETS - European Union Emission Trading System

LULUCF - Land Use, Land Use Change, and Forestry

NGCC - natural gas combined cycle

OTSC - once through supercritical technology

ODP - Ozone Depletion Potential

BAT - Best Available Technique

CCS - Carbon Capture and Storage

CHP - Combined Heat and Power

DAC - Direct Air Capture

DR-VPSA - Dual-Reflux Vacuum Pressure Swing Adsorption

EPP 2040 - Energy Policy of Poland until 2040

EEA - Environmental Energy Agency

EGD - European Green Deal

EU - European Union

GWP - Global Warming Potential

GHG - Greenhouse Gases

IEA - International Energy Agency

IPCC - International Panel on Climate Change

ISO - International Standards Organization

LCA - Life Cycle Assessment

LCIA - Life Cycle Impact Assessment

LCI - Life Cycle Inventory

LHV - Lower Heating Value

PC - pulverized coal-fired boiler

KOBiZE - the National Centre for Emission Management

MLC DB – Managed Life Cycle Assessment Content Database

TES -Total Energy Supply

USB - Upper Silesia Basin

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# Exergetic Analysis of DME Synthesis from $CO_2$ and Renewable Hydrogen

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**Abstract:** Carbon Capture and Utilization (CCU) is a viable solution to valorise the $CO_2$ captured from industrial plants' flue gas, thus avoiding emitting it and synthesizing products with high added value. On the other hand, using $CO_2$ as a reactant in chemical processes is a challenging task, and a rigorous analysis of the performance is needed to evaluate the real impact of CCU technologies in terms of efficiency and environmental footprint. In this paper, the energetic performance of a DME and methanol synthesis process fed by 25% of the $CO_2$ captured from a natural gas combined cycle (NGCC) power plant and by the green hydrogen produced through an electrolyser was evaluated. The remaining 75% of the $CO_2$ was compressed and stored underground. The process was assessed by means of an exergetic analysis and compared to post-combustion Carbon Capture and Storage (CCS), where 100% of the $CO_2$ captured was stored underground. Through the exergy analysis, the quality degradation of energy was quantified, and the sources of irreversibility were detected. The carbon-emitting source was a 189 MW Brayton–Joule power plant, which was mainly responsible for exergy destruction. The CCU configuration showed a higher exergy efficiency than the CCS, but higher exergy destruction per non-emitted carbon dioxide. In the DME/methanol production plant, the main contribution to exergy destruction was given by the distillation column separating the reactor outlet stream and, in particular, the top-stage condenser was found to be the component with the highest irreversibility (45% of the total). Additionally, the methanol/DME synthesis reactor destroyed a significant amount of exergy (24%). Globally, DME/methanol synthesis from $CO_2$ and green hydrogen is feasible from an exergetic point of view, with 2.276 MJ of energy gained per 1 MJ of exergy destroyed.

**Keywords:** carbon capture and utilization; methanol and DME production; exergy analysis

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## 1. Introduction

Climate change mitigation is a worldwide effort that involves all countries around the world. Among all problems, greenhouse gas (GHG) emissions have a significant impact on the environment. Regarding this matter, the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Climate Change Conference have established the needs of reducing $CO_2$ emissions (recognized as the gas mainly responsible for climate change) and mitigating the global average temperature increase. Targets were set up, proposals to reach them were provided, and some technologies were identified as a solution in counteracting this issue.

The extensive concentration of carbon dioxide in the atmosphere is a threat to environmental safety, contributing to the greenhouse effect, but $CO_2$ is a source of carbon for plants and can also be used as a reactant in chemical reactions [1–3]. This concept has led to the development of Carbon Capture and Utilization (CCU) technologies, which are perceived as a more justified and socially acceptable technology for $CO_2$ management than Carbon Capture and Storage (CCS). However, even if they can be considered a feasible solution, their cost is still an issue. Hasan et al. proposed a national Carbon Capture Utilization and Storage (CCUS) supply chain network for a U.S. case study in their multiscale framework analysis [4]. With the proposed solution focused on profit rather than maximizing $CO_2$ utilization, average profits between \$0.3 and \$17.6 per ton of $CO_2$ were achieved (depending on the weighted average total costs of capturing and utilizing a ton of $CO_2$).

There are plenty of ways to apply CCU technology wherever there is a $CO_2$-emitting source, e.g., energy-intensive industry branches, such as energy, petrochemical and cement or iron and steel production. Additionally, CCU reactions can be supported with green technologies, such as renewable energy sources (RES).

The first step in a CCU process is the capturing of $CO_2$ through well-known technologies, such as oxyfuel combustion, pre-combustion or post-combustion, or as a direct-air capture process [5,6]. Post-combustion carbon capture can be achieved by physical or chemical separation methods, such as membranes, adsorption, absorption and cryogenic processes. Many of these technologies are already applied in industry [7]. Pre-combustion processes capture $CO_2$ prior to the combustion reaction and it can be achieved with the coal gasification process or with oil or gas fuel-reforming processes [8].

After having captured and concentrated the $CO_2$, it can be fed to a chemical reactor for its conversion into products, such as syngas, urea, methane, ethanol, formic acid, etc. This paper is focused on the analysis of configurations to synthesize methanol and dimethyl ether (DME) from $CO_2$.

Dimethyl ether (DME) or methoxymethane is the simplest aliphatic ether with the molecular formula $CH_3OCH_3$. It is a colourless, near-odourless gas under ambient conditions. It is neither a toxic nor carcinogenic compound, with properties similar to liquid petroleum gas (LPG); thus, it can be easily blended with it and used as a fuel [9–11]. In the chemical industry, it is mainly used to produce diethyl sulphate, methyl acetate, light olefins and gasoline [12]. Nowadays, it is considered an alternative fuel with low emissions of NOx, hydrocarbons and carbon monoxide [2,13]. DME can be obtained in two ways: direct synthesis and through the methanol dehydration process. The first method's reactions are:

$$CO + 2H_2 \rightleftarrows CH_3OH \quad (1)$$

$$2CH_3OH \rightleftarrows CH_3OCH_3 + H_2O \quad (2)$$

$$H_2O + CO \rightleftarrows H_2 + CO_2 \quad (3)$$

The process of direct DME synthesis is exothermic (c.a. 246.2 kJ/mol DME); therefore, the heat produced during the reactions has to be removed. The inlet reactant mixture is composed of CO and $H_2$.

Methanol dehydration to produce DME is also an exothermic process. $CO_2$ can be used to produce methanol and then dehydrate it to DME. This has been proven to be a very economical way of utilizing carbon dioxide [2,14,15]. The chemical reactions occurring during the process are presented below:

Methanol formation

$$CO_2 + 3H_2 \rightleftarrows CH_3OH + H_2O \quad (4)$$

Methanol dehydration

$$2CH_3OH \rightleftarrows CH_3OCH_3 + H_2O \quad (5)$$

Reverse water–gas shift (rWGS)

$$CO_2 + H_2 \rightleftarrows CO + H_2O \quad (6)$$

Net reaction

$$2CO_2 + 6H_2 \rightleftarrows CH_3OCH_3 + 3H_2O \quad (7)$$

In Ref. [16], the authors explored the profitability of DME production from biogas; in Ref. [17], a techno-economic assessment of bio-DME and bio-methanol production from oil palm residue was proposed. Methanol is a colourless, flammable liquid under ambient conditions with a characteristic odour. As one of the most important raw materials, it is a substrate in many syntheses of chemical compounds, including formaldehyde, acetic acid and chloromethane. It is also a very good solvent and it is easily miscible with water, alcohols and organic solvents. Due to its wide application in many industries (fuel, chemical and other industries), the demand for methanol is constantly growing, i.e., from 47 Mt/a in 2011 [18] to 100 Mt/a in 2021 [19]. According to the report made by the International Renewable Energy Agency [19], in 2021, only 0.2% of global production of methanol came from renewable sources—more than 60% was converted by natural gas reformation and the rest was produced by natural coal gasification.

Methanol can be synthesized from a gas containing either carbon monoxide or carbon dioxide when it reacts with hydrogen:

$$CO_2 + 3H_2 \rightleftarrows CH_3OH + H_2O \quad (8)$$

$$CO + 2H_2 \rightleftarrows CH_3OH \quad (9)$$

The main properties of DME and methanol in comparison with LNG and diesel oil are shown in Table 1. Moreover, several potential major applications of DME and methanol are shown below in Figures 1 and 2.

**Table 1.** Properties of DME and methanol compared with other fuels.

| Properties | DME [20] | Methanol [18] | Methane * [21] | Diesel Fuel [22,23] |
|---|---|---|---|---|
| Molecular formula | $C_2H_6O$ | $CH_3OH$ | $CH_4$ | — |
| CAS Number | 115-10-6 | 67-58-1 | 74-82-8 | 68334-30-5 |
| Molar mass (g/mol) | 46.07 | 32.04 | 16.04 | — |
| Cetane number ** | 55 to 60 | ~5 | 0 | 40 to 55 |
| Melting point (°C) | −141 | −97.88 | −182.47 | −40 |
| Boiling point (°C) at 1 atm | −24.8 | 64.65 | −161.5 | 141 |
| Density at 25 °C and 1 atm (kg/m$^3$) | 668.3 | 786.68 | 0.657 | 800–910 |
| Autoignition temperature (°C) | 235 | 440 | 537 | 250 |
| Miscible with water? | Yes | Yes | Yes | No |
| Miscible with organic solvents? *** | Yes | Yes | Yes | Yes |

* Methane as main part of Liquid Natural Gas (LNG), ** average value, *** with most popular polar and nonpolar organic solvents.

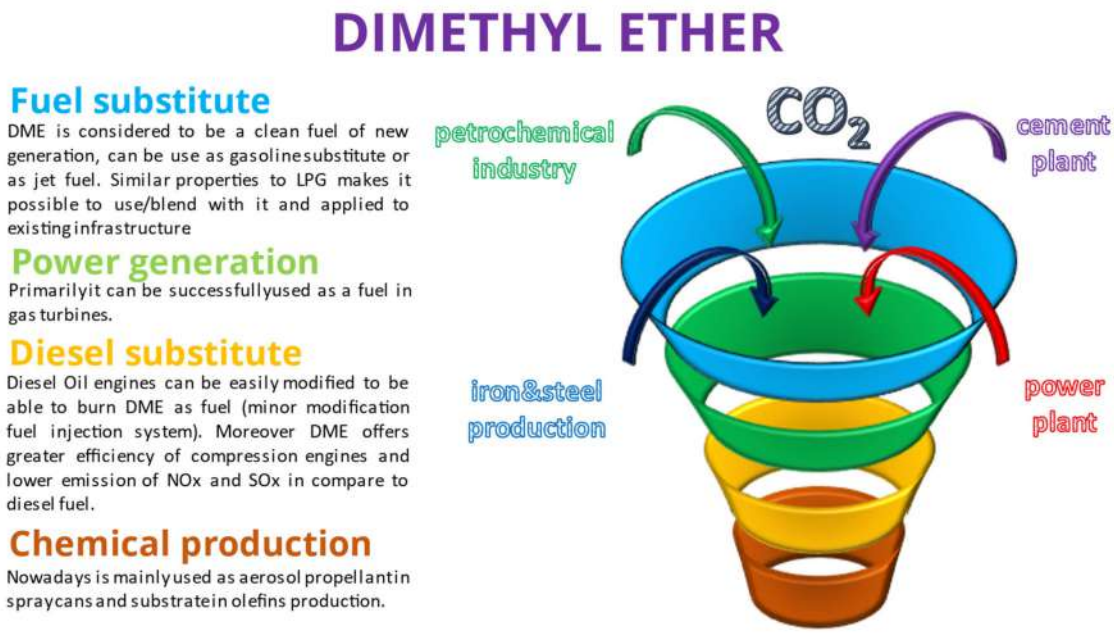



**Figure 1.** Applications of DME [20,24].

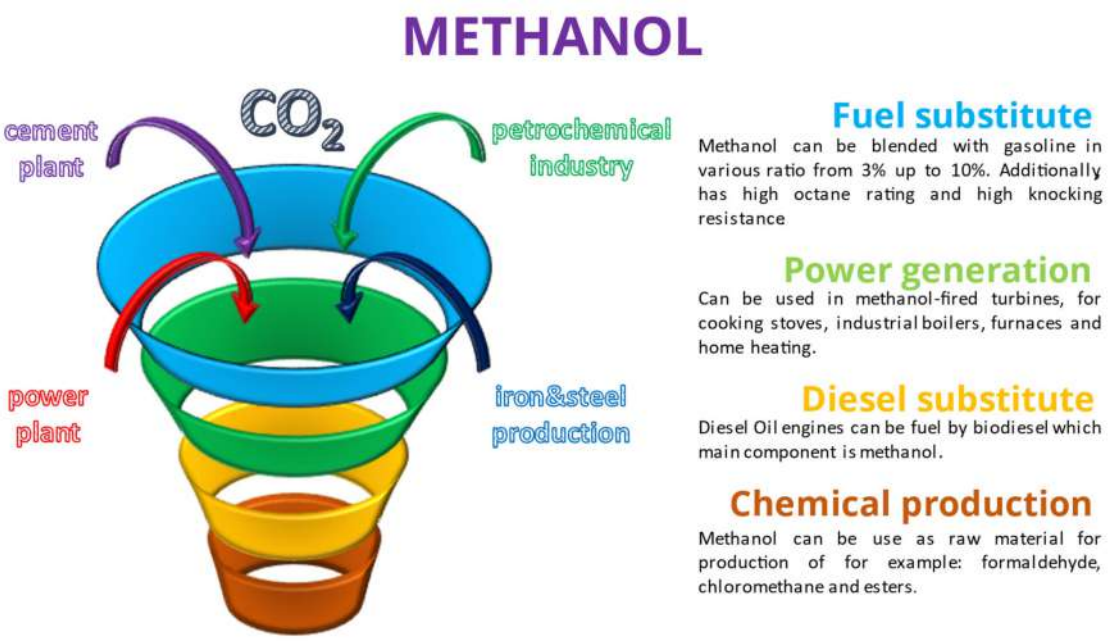



**Figure 2.** Applications of methanol [18,19,25].

*State-of-the-Art Production of DME/Methanol from Green Hydrogen and $CO_2$*

Converting $CO_2$ into DME requires an energy input in the form of hydrogen, as shown in Equations (1)–(9). In order to meet the goal of reducing carbon emissions, green hydrogen is needed [1,5,26,27].

Hydrogen can be synthesized in different ways: chemical, biological, catalytic, electrochemical and thermal. To reduce the carbon footprint of the CCU process, a low-emission hydrogen production technology has to be applied. Among several possible approaches, the production of "green hydrogen" using an electrolyser powered by a renewable energy source is the most interesting [28,29].

Barbato et al. [24] presented a process for carbon dioxide conversion to green methanol where $CO_2$ captured from a power plant was combined with hydrogen from an electrolyser

powered by hydropower energy. In the calculations and conclusions, the price (with cost calculations at the prevailing rate) of methanol production resulted to be 294 €/ton and it was successfully reduced by 20% compared to the price of methanol produced traditionally.

While there are a number of pilot or demonstration-scale facilities, there are a few commercial units producing either DME or methanol on an industrial scale. Regarding existing facilities with a power plant as a carbon dioxide source, two projects developed in Germany can be taken into consideration.

The first was funded by Europe's Horizon 2020 program (Mef$CO_2$, Project No. 637016). Nine partners established in 2014 an international cooperation to research the feasibility of CCU technology along with the production of green methanol. The main aims of the project were to demonstrate the economic feasibility of utilizing captured $CO_2$ by converting it into a usable fuel, such as methanol, and further providing green hydrogen produced from excess energy from renewable sources. The source of carbon dioxide was a lignite-fired power plant located in Niederaussem, Germany. The project ended in 2019 with the development of one of the largest facilities in the European Union to synthesize methanol from $CO_2$ from flue gases, capable of producing 1 ton of methanol per day while capturing more than 1.5 tons of carbon dioxide per day [30–37].

Carbon Recycling International Ltd. (CRI, Reykjavik, Iceland), known for producing renewable methanol since 2007, participated in this project. CRI's pilot unit is located near Iceland's capital—Reykjavik. Industrial-scale green methanol production began in 2012 in the first pilot plant with an annual capacity of about 4000 tonnes of methanol (c.a. 12 t/d). The process is based on the conversion of $CO_2$ from geothermal sources with the hydrogen produced by water electrolysis using geothermal energy [1,36,38]. The methanol produced in this facility is used in a number of applications, including blending with gasoline, biodiesel production, and wastewater denitrification. Additionally, the CRI methanol production process reduces the environmental impact by 90% compared to conventional methods [19]. Furthermore, CRI, in cooperation with China Henan Shuncheng Group, developed in 2021 the world's first green methanol plant with a capacity of 110,000 tons per year [39].

The ALIGN-CCUS (Project No 271501) demonstration plant is also located at Niederaussem, Germany. The project was funded through the ERA-NET ACT program and it was co-funded by the European Commission under the Horizon 2020 program ACT [40]. The source of the captured $CO_2$ is a 1000 MW power plant unit, and the hydrogen comes from a 140 kWel alkaline electrolyser providing 22 kg of hydrogen per day. The daily production of DME is about 50 kg. For DME synthesis, a Mitsubishi Power bifunctional catalyst was used, which was responsible for both methanol synthesis and the dehydration process [41].

In this paper, we evaluate the energetic performance of a DME and methanol synthesis process fuelled by the $CO_2$ captured from a natural gas combined cycle (NGCC) power plant and by the green hydrogen produced using an electrolyser (alkaline). The process configuration performance is assessed by means of an exergetic analysis and compared to a post-combustion CCS. Through exergy, these two different processes can be evaluated [42–44], assessing the quality degradation of energy and individuating sources of irreversibility.

The post-combustion CCS is a common basis to compare new strategies to avoid carbon emissions. Olaleye et al. deeply discussed post-combustion carbon capture from a coal-fired power plant [45,46].

Blumbert et al. presented an NG-based low-pressure synthesis process for the production of methanol with $CO_2$ utilization [47]. In their paper, the authors conducted an extended exergy analysis dividing the methanol production plant into various subsystems and evaluated the performance of each of them. Nakyai et al. [48] conducted an energy and exergy analysis of the DME production from CO and $CO_2$ in a single-stage process. Farooqui et al. [49] evaluated from an energetic and an exergetic point of view a poly-generation plant with oxyfuel carbon capture for combined power and DME production. In our paper, we proposed a new configuration for DME and methanol production in a

single-stage process, in which a 90% $CO_2$ conversion rate was achieved. We compared this process with post-combustion CCS and evaluated all of the chain from the NGCC power plant to the DME and methanol production. Through the exergetic analysis, we spotted the irreversibilities, calculated the conventional performance indicators [45–47] and defined new performance indicators to assess the goodness of our configuration with respect to energy transformation and exergy destruction.

The proposed configuration is described in Section 2. Section 3 introduces the adopted methodology and the process assumptions that were made. Section 4 presents the results of the exergy analysis and Section 5 gathers the main conclusions of the work.

## 2. Systems Description

In this section, the proposed system to reduce carbon emissions and to produce valuable products, such as DME and methanol, is described (Figure 3). The carbon dioxide-emitting source is a natural gas combined cycle (NGCC) power plant whose flue gas is washed with an MDEA water solution to capture the $CO_2$ (refer to Section 2.1). The recovered carbon dioxide is partly stored underground and partly converted into DME and methanol, reported in Sections 2.2 and 2.3, respectively.

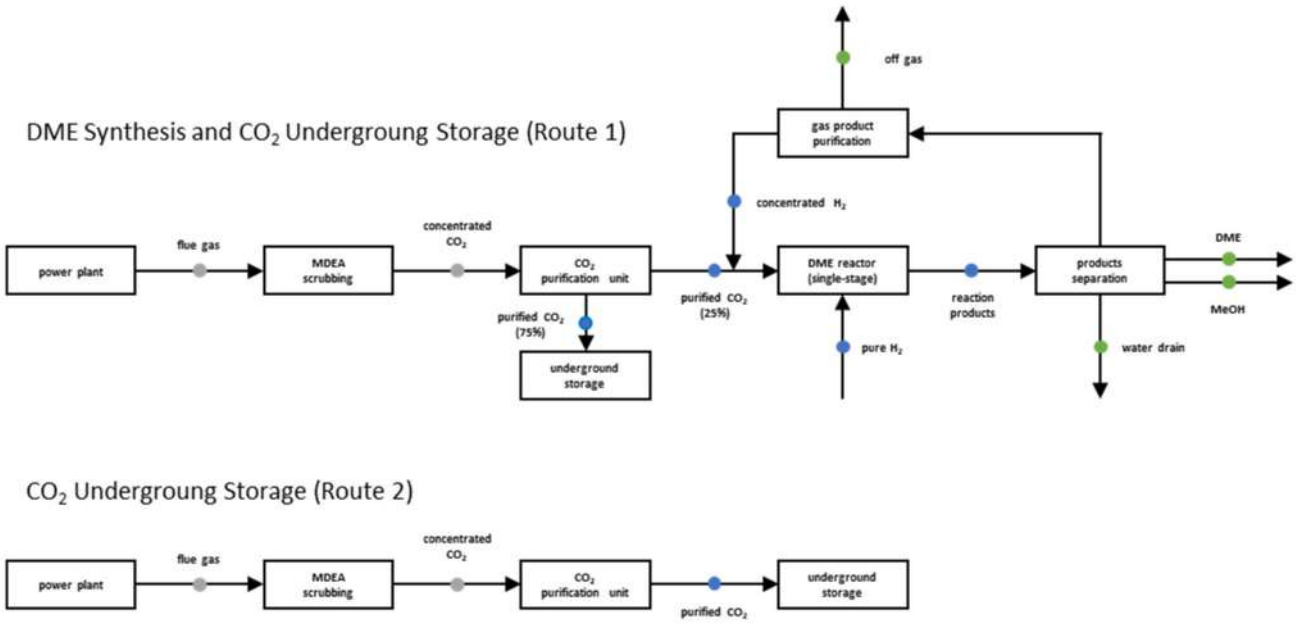



**Figure 3.** Configuration of the proposed solution (**top**) and of the comparison basis.

### *2.1. Power Plant and Post Combustion Carbon Capture*

The simplified scheme of the NGCC power plant with Post-Combustion Carbon Capture (PCCC) is depicted in Figure 4. The parameters and process configuration are taken from [50]. The overall scheme is presented in Figure 4 and the main inputs, outputs and assumptions are listed in Table 2.

The Heat-Recovery Steam Generator (HRSG) of the power plant has three pressure levels:

- 4.6 bar, low pressure (LP);
- 40 bar, intermediate pressure (IP);
- 150 bar, high pressure (HP).

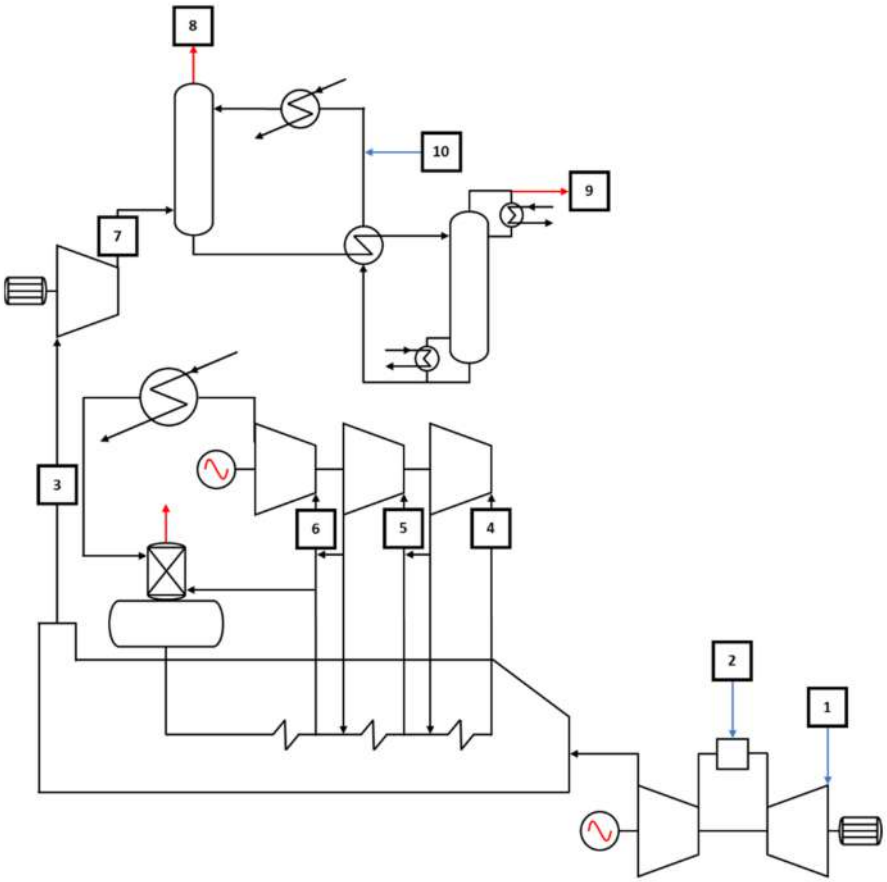



**Figure 4.** Power Plant—PCCC block scheme (the numbers represent the flow rates between the units).

**Table 2.** Power Plant and PCCC Process Assumptions.

| Operating Parameter | Value |
|---|---|
| Natural Gas Flow Rate (kg/h) | 50,000 |
| Air Flow Rate (kg/h) | 2,572,034 |
| Compressed Air Pressure (bar) | 18.2 |
| Gas Turbine Outlet Temperature (K) | 898 |
| Compressors Polytropic Coefficients | 0.9215–0.9315 |
| Compressors Mechanical Efficiency | 0.9 |
| Turbines Mechanical Efficiency | 0.9 |
| TG Isentropic Efficiency | 0.75 |
| Water Flow Rate (kg/h) | 169,197 |
| High Pressure (bar) | 150 |
| Intermediate Pressure (bar) | 40 |
| Low Pressure (bar) | 4.6 |
| HT Isentropic Efficiency | 0.92 |
| IP Isentropic Efficiency | 0.94 |
| LP Isentropic Efficiency | 0.88 |
| Condensing Temperature (K) | 311.5 |
| Net Power from Power Plant (MW) | 188.5 |
| Solvent | 40% MDEA (mass basis) |
| Absorber Pressure (bar) | 3.8 |
| Absorber Number of Stages | 10 |
| Stripper Pressure (bar) | 1.1 |
| Stripper Number of Stages | 5 |
| Stripper Reboiler | Kettle |

The outlet steam of the low-pressure turbine (LT) is condensed and fed to the deaerator unit with the condensate pump (CP) at 3 bar. Here, a vent is purged and the liquid collected at the bottom is pressurized at 4.6 bar with the low-pressure pump (LPP) before being mixed with the almost-saturated liquid water from the reboiler of the stripper column in the PCCC unit. The resulting liquid stream is partially vaporized in the HRSG. The liquid and vapour are separated, the vapour fraction is further heated in the HRSG, the liquid fraction is once again split, one part is fed to the intermediate pressure pump (IPP) and the other part to the high-pressure pump (HPP). Both pressurized liquids are heated in the HRSG; a fraction of the IP liquid is used to preheat the natural gas entering the combustion chamber and recirculate it with the saturated water from the reboiler of the stripper. The HP superheated steam is expanded in the high-pressure turbine (HT) to 40 bar; it is then mixed with the IP superheated steam and reheated in the HRSG. The resulting IP superheated steam is expanded in the intermediate-pressure turbine (IT) to the LP level and again mixed with the LP superheated steam. The resulting stream is split to feed both the stripper reboiler and the deaerator. The remaining fraction is expanded in the LT.

The oxidant in the natural gas combustion is air, which is compressed at 18.2 bar in a three-stage intercooled compressor. After combustion, the flue gas is expanded in a turbine (GT) until 1.03 bar [50]. The gas leaves the GT and enters the HRSG at 898 K, where it is cooled to 437 K. The heat recovered in the HRSG supplies the Rankine cycle. In the HRSG, the flue gas is cooled to 303 K and subsequently compressed in a two-stage intercooled compressor at 4 bar to be fed to the PCCC unit. Condensed water is expelled at the outlet of each compression–refrigeration stage.

Flue gas is fed to an absorber working at 3.8 bar from the bottom of the column. In the outlet section, the $CO_2$-rich stream is sent to a stripper, where the weak bond between MDEA and $CO_2$ is thermally broken in the reboiler. The lean solvent is collected at the bottom of the stripper and recirculated to the absorber, while almost-pure $CO_2$ is collected at the top of the stripper.

In particular, the polytropic coefficient for compressors was set to equal 0.9215 for the inter-refrigerated stages and equal 0.9315 for the non-inter-refrigerated ones.

### *2.2. Underground Storage*

One route to avoid carbon emissions is the underground storage of the captured $CO_2$. This is accomplished by purifying and pressurizing the $CO_2$ collected at the top of the stripper. Carbon dioxide can be stored at different thermodynamic conditions. In this work, we supposed storing it as a supercritical liquid. Therefore, the gas stream containing pure $CO_2$ was pressurized at 153 bar in a five-stage intercooled compressor. Carbon dioxide was liquefied and stored at 153 bar and 303 K. The overall scheme is presented in Figure 5 and the main inputs, outputs and assumptions are listed in Table 3.

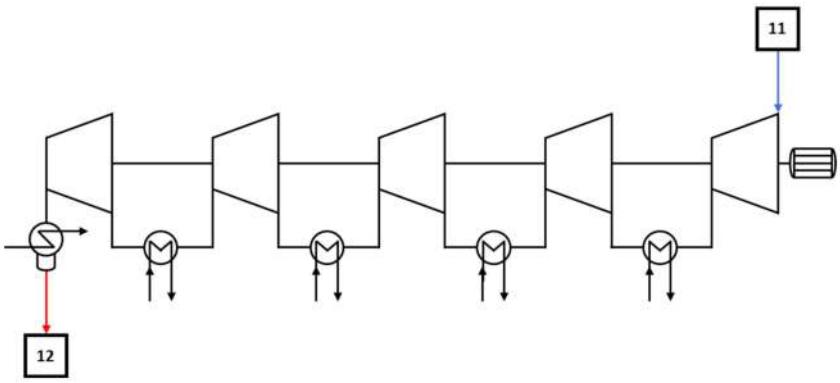



**Figure 5.** Underground storage block scheme (line 11 is the inlet pure $CO_2$ gas stream, line 12 is the pressurized and liquefied $CO_2$ stream).

**Table 3.** Underground storage process assumptions.

| Operating Parameter | Value |
|---|---|
| Interstage Temperature (K) | 303.15 |
| Stored $CO_2$ Temperature (K) | 303.15 |
| Stored $CO_2$ Pressure (bar) | 153 |
| Pressure Drop at the inter coolers (bar) | 0.2 |

### *2.3. DME Production Plant*

As an alternative to total carbon dioxide geological storage, we considered carbon utilization for dimethyl ether (DME) production in a single-step reaction process. In this configuration, the DME production plant is fed with 25% of the total $CO_2$, leaving the remaining share destined to the underground storage as in the previously described case. Figure 6 shows the $CO_2$ conversion process scheme. A gaseous stream of $CO_2$ collected at the top of the stripper in the PCCC unit is purified and pressurized at 30 bar in a four-step intercooled compressor [51]. Then, the stream from the compressor is mixed with a pure $H_2$ stream and the stream recirculated from the top of the distillation column and containing $CO_2$ and $H_2$. The flow rate of $H_2$ has the value needed to achieve a hydrogen to carbon ratio (H/C) equal to 3. Then, the $H_2$–$CO_2$ mixture is heated up to 473.15 K and fed to the reactor, where the reactions of $CO_2$ hydrogenation, water–gas shift and methanol (MeOH) dehydration happen [51]:

$$CO_2 + 3H_2 \rightleftarrows CH_3OH + H_2O \qquad \Delta H_0 = -49.4\ \text{kJ/mol} \tag{10}$$

$$CO + H_2O \rightleftarrows CO_2 + H_2 \qquad \Delta H_0 = -41.0\ \text{kJ/mol} \tag{11}$$

$$2CH_3OH \rightleftarrows CH_3OCH_3 + H_2O \qquad \Delta H_0 = -23.0\ \text{kJ/mol} \tag{12}$$

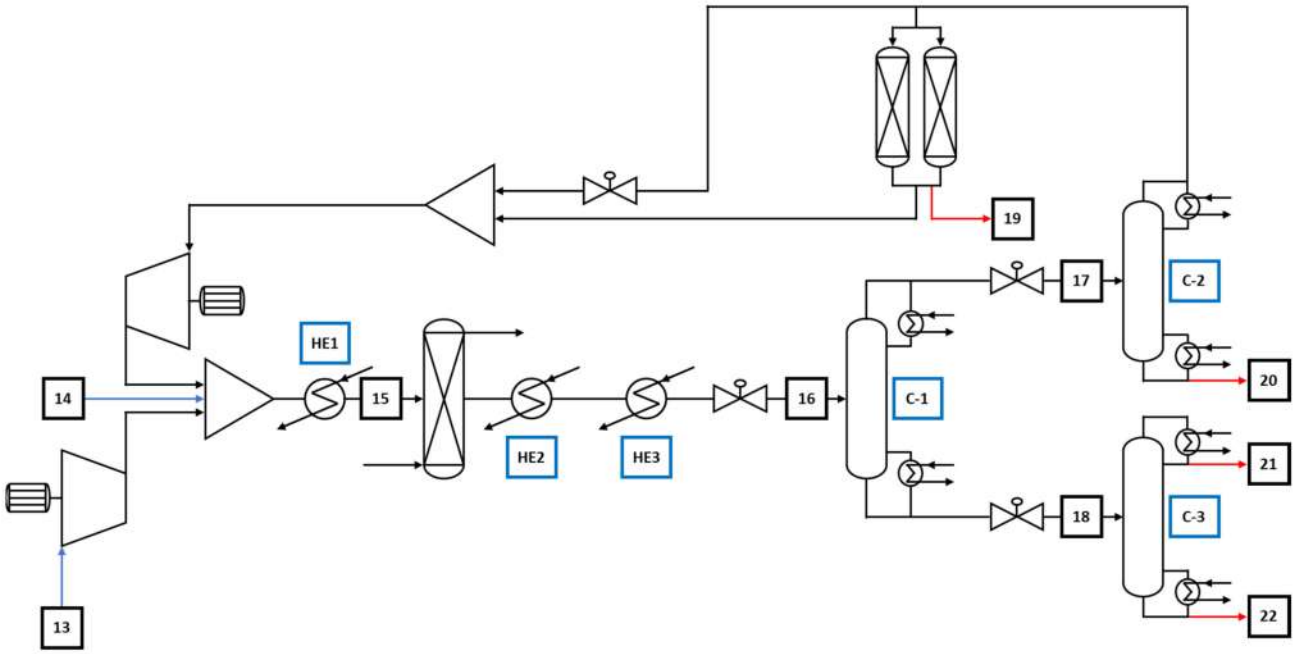



**Figure 6.** DME production plant block scheme (the tag HE represents the heat exchangers, the tag C represents the columns for product separation).

The heat generated by the exothermic reactions is removed from the reactor in order to maintain the temperature reaction constant at 473.15 K and supplied to the reboiler of column C-1. The duty from the reboiler covers around 43% of the thermal demand at the reboiler of column C-1. Then, the reaction products are cooled at 440 K in two heat

exchangers. The heat exchanger HE2 supplies the duty of the column C-3 reboiler, while the heat exchanger HE3 provides the heat needed by the column C-2 reboiler. After being cooled, the reaction products enter column C-1 at 21.3 bar. Here the heavy compounds, MeOH and water, are separated from the light ones (DME, CO, $CO_2$ and $H_2$). The light compounds are collected at the top of C-1 as a vaporous mixture and fed to column C-2 operating at 19 bar to separate the DME. The distillate of column C-2 contains unreacted CO, $CO_2$ and $H_2$, which are recycled to the reactor for 95% of their amount in the distillate, the remaining part enters a PSA to extract the hydrogen in it. Eighty percent of the hydrogen in the PSA is collected at the outlet section. The overall rate of $CO_2$ conversion is around 90%. MeOH and water are collected at the bottom of column C-1 as a liquid mixture and separated in column C-3 operating at 1.8 bar. Both columns C-1 and C-2 have partial condensers at their top stages working below the environmental temperature. In particular, the condensing temperatures at C-1 and C-2 are 262.48 K and 246.89 K, respectively. Therefore, refrigeration cycles are used to reach these temperatures, and 3.14 is the value supposed for the Coefficient of Performance (COP) of both cycles [52]. The overall scheme is presented in Figure 6 and the main inputs, outputs and assumptions are listed in Table 4.

**Table 4.** DME production plant process assumptions.

| Operating Parameter | Value |
|---|---|
| Reactor Pressure (bar) | 30 |
| Reaction Temperature (K) | 473.15 |
| C-1 Pressure (bar) | 20.5 |
| C-1 Number of Stages | 15 |
| C-1 Condenser | Partial vapour |
| C-1 Reboiler | Kettle |
| C-2 Pressure (bar) | 19 |
| C-2 Number of Stages | 15 |
| C-2 Condenser | Partial vapour |
| C-2 Reboiler | Kettle |
| C-3 Pressure (bar) | 1.8 |
| C-3 Number of Stages | 15 |
| C-3 Condenser | Total |
| C-3 Reboiler | Kettle |
| COP | 3.14 |

## 3. Assumptions and Methodology

All processes were simulated with the software Aspen Plus V10. The Peng–Robinson model was applied to the Brayton–Joule cycle of the power plant, while the Steam–Table model was chosen for the Rankine cycle of the plant. To control the process, eight design specifications were introduced to adjust the temperature at the outlet of the GT, the pinch temperature differences in the HRSG, the vent purge in the deaerator, the water make-up and the steam to be sent at the reboiler of the stripper in the PCCC unit. A calculator was used to evaluate the power generated by the plant. The natural gas properties were taken from [51]. The combustion chamber was simulated with an RGibbs reactor, which minimized the Gibbs free energy, and the deaerator with a Flash2 separator.

With respect to the PCCC unit, for all of the blocks within this unit, the ENRT-RK model was used, which consisted of an unsymmetric electrolyte NRTL model with the Redlich–Kwong equation of state and Henry's law for electrolyte systems. The electrolyte species were due to the presence of the amine MDEA as solvent.

To control the PCCC process, four design specifications were introduced to adjust the $CO_2$ content in the gas stream leaving the absorber from the top, the molar composition of the residue of the stripper, the water make-up and the solvent make-up. The absorber was simulated with a RadFrac column with no condenser nor reboiler of 10 theoretical stages working at 3.8 bar. The stripper was simulated with a RadFrac column too, without the

condenser, but with a Kettle reboiler fed with the LP steam from the power plant. It had five theoretical stages and a working pressure of 1.1 bar.

Regarding the DME production plant, the NRTL and the Peng–Robinson models were implemented. The former was for the distillation columns, which worked below 20 bar, and the latter was used for the other blocks, which worked at higher pressures. The single-stage reactor was modelled with an RGibbs reactor minimizing the Gibbs free energy with an implemented temperature approach of equilibrium of 20 K. The distillation columns used to separate the reaction products were all modelled with the RadFrac column. Every distillation column had 15 theoretical stages and a Kettle reboiler. Columns C-1 and C-2 were equipped with a partial condenser and their distillate was vaporous, while column C-3 had a total condenser providing a liquid distillate. DME was the primary product of the plant, while MeOH was a secondary product. The simulation included seven design specifications with the objective of setting the molar ratio between hydrogen and carbon at the inlet of the reactor and the distillates' flow rate and purity at each distillation column.

The exergy analysis with the aim of evaluating thermodynamics inefficiencies and rigorous performances of the process was based on the conventional methodology described in the following and found in some similar papers [45,47].

The ambient conditions were assumed at 298.15 K and 1.013 bar. The exergy flow rate $E_i$ of the $i$-th stream was the sum of the physical and chemical exergies, as reported in Equation (13), and was obtainable from the Aspen Plus simulations, while the kinetic and potential exergies were neglected. For further details, please refer to [44].

$$E_i = E_i^{PH} + E_i^{CH} \tag{13}$$

The exergy destruction rate in the $j$-th component was calculated as follows:

$$E_{D,j} = E_{F,j} + E_{P,j} \tag{14}$$

where $E_{F,j}$, $E_{P,j}$ and $E_{D,j}$ are respectively the exergy of the streams fed to the $j$-th component, the exergy of the streams leaving the $j$-th component, and the exergy destroyed in the $j$-th component. Table 5 shows how $E_{F,j}$ and $E_{P,j}$ were defined for each component.

**Table 5.** Exergy of fuels and products for different components.

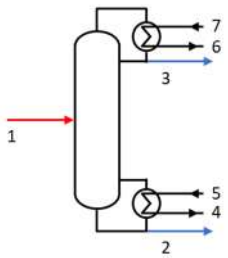
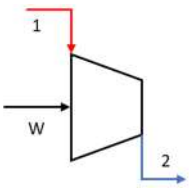
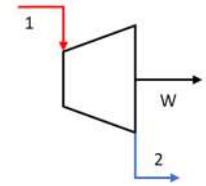
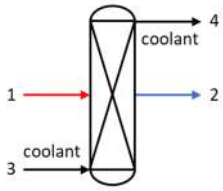
| Component | | $E_F$ | $E_P$ |
|---|---|---|---|
| Distillation Column |   | $E_5 - E_4$ | $E_2 + E_3 - E_1 + E_6 - E_7$ |
| Heat Exchanger | | $E_3 - E_4$ | $E_3 - E_1$ |
| Compressor |   | $E_1 + W$ | $E_2$ |

**Table 5.** *Cont.*

| Component | | $E_F$ | $E_P$ |
|---|---|---|---|
| Turbine |   | $E_1$ | $E_2 + W$ |
| Reactor |   | $E_1$ | $E_2 - E_3 + E_4$ |
| Valve | | $E_1$ | $E_2$ |

For every component, the following parameters were calculated:

$$\delta_j = \frac{E_{D,j}}{E_F} \tag{15}$$

$$\gamma_j = \frac{E_{D,j}}{\sum_j E_{D,j}} \tag{16}$$

where $E_F$ is the sum of the exergy of the inlet streams in every process and $E_P$ is the exergy of all the products of every process. For every unit, the exergy efficiency $\eta$ is quantified by Equation (17).

The novel performance parameter $\nu$ is introduced for the PCCC, the underground storage and the DME production plant, defined by Equation (18) as the ratio between the destroyed exergy in the unit and the non-emitted $CO_2$ $m^a_{CO2}$:

$$\eta = \frac{E_P}{E_F} \tag{17}$$

$$\nu = \frac{\sum_j E_{D,j}}{m^a_{CO2}} \tag{18}$$

The values of the mass exergy of natural gas, DME, methanol and hydrogen were miscalculated by the software Aspen Plus V10; in fact, the software underestimated those values when the components were below their ignition point. The software mass exergy values for the streams carrying the above-mentioned components were corrected by adding the mass lower heating value weighted on the components' mass fraction in the stream. The standard lower heating value of natural gas was taken from [50]. The standard lower heating values of DME, methanol and hydrogen were taken from [53].

## 4. Results and Discussion

Exergy analysis was performed to detect the inefficiencies of the proposed process scheme, to locate the elements showing interesting improvement potentials and to compare the suggested hybrid solution (Route 1) to the complete underground storage (Route 2). The power plant and the PCCC were analysed with a process-integrated approach as they represented the common path for both process configurations. Instead, a very detailed exergy analysis on the underground storage unit and on the DME production plant was performed.

### *4.1. DME Synthesis and $CO_2$ Underground Storage Configuration (Route 1)*

In this section, the exergy analysis of the proposed process solution to avoid carbon emissions is presented. The recovered carbon dioxide generated by the power plant was treated to be stored in geological sites for 75% and to be transformed into DME and MeOH for 25%. Table 6 shows the thermodynamic properties of the main material streams.

**Table 6.** Thermodynamic properties of selected material streams.

| No. | Fluid | Unit | $\xi$ (kJ/kg) | $m$ (kg/h) | T (K) | P (bar) |
|---|---|---|---|---|---|---|
| 1 | Natural Gas | Power Plant | 47,206 | 50,000 | 288.15 | 18.2 |
| 2 | Air | | 0 | 2,572,034 | 298.15 | 1.013 |
| 3 | Off Gas | | 1.877 | 2,622,034 | 303.15 | 1.03 |
| 4 | H-Steam | | 1491 | 323,828 | 813.15 | 149.4 |
| 5 | I-Steam | | 1390 | 378,823 | 813.50 | 39.2 |
| 6 | L-Steam | | 719 | 168,047 | 489.37 | 3.4 |
| 7 | Flue Gas | PCCC | 122 | 2,532,475 | 303.15 | 3.8 |
| 8 | Clean Gas | | 114 | 2,410,825 | 303.15 | 3.8 |
| 9 | Captured $CO_2$ | | 5.13 | 125,015 | 294.11 | 1.1 |
| 10 | Make up | | 1.36 | 3415 | 311.15 | 3.8 |
| 11 | $CO_2$ | Underground Storage | 4.75 | 89,288 | 294.11 | 1.1 |
| 12 | Liquefied $CO_2$ | | 223 | 89,288 | 303.15 | 153 |
| 13 | $CO_2$ | DME Production Plant | 4.62 | 29,780 | 294.11 | 1.1 |
| 14 | $H_2$ | | 120,000 | 3751.35 | 473.15 | 30 |
| 15 | Reactants | | 15,991 | 108,554 | 473.15 | 30 |
| 16 | C-1 Feed | | 15,586 | 108,554 | 440.63 | 21.3 |
| 17 | C-2 Feed | | 17,858 | 89,061 | 262.48 | 19.5 |
| 18 | C-3 Feed | | 4523.9 | 19,493 | 382.38 | 2.0 |
| 19 | Off Gas | | 6580.8 | 3931 | 251.58 | 1.3 |
| 20 | DME | | 26,662 | 10,444 | 343.10 | 19 |
| 21 | MeOH | | 19,497 | 3293.3 | 349.60 | 1.8 |
| 22 | Dirty Water | | 49.71 | 16,200 | 384.00 | 1.8 |

For every component $j$ in the DME production plant, the exergy destruction $E_{D,j}$ and the parameters $\delta_j$ and $\gamma_j$ were calculated based on the method reported in Table 5.

The exergetic efficiencies of the different units were calculated as follows:

$$\eta_{BJ} = \frac{W_{NET,BJ} + E_{HRSG}}{E_2} \tag{19}$$

$$\eta_R = \frac{W_{NET,R} + E_{Reb}}{E_{HRSG}} \tag{20}$$

$$\eta_{PCCC} = \frac{E_8 + E_9}{E_{reb} + W_{PCCC} + E_3} \tag{21}$$

$$\eta_{US} = \frac{E_{12}}{E_{11} + W_{US}} \tag{22}$$

$$\eta_{DME} = \frac{E_{19} + E_{20} + E_{21} + E_{22}}{E_{13} + E_{14} + W_{DME} + E_{F,HE1} + E_{F,C-3}} \tag{23}$$

where $W_{NET,BJ}$ and $W_{NET,R}$ are the net electric power in the Brayton–Joule and Rankine cycles, $E_{HRSG}$ is the exergy exchanged in the Heat Recovery Steam Generator, $E_i$ is the exergy associated with the $i$-th stream in Figure 4, $E_{Reb}$ is the exergy exported to the reboiler of the stripper in the PCCC unit, and $W_{PCCC}$ and $W_{DME}$ are the electric power demand in the PCCC and DME production plant units, respectively. The exergy associated with the compressor of the off gas (stream no. 3 in Figure 4) was counted in the PCCC unit. The heat exchanger HE1 in Figure 6 heated up the reactants to 473.15 K; such an amount of heat was not recovered from anywhere in the process and it was supposed to be provided by a hot source at a constant temperature of 488.15 K. Instead, HE2 and HE3 supplied the heat

at the reboilers of C-3 and C-2 respectively. Approximately 42.65% of the heat needed at the reboiler of C-3 was supplied by the exothermic reactions (1)–(3). The remaining part was supposed to be provided by a hot source at a constant temperature of 479.64 K (15 K higher than the temperature at the reboiler of C-3). Therefore, the values of $E_{F,HE1}$ and of $E_{F,C-3}$ were calculated as shown in [54].

The values of $\eta_{BJ}$, $\eta_R$, $\eta_{PCC}$, $\eta_{US}$ and $\eta_{DME}$, as well as the values of the destroyed exergies in the unit, are listed in Table 7, where the results of the exergy analysis of the different units are listed. The destroyed exergy in each unit was given by the difference between the denominator and the nominator of the corresponding exergy efficiency.

**Table 7.** Exergy analysis results.

| Unit | $E_D$ (MW) | $\eta$ (%) | $v$ (MJ/kg) |
|---|---|---|---|
| Brayton–Joule Cycle | 277.90 | 45.57 | |
| Rankine Cycle | 108.96 | 50.05 | |
| PCCC | 150.23 | 36.96 | 40.80 |
| Underground Storage | 3.25 | 62.96 | 0.13 |
| DME Production Plant | 41.09 | 75.74 | 4.97 |

Figures 7 and 8 show the result of the exergy analysis of the DME production plant. The distillation column C-1 was mainly responsible for the exergy destruction, as it represented 45.19% of all exergy destruction, and its impact on exergy fuel reduction was worth 12.37%. In particular, the refrigeration cycle at the top stage of C-1 was the operation associated with the highest irreversibility, as shown in Figure 9. These values were higher than those of columns C-2 and C-3, because column C-1 dealt with higher flow rates and separated very different chemical species. Furthermore, as shown in Table 6, much of the stream fed to column C-1 left the column from the top at a temperature lower than the feed temperature. This fact determines the high exergy destruction in the column C-1 condenser. The reactor was the second-most responsible unit for exergy destruction, and column C-3 was the third. In particular, the exergy destruction associated with column C-3 was due to the difference in the specific exergy $\xi$ of the streams. This is shown in Table 6; in fact, the specific exergy of the residue $\xi_{22}$ was lower than the specific exergy of the feed $\xi_{18}$ and specifically of the distillate $\xi_{21}$, but the mass flow of the residue was almost five times the mass flow of the distillate. The exergy destruction associated with the reactor was also due to the chemical exergy difference in reagents and products.

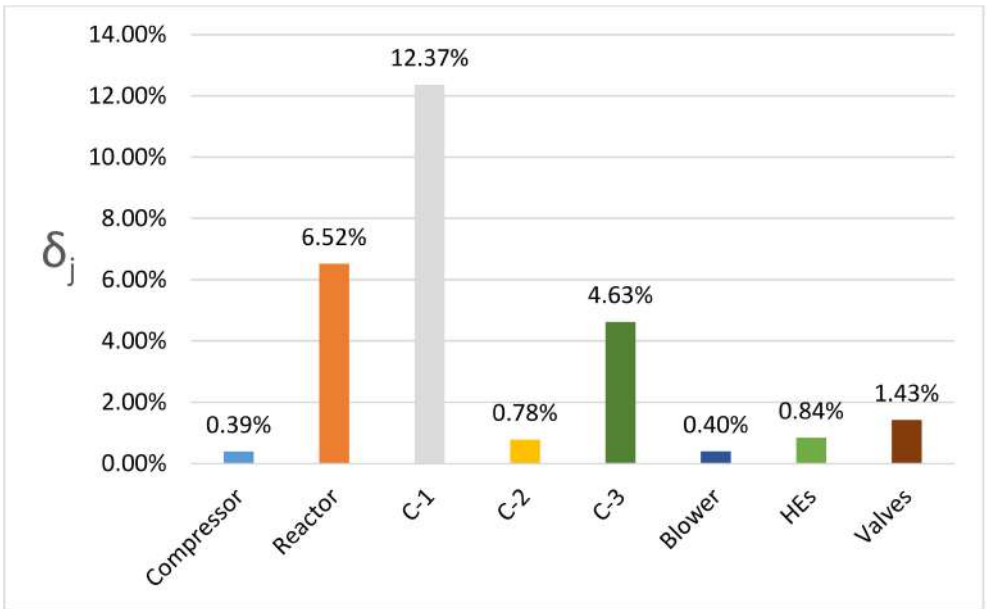



**Figure 7.** Percentage of fuel exergy ($E_F$ = 150.13 MW) destroyed per component.

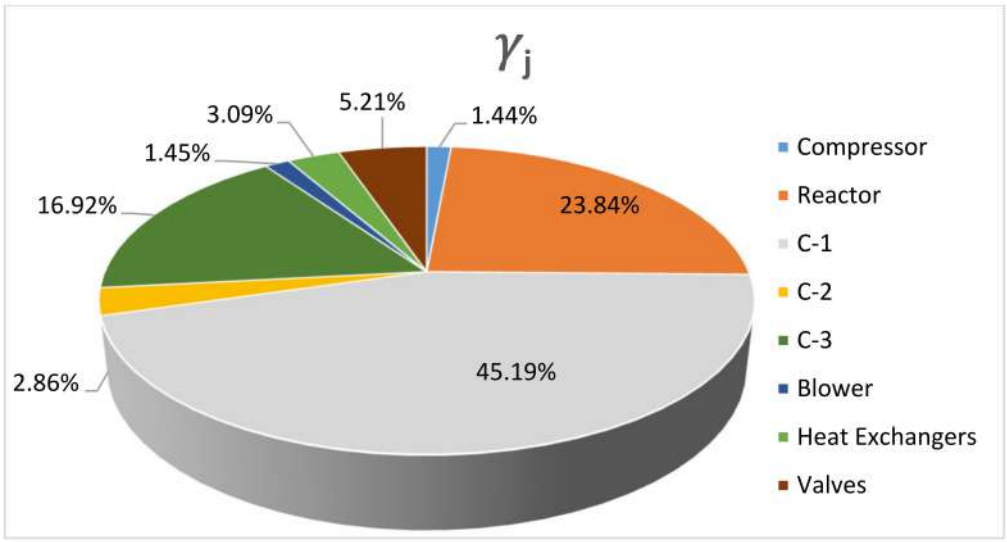



**Figure 8.** Percentage of destroyed exergy per component ($\sum_j E_{D,j} = 41.09$ MW).

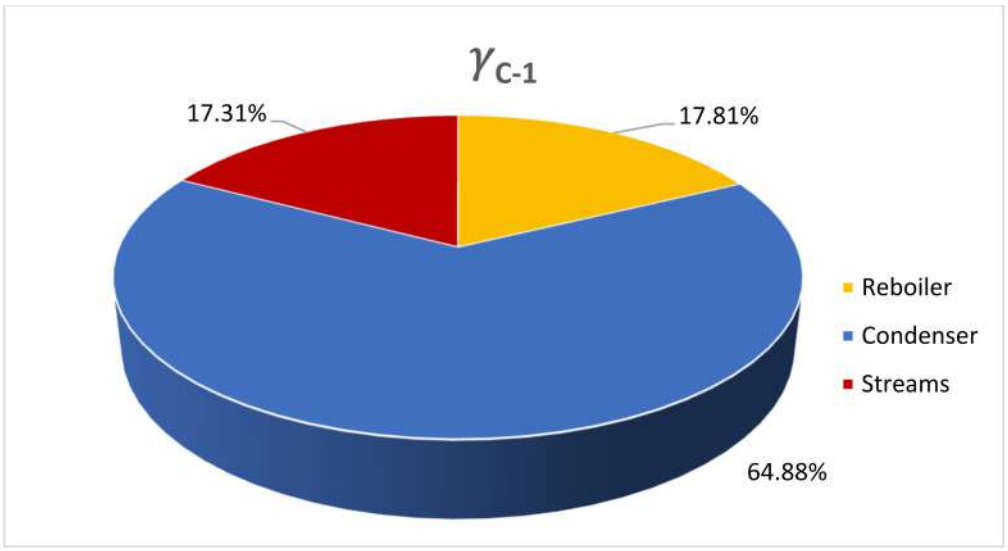



**Figure 9.** Distribution of destroyed exergy in C-1.

Figure 10 shows how the exergy destructions were distributed among the units. The Brayton–Joule cycle was mainly responsible for exergy destruction [55], while underground storage had the lowest impact.

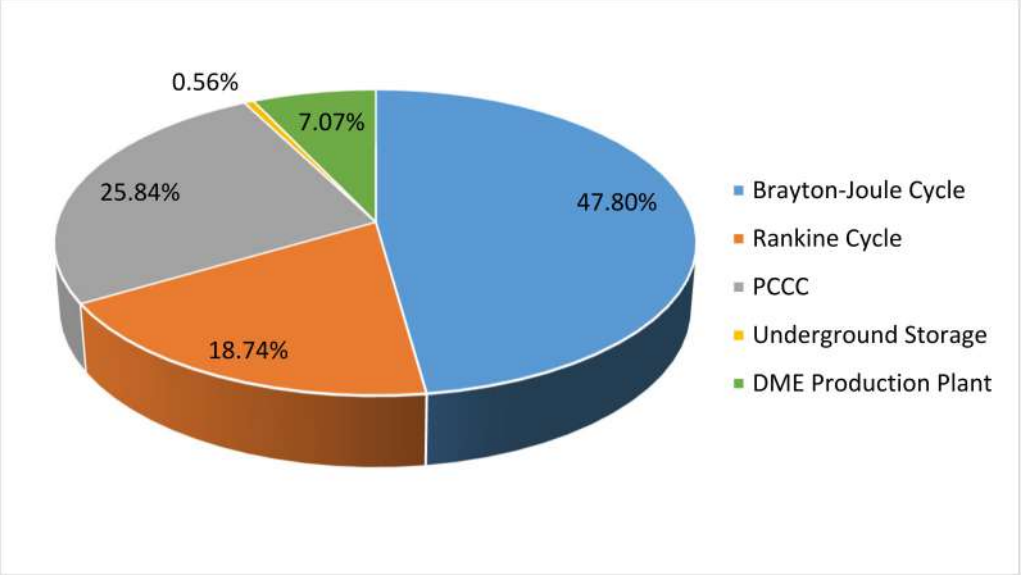



**Figure 10.** Distribution of exergy destruction between the units (total $E_D = 581.43$ MW).

*4.2. Comparison with $CO_2$ Underground Storage (Route 2)*

The results of the previous section are hereby compared with the Route 2 solution to avoid carbon emissions, i.e., 100% underground storage of recovered $CO_2$. The same power plant and PCCC were analysed; therefore the results for those units were the same as those in Route 1. The recovered carbon dioxide was supposed to be treated in order to be completely stored in geological sites. The thermodynamic properties of the material streams of the power plant and PCCC units in Table 6 are still valid. Figure 11 shows the exergy destructions distribution among the units.

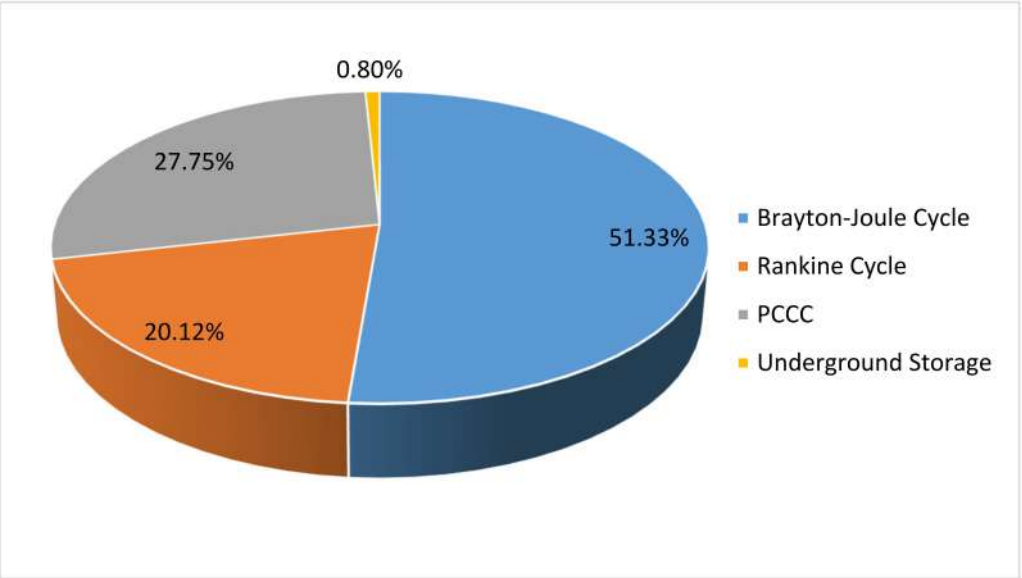



**Figure 11.** Distribution of exergy destruction between the units (total $E_D = 541.42$ MW).

The same conditions for temperature and pressure were set for the underground stored carbon dioxide in both routes, as shown in Tables 6 and 8. Therefore, the exergy efficiencies of the underground storage unit in Route 1 and in Route 2 were the same, but exergy destruction in this case accounted for 4.33 MW.

**Table 8.** Thermodynamic properties of selected stream materials.

| No. | Fluid | Unit | $\xi$ (kJ/kg) | $m$ (kg/h) | T (K) | P (bar) |
|---|---|---|---|---|---|---|
| 11 | $CO_2$ | Underground Storage | 4.75 | 119,068 | 294.11 | 1.1 |
| 12 | Liquefied $CO_2$ | | 223 | 119,068 | 303.15 | 153 |

The results show a decrease in the total exergy destruction of 6.88% due to the complete storage of the recovered carbon dioxide. Focusing on the units treating the recovered $CO_2$, the destroyed exergy in Route 2 was approximately a tenth of the destroyed exergy in Route 1 (44.34 MW). Despite the consistent reduction in the destroyed exergy, the DME production plant unit had higher exergy efficiency than the underground storage unit. The process' intrinsic exergy efficiency was higher, but the additional use of high-value energy and material streams increased the overall exergy destruction. The exergy efficiencies and the destroyed exergy per non-emitted $CO_2$ coefficient are presented in Table 9 for the units treating the recovered $CO_2$.

**Table 9.** Comparison between the Route 1 and Route 2 $CO_2$-treating units.

| | $\eta$ (%) | $\nu$ (MJ/kg) | Avoided $CO_2$ |
|---|---|---|---|
| Route 1 | 75.03 | 1.34 | 97.50% |
| Route 2 | 62.96 | 0.13 | 100% |

Furthermore, the DME production plant unit was able to release available energy to the environment in the form of DME and MeOH streams. This energy value was quantified with the lower heating value of material streams 20 and 21 in Figure 6. The energy gain (EG) we obtained from DME and MeOH production in the DME production plant was calculated as the ratio between the sum of the energy transported by streams 20 and 21 and the exergy destroyed in the Route 1 $CO_2$-treating units:

$$EG = \frac{m_{20} LHV_{20} + m_{21} LHV_{21}}{E_{D,US} + E_{D,DME}} \quad (24)$$

The $EG$ value is 2.276 MJ/MJ; in particular, it was 1.875 MJ/MJ for DME production and 0.401 MJ/MJ for MeOH production.

## 5. Conclusions

In the present study, an exergy analysis of a process configuration able to avoid carbon emissions and to produce DME and methanol is presented. The carbon-emitting source in this study was a 189 MW power plant. The Brayton–Joule cycle in the power plant was mainly responsible for exergy destruction, 75% of the produced carbon dioxide was captured to be stored underground and the remaining 25% was to be transformed into DME and methanol via reactions with hydrogen. In the plant, the total $CO_2$ generated by the power cycle was 119,068 kg/h, the amount stored was 89,288 kg/h, the stream converted was 26,815 kg/h and the amount vented to the atmosphere was 2965 kg/h (2.5% of the total). The reaction sections converted the $CO_2$ stream into DME (10,381 kg/h) and methanol (3214.1 kg/h). A second route was considered, i.e., the storage of 100% of the $CO_2$ generated by the power plant.

Of those two routes to avoid carbon emissions, the underground storage offers a much lower exergy destruction per mass of non-emitted carbon. Inside the DME production plant, the main contribution to exergy destruction was from the distillation column separating the reactor outlet stream and, in particular, the top-stage condenser was found to be the component with the highest irreversibility. This DME synthesis showed a higher efficiency than the underground storage unit, but a higher exergy destruction per non-emitted carbon dioxide ratio. As a consequence, the process configuration we propose has higher exergetic efficiency and exergy destruction than full geological storage, and produces valuable compounds, such as DME and methanol. Its feasibility is strictly correlated with the

development of the hydrogen industry, and a future study should evaluate the impact of hydrogen production at different carbon dioxide shares between DME production and underground storage. Future works should investigate the optimal $CO_2$ split between Route 1 and Route 2 and extend exergy analysis to green hydrogen production.

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## Nomenclature

| | |
|---|---|
| DME | Dimethyl Ethanol |
| MeOH | Methanol |
| NGCC | Natural Gas Combined Cycle |
| PCCC | Post-Combustion Carbon Capture |
| HRSG | Heat Recovery Steam Generator |
| HP | High-Pressure Level |
| IP | Intermediate-Pressure Level |
| LP | Low-Pressure Level |
| GT | Gas Turbine |
| HT | High-Pressure Turbine |
| IT | Intermediate-Pressure Turbine |
| LT | Low-Pressure Turbine |
| C-x | Distillation Column number x |
| HEx | Heat Exchanger number x |
| H/C | Hydrogen to Carbon ratio |
| COP | Coefficient of Performance |
| EG | Energy Gain |
| $E_i$ | Exergy flow rate of *i*-th material stream |
| $E_i^{PH}$ | Physical Exergy flow rate of *i*-th material stream |
| $E_i^{CH}$ | Chemical Exergy flow rate of *i*-th material stream |
| $E_{D,j}$ | Desytroyed Exergy flow rate in the *j*-th component |
| $E_{F,j}$ | Fuel Exergy flow rate to the *j*-th component |
| $E_{P,j}$ | Product Exergy flow rate of the *j*-th component |
| $\xi$ | Specific Mass Exergy |
| $m$ | Mass flow rate |
| $m^a_{CO_2}$ | Mass flow rate of avoided $CO_2$ |
| $\delta_j$ | Destroyed Exergy to Fuel Exergy ratio for the *j*-th component |
| $\gamma_j$ | Specific Destroyed Exergy in the *j*-th component |
| $\nu$ | Destroyed exergy per avoided carbon emissions |
| $\eta$ | Exergetic Efficiency |
| T | Temperature |
| P | Pressure |

## References


1. Majchrzak-Kucęba, I.; Szymanek, P. CCU Technologies in the Green Economy. *Eng. Prot. Environ.* **2018**, *21*, 261–271. [CrossRef]
2. Catizzone, E.; Bonura, G.; Migliori, M.; Frusteri, F.; Giordano, G. $CO_2$ recycling to dimethyl ether: State-of-the-art and perspectives. *Molecules* **2018**, *23*, 31. [CrossRef] [PubMed]
3. Masson-Delmotte, V.P.; Zhai, A.; Pirani, S.L.; Connors, C.; Péan, S.; Berger, N.; Caud, Y.; Chen, L.; Goldfarb, M.I.; Gomis, M.; et al. *The Physical Science Basis. Contribution of Working Group I to the 552 Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021.
4. Hasan, M.M.F.; First, E.L.; Boukouvala, F.; Floudas, C.A. A multi-scale framework for $CO_2$ capture, utilization, and sequestration: CCUS and CCU. *Comput. Chem. Eng.* **2015**, *81*, 2–21. [CrossRef]
5. Koytsoumpa, E.I.; Bergins, C.; Kakaras, E. The $CO_2$ economy: Review of $CO_2$ capture and reuse technologies. *J. Supercrit. Fluids* **2018**, *132*, 3–16. [CrossRef]
6. Leung, D.Y.C.; Caramanna, G.; Maroto-Valer, M.M. An overview of current status of carbon dioxide capture and storage technologies. *Renew. Sustain. Energy Rev.* **2014**, *39*, 426–443. [CrossRef]
7. Chauvy, R.; De Weireld, G. $CO_2$ Utilization Technologies in Europe: A Short Review. *Energy Technol.* **2020**, *8*, 2000627. [CrossRef]
8. Dieterich, V.; Buttler, A.; Hanel, A.; Spliethoff, H.; Fendt, S. Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: A review. *Energy Environ. Sci.* **2020**, *13*, 3207–3252. [CrossRef]
9. Lee, D.; Lee, J.S.; Kim, H.Y.; Chun, C.K.; James, S.C.; Yoon, S.S. Experimental study on the combustion and no x emission characteristics of DME/LPG blended fuel using counterflow burner. *Combust. Sci. Technol.* **2012**, *184*, 97–113. [CrossRef]
10. Kim, H.J.; Suh, H.K.; Park, S.H.; Lee, C.S. An experimental and numerical investigation of atomization characteristics of biodiesel, dimethyl ether, and biodiesel-ethanol blended fuel. *Energy Fuels* **2008**, *22*, 2091–2098. [CrossRef]
11. Wang, S.; Fu, Z. Thermodynamic and economic analysis of solar assisted CCHP-ORC system with DME as fuel. *Energy Convers. Manag.* **2019**, *186*, 535–545. [CrossRef]
12. Cheng, C.; Zhang, H.; Ying, W.; Fang, D. Intrinsic kinetics of one-step dimethyl ether synthesis from hydrogen-rich synthesis gas over bi-functional catalyst. *Korean J. Chem. Eng.* **2011**, *28*, 1511–1517. [CrossRef]
13. Zhang, Y.; Zhang, S.; Benson, T. A conceptual design by integrating dimethyl ether (DME) production with tri-reforming process for $CO_2$ emission reduction. *Fuel Process. Technol.* **2015**, *131*, 7–13. [CrossRef]
14. Catizzone, E.; Freda, C.; Braccio, G.; Frusteri, F.; Bonura, G. Dimethyl ether as circular hydrogen carrier: Catalytic aspects of hydrogenation/dehydrogenation steps. *J. Energy Chem.* **2021**, *58*, 55–77. [CrossRef]
15. Bonura, G.; Todaro, S.; Frusteri, L.; Majchrzak-Kucęba, I.; Wawrzyńczak, D.; Pászti, Z.; Tálas, E.; Tompos, A.; Ferenc, L.; Solt, H.; et al. Inside the reaction mechanism of direct $CO_2$ conversion to DME over zeolite-based hybrid catalysts. *Appl. Catal. B Environ.* **2021**, *294*, 120255. [CrossRef]
16. Baena-Moreno, F.M.; Gonzalez-Castaño, M.; Arellano-García, H.; Reina, T.R. Exploring profitability of bioeconomy paths: Dimethyl ether from biogas as case study. *Energy* **2021**, *225*, 120230. [CrossRef]
17. Im-orb, K.; Arpornwichanop, A. Comparative techno-economic assessment of bio-methanol and bio-DME production from oil palm residue. *Energy Convers. Manag.* **2022**, *258*, 115511. [CrossRef]
18. Ott, J.; Gronemann, V.; Pontzen, F.; Fiedler, E.; Grossmann, G.; Kersebohm, B.; Weiss, G.; Witte, C. Methanol. In *Ullmann's Encyclopedia of Industrial Chemistry*; Wiley-VCH Verlag GmbH & Co.: Berlin, Germany, 2012.
19. Kang, S.; Boshell, F.; Goeppert, A.; Prakash, S.G.; Landälv, I. *Innovation Outlook: Renewable Methanol*; IRENA: Abu Dhabi, United Arab Emirates, 2021.
20. Müller, M.; Hübsch, U. Dimethyl Ether. In *Ullmann's Encyclopedia of Industrial Chemistry*; Wiley-VCH Verlag GmbH & Co.: Berlin, Germany, 2000.
21. PubChem. Available online: https://pubchem.ncbi.nlm.nih.gov/compound/Methane (accessed on 17 February 2022).
22. Trafigura. Available online: https://www.trafigura.com/media/1687/en_sds_fuel-diesel-vgo_cas-68334-30-5.pdf (accessed on 17 February 2021).
23. Speight, J.G. *Handbook of Petroleum Product Analysis*; Wiley: Hoboken, NJ, USA, 2015; Volume 53.
24. Barbato, L.; Iaquaniello, G.; Mangiapane, A. Reuse of $CO_2$ to Make Methanol Using Renewable Hydrogen. In *$CO_2$: A Valuable Source of Carbon*; De Falco, M., Iaquaniello, G., Centi, G., Eds.; Green Energy and Technology; Springer: London, UK, 2013. [CrossRef]
25. Hobson, C.; Marquez, C. *Renewable Methanol Report*; Methanol Institute: Brussels, Belgium, 2018.
26. Huang, C.H.; Tan, C.S. A Review: $CO_2$ Utilization. *Aerosol Air Qual. Res.* **2014**, *14*, 480–499. [CrossRef]
27. de Falco, M.; Iaquaniello, G.; Centi, G. *$CO_2$: A Valuable Source of Carbon*; Green Energy and Technology; Springer: London, UK, 2013; Volume 137. [CrossRef]
28. Scott, K. *Sustainable and Green Electrochemical Science and Technology*; John Wiley and Sons Ltd.: Hoboken, NJ, USA, 2016.
29. Pérez-Fortes, M.; Schöneberger, J.C.; Boulamanti, A.; Tzimas, E. Methanol synthesis using captured $CO_2$ as raw material: Techno-economic and environmental assessment. *Appl. Energy* **2016**, *161*, 718–732. [CrossRef]
30. RWE. Available online: https://www.rwe.com/en/press/rwe-power/2019-05-28-niederaussem-becomes-the-setting-for-important-technological-progress (accessed on 22 February 2022).
31. Mef$CO_2$. Available online: http://www.mefCO2.eu/ (accessed on 21 February 2022).

32. Freyr, Ó.; Magistri, L.; Licozar, B.; Diaz, A.S. Green Methanol for a Green Future. Mef$CO_2$. 2020. Available online: http://www.mefco2.eu/news/green-methanol-for-a-green-future.php (accessed on 23 February 2022).
33. Fernández-González, J.; Rumayor, M.; Domínguez-Ramos, A.; Irabien, A. Hydrogen Utilization in the Sustainable Manufacture of $CO_2$-Based Methanol. *Ind. Eng. Chem. Res.* **2022**. [CrossRef]
34. European Commission. Available online: https://cordis.europa.eu/article/id/257671-energyintensive-sectors-can-be-part-of-low-carbon-transition (accessed on 21 February 2022).
35. Ayala, P. Methanol Fuel from $CO_2$. Synthesis of Methanol from Captured Carbon Dioxide Using Surplus Electricity. Mef$CO_2$. 13 September 2018. Available online: https://etipwind.eu/wp-content/uploads/MefCO2-slides.pdf (accessed on 23 February 2022).
36. Danish Energy Agency Technology Data for Renewable Fuels. 2017. Available online: https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-renewable-fuels (accessed on 24 February 2022).
37. Harp, G.; Tran, K.C.; Bergins, C.; Buddenberg, T.; Drach, I.; Sigurbjornsson, O. Application of Power to Methanol Technology to Integrated Steelworks for Profitability, Conversion Efficiency, and $CO_2$ Reduction. In Proceedings of the METEC 2nd ESTAD, Düsseldorf, Germany, 15–19 June 2016.
38. Andrei, B.D.; del Mar, P.F.M.; Evangelos, T.; Thea, S. *Carbon Capture and Utilisation Workshop: Background and Proceedings*; Publications Office of the European Union: Luxembourg, 2013.
39. Carbon Recycling International Ltd. Available online: https://www.carbonrecycling.is/ (accessed on 22 February 2022).
40. Mann, I. Deep Decarbonisation is Within Reach of Europe's Industrial Regions. March 2021. Available online: https://www.alignccus.eu/news/align-ccus-findings-unveiled-deep-decarbonisation-within-reach-europe%E2%80%99s-industrial-regions (accessed on 24 February 2022).
41. van Os, P. Accelerating low carbon industrial growth through carbon capture, utilization and storage (CCUS). *Greenh. Gases Sci. Technol.* **2018**, *8*, 994–997. [CrossRef]
42. Moran, M.J.; Sciubba, E. Exergy Analysis: Principles and Practice. *J. Eng. Gas Turbines Power* **1994**, *116*, 285–290. [CrossRef]
43. Mistry, K.H.; Lienhard, J.H. Generalized least energy of separation for desalination and other chemical separation processes. *Entropy* **2013**, *15*, 2046. [CrossRef]
44. Bejan, A. *Advanced Engineering Thermodynamics*; John Wiley & Sons: Hoboken, NJ, USA, 2016.
45. Olaleye, A.K.; Wang, M.; Kelsall, G. Steady state simulation and exergy analysis of supercritical coal-fired power plant with $CO_2$ capture. *Fuel* **2015**, *151*, 57–72. [CrossRef]
46. Olaleye, A.K.; Wang, M. Conventional and advanced exergy analysis of post-combustion $CO_2$ capture based on chemical absorption integrated with supercritical coal-fired power plant. *Int. J. Greenh. Gas Control* **2017**, *64*, 246–256. [CrossRef]
47. Blumberg, T.; Morosuk, T.; Tsatsaronis, G. Exergy-based evaluation of methanol production from natural gas with $CO_2$ utilization. *Energy* **2017**, *141*, 2528–2539. [CrossRef]
48. Nakyai, T.; Saebea, D. Energy and exergy analyses of dimethyl ether production using CO and $CO_2$ hydrogenation. *Int. J. Smart Grid Clean Energy* **2019**, *8*, 544–549. [CrossRef]
49. Farooqui, A.; Di Tomaso, F.; Bose, A.; Ferrero, D.; Llorca, J.; Santarelli, M. Techno-economic and exergy analysis of polygeneration plant for power and DME production with the integration of chemical looping $CO_2/H_2O$ splitting. *Energy Convers. Manag.* **2019**, *186*, 200–219. [CrossRef]
50. Fout, T.; Zoelle, A.; Keairns, D.; Turner, M.; Woods, M.; Kuehn, N.; Shah, V.; Chou, V.; Pinkerton, L. *Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3*; National Energy Technology Laboratory (NETL): Pittsburgh, PA, USA; Morgantown, WV, USA, 2015; Volume 1a.
51. De Falco, M.; Capocelli, M.; Giannattasio, A. Membrane Reactor for one-step DME synthesis process: Industrial plant simulation and optimization. *J. $CO_2$ Util.* **2017**, *22*, 33–43. [CrossRef]
52. Dincer, I.; Rosen, M.A.; Khalid, F. Ocean (Marine) Energy Production. In *Comprehensive Energy Systems*; Elsevier: Amsterdam, The Netherlands, 2018; Volumes 3–5.
53. Perry, R.H.; Green, D.W. *Perry's Chemical Engineers' Handbook*, 8th ed.; McGraw-Hill: New York, NY, USA, 2013; Volume 53.
54. Demirel, Y.; Sieniutycz, S. Nonequilibrium Thermodynamics: Transport and Rate Processes in Physical and Biological Systems. *Appl. Mech. Rev.* **2003**, *56*, 275–540. [CrossRef]
55. Ertesvåg, I.S.; Kvamsdal, H.M.; Bolland, O. Exergy analysis of a gas-turbine combined-cycle power plant with precombustion $CO_2$ capture. *Energy* **2005**, *30*, 5–39. [CrossRef]

# References


Adamczyk J, Dzikuć M (2014) The analysis of suppositions included in the Polish Energetic Policy using the LCA technique—Poland case study. Renewable and Sustainable Energy Reviews 39:42–50. https://doi.org/10.1016/j.rser.2014.07.083

Adewole JK, Ahmad AL, Ismail S, Leo CP (2013) Current challenges in membrane separation of CO2 from natural gas: A review. International Journal of Greenhouse Gas Control 17:46–65. https://doi.org/10.1016/j.ijggc.2013.04.012

Alper E, Yuksel Orhan O (2017) CO2 utilization: Developments in conversion processes. Petroleum 3:109–126. https://doi.org/10.1016/j.petlm.2016.11.003

Anggarani R, Wibowo CS, Rulianto D (2014) Application of Dimethyl Ether as LPG Substitution for Household Stove. Energy Procedia 47:227–234. https://doi.org/10.1016/j.egypro.2014.01.218

Anheden M, Andersson A, Bernstone C, et al (2005) CO2 quality requirement for a system with CO2 capture, transport and storage. In: Rubin ES, Keith DW, Gilboy CF, et al. (eds) Greenhouse Gas Control Technologies 7. Elsevier Science Ltd, Oxford, pp 2559–2564

Anika OC, Nnabuife SG, Bello A, et al (2022) Prospects of low and zero-carbon renewable fuels in 1.5-degree net zero emission actualisation by 2050: A critical review. Carbon Capture Science & Technology 5:100072. https://doi.org/10.1016/j.ccst.2022.100072

Aristizábal-Marulanda V, Cardona Alzate CA (2019) Methods for designing and assessing biorefineries: Review. Biofuels, Bioproducts and Biorefining 13:789–808. https://doi.org/10.1002/bbb.1961

Armstrong K, Styring P (2015) Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO2 Emissions Reduction. Front Energy Res 3:. https://doi.org/10.3389/fenrg.2015.00008

Azzolina NA, Hamling JA, Peck WD, et al (2017) A Life Cycle Analysis of Incremental Oil Produced via CO2 EOR. Energy Procedia 114:6588–6596. https://doi.org/10.1016/j.egypro.2017.03.1800

Bachmann M, Kätelhön A, Winter B, et al (2021) Renewable carbon feedstock for polymers: environmental benefits from synergistic use of biomass and CO 2. Faraday Discussions 230:227–246. https://doi.org/10.1039/D0FD00134A

Bachu S (2003) Screening and ranking of sedimentary basins for sequestration of CO2 in geological media in response to climate change. Env Geol 44:277–289. https://doi.org/10.1007/s00254-003-0762-9

Baitz M, Albrecht S, Brauner E, et al (2013) LCA's theory and practice: like ebony and ivory living in perfect harmony? Int J Life Cycle Assess 18:5–13. https://doi.org/10.1007/s11367-012-0476-x

Bardow A (2017) To Utilize or Not to Utilize? A Life-Cycle Assessment Perspective on Carbon Dioxide Utilization. CO2 Summit III: Pathways to Carbon Capture, Utilization, and Storage Deployment

Bare J (2011) TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Technologies and Environmental Policy 13:687–696. https://doi.org/10.1007/s10098-010-0338-9

Barisic V, Coda Zabetta E, Eriksson T, et al (2009) CFB technology provides solutions for reducing CO2 emissions. The Journal of the Southern African Institute of Mining and Metallurgy 108:107–119

Barros MV, Salvador R, Piekarski CM, et al (2020) Life cycle assessment of electricity generation: a review of the characteristics of existing literature. Int J Life Cycle Assess 25:36–54. https://doi.org/10.1007/s11367-019-01652-4

Batuecas E, Liendo F, Tommasi T, et al (2021) Recycling CO2 from flue gas for CaCO3 nanoparticles production as cement filler: A Life Cycle Assessment. Journal of CO2 Utilization 45:101446. https://doi.org/10.1016/j.jcou.2021.101446

Belmabkhout Y, Serna-Guerrero R, Sayari A (2010) Adsorption of CO2-Containing Gas Mixtures over Amine-Bearing Pore-Expanded MCM-41 Silica: Application for Gas Purification. Ind Eng Chem Res 49:359–365. https://doi.org/10.1021/ie900837t

Bielicki JM, Clarens AF, Middleton RS, et al (2014) Shifting Sands in a CO2 Desert: Replacing Extracted CO2 with By-product CO2 for Use in Enhanced Oil Recovery. Energy Procedia 63:6557–6564. https://doi.org/10.1016/j.egypro.2014.11.692

Błaszczuk A, Komorowski M, Nowak W (2012a) Distribution of Solids Concentration and Temperature in the Combustion Chamber of the SC-OTU CFB Boiler. Journal of Power Technologies 92:27–33

Błaszczuk A, Nowak W, Klajny M, et al (2012b) NOx emissions from the 460 MWe supercritical CFB boiler

Bonura G, Todaro S, Cannilla C, Frusteri F (2022) CO2 hydrogenation into dimethyl ether: Conventional and innovative catalytic routes. In: The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies. CRC Press

Bonura G, Todaro S, Frusteri L, et al (2021) Inside the reaction mechanism of direct CO2 conversion to DME over zeolite-based hybrid catalysts. Applied Catalysis B: Environmental 294:120255. https://doi.org/10.1016/j.apcatb.2021.120255

Bui M, Adjiman C, Bardow A, et al (2018) Carbon capture and storage (CCS): The way forward. Energy and Environmental Science 11:. https://doi.org/10.1039/c7ee02342a

Burchart-Korol D, Pustejovska P, Blaut A, et al (2018) Comparative life cycle assessment of current and future electricity generation systems in the Czech Republic and Poland. Int J Life Cycle Assess 23:2165–2177. https://doi.org/10.1007/s11367-018-1450-z

Cai R, Ke X, Huang Y, et al (2019) Applications of Ultrafine Limestone Sorbents for the Desulfurization Process in CFB Boilers. Environ Sci Technol 53:13514–13523. https://doi.org/10.1021/acs.est.9b04747

Catizzone E, Bonura G, Migliori M, et al (2017a) CO2 Recycling to Dimethyl Ether: State-of-the-Art and Perspectives. Molecules 23:31. https://doi.org/10.3390/molecules23010031

Catizzone E, Bonura G, Migliori M, et al (2017b) CO2 Recycling to Dimethyl Ether: State-of-the-Art and Perspectives. Molecules 23:31. https://doi.org/10.3390/molecules23010031

Catizzone E, Freda C, Braccio G, et al (2021) Dimethyl ether as circular hydrogen carrier: Catalytic aspects of hydrogenation/dehydrogenation steps. Journal of Energy Chemistry 58:55–77. https://doi.org/10.1016/j.jechem.2020.09.040

Cetinkaya E, Dincer I, Naterer GF (2012) Life cycle assessment of various hydrogen production methods. International Journal of Hydrogen Energy 37:2071–2080. https://doi.org/10.1016/j.ijhydene.2011.10.064

Chauvy R, De Weireld G (2020) CO 2 Utilization Technologies in Europe: A Short Review. Energy Technol 8:2000627. https://doi.org/10.1002/ente.202000627

Chehrazi M, Moghadas BK (2022) A review on CO2 capture with chilled ammonia and CO2 utilization in urea plant. Journal of CO2 Utilization 61:102030. https://doi.org/10.1016/j.jcou.2022.102030

Chelvam K, Hanafiah MM (2023) Life cycle assessment of carbon capture, utilisation and storage technologies: An analytical review. IOP Conf Ser: Earth Environ Sci 1167:012036. https://doi.org/10.1088/1755-1315/1167/1/012036

Chwoła T, Spietz T, Więcław-Solny L, et al (2020) Pilot plant initial results for the methanation process using CO2 from amine scrubbing at the Łaziska power plant in Poland. Fuel 263:116804. https://doi.org/10.1016/j.fuel.2019.116804

CO2 Stored Project Homepage CO2 Stored Homepage. http://www.co2stored.co.uk/home/index. Accessed 3 Jan 2023

Cobo Gutiérrez S (2015) Carbon footprint of biogenic carbon capture, storage and utilization via electrochemical reduction to methanol

Coda Zabetta E, Barisic V, Peltola K, Hotta A (2008) Foster Wheeler Experience with Biomass and Waste in CFBs

Coquelet C, Stringari P, Hajiw M, et al (2017) Transport of CO2: Presentation of New Thermophysical Property Measurements and Phase Diagrams. Energy Procedia 114:6844–6859. https://doi.org/10.1016/j.egypro.2017.03.1822

Cordero-Lanzac T, Ramirez A, Navajas A, et al (2021) A techno-economic and life cycle assessment for the production of green methanol from CO2: Catalyst and process bottlenecks. Journal of Energy Chemistry. https://doi.org/10.1016/j.jechem.2021.09.045

Cormos Ana-Maria, Dragan Simion, Petrescu Letitia, et al (2019) Reducing Carbon Footprint of Energy-Intensive Applications by CO2 Capture Technologies: An Integrated Technical and Environmental Assessment. Chemical Engineering Transactions 76:1033–1038. https://doi.org/10.3303/CET1976173

Corsten M, Ramírez A, Shen L, et al (2013) Environmental impact assessment of CCS chains – Lessons learned and limitations from LCA literature. International Journal of Greenhouse Gas Control 13:59–71. https://doi.org/10.1016/j.ijggc.2012.12.003

Cuéllar-Franca RM, Azapagic A (2015a) Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of CO2 Utilization 9:82–102. https://doi.org/10.1016/j.jcou.2014.12.001

Cuéllar-Franca RM, Azapagic A (2015b) Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of CO2 Utilization 9:82–102. https://doi.org/10.1016/j.jcou.2014.12.001

Czaplicka-Kolarz K, Wachowicz J, Bojarska-Kraus M (2004) A life cycle method for assessment of a colliery's eco-indicator. Int J LCA 9:247–253. https://doi.org/10.1007/BF02978600

Davis RE, Markham JN, Kinchin CM, et al (2018) 2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling. National Renewable Energy Lab. (NREL), Golden, CO (United States)

De Falco M, Natrella G, Capocelli M, et al (2022) Exergetic Analysis of DME Synthesis from CO2 and Renewable Hydrogen. Energies 15:3516. https://doi.org/10.3390/en15103516

de Miranda PEV (ed) (2019) Chapter 5.3.2 - Application of Hydrogen Combustion for Electrical and Motive Power Generation. In: Science and Engineering of Hydrogen-Based Energy Technologies. Academic Press, pp 259–278

Deutz S, Bardow A (2021) Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Nat Energy 6:203–213. https://doi.org/10.1038/s41560-020-00771-9

Dincer I, Rosen MA, Al-Zareer M (2018) 3.11 Chemical Energy Production. In: Dincer I (ed) Comprehensive Energy Systems. Elsevier, Oxford, pp 470–520

DNV AS, Carbon Limits AS (2021) Re-Stream—Study on the Reuse of Oil and Gas Infrastructure for Hydrogen and CCS in Europe. Carbon Limits, Norway

Driver JG, Owen RE, Makanyire T, et al (2019) Blue Urea: Fertilizer With Reduced Environmental Impact. Front Energy Res 7:. https://doi.org/10.3389/fenrg.2019.00088

Dubiński J, Wachowicz J, Koteras A (2010) Podziemne składowanie dwutlenku węgla - możliwości wykorzystania technologii CCS w polskich uwarunkowaniach. Górnictwo i Geologia 5, Zeszyt 1:15

Dumée L, Scholes C, Stevens G, Kentish S (2012) Purification of aqueous amine solvents used in post combustion CO2 capture: A review. International Journal of Greenhouse Gas Control 10:443–455. https://doi.org/10.1016/j.ijggc.2012.07.005

Dziejarski B, Krzyżyńska R, Andersson K (2023) Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel 342:127776. https://doi.org/10.1016/j.fuel.2023.127776

Dzikuć M (2015) Environmental management with the use of LCA in the Polish energy system. Management 19:89–97. https://doi.org/10.1515/manment-2015-0007

Dzikuć M, Dzikuć M (2013) Determining the environmental and economic benefits of life cycle assessment on example of the power plants in Poland. Chinese Business Review Vol. 12, no. 12:846–852

Dzikuć M, Piwowar A (2015) Life Cycle Assessment as an Eco-Management Tool within the Power Industry. Pol J Environ Stud 24:2381–2385. https://doi.org/10.15244/pjoes/58889

e Silva DF de C (2006) DME as Alternative Diesel Fuel: Overview. pp 2006-01–2916

El-Shafie M (2023) Hydrogen production by water electrolysis technologies: A review. Results in Engineering 20:101426. https://doi.org/10.1016/j.rineng.2023.101426

EPLCA (2024) European Platform on LCA | EPLCA. https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html. Accessed 15 Jun 2024

European Commission (2019) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - The European Green Deal

European Commission, Joint Research Centre, Baleva S, et al (2021) SET plan progress report 2021: contributing to the EU Green Deal and the path forward to a green recovery. Publications Office

European Commission, Joint Research Centre, Institute for Environment and Sustainability (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance., 1st edn. Publications Office of the European Union, Luxembourg

European Environment Agency (2021) EEA greenhouse gases - data viewer — European Environment Agency. In: European Environment Agency Official Website. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer. Accessed 24 Oct 2022

Fabiszewska-Solares J, Kobyłka K, Laskowski K, et al (2021) Assessment of current state, past experiences and potential for CCS deployment in the CEE region. WiseEuropa, Poland

Facchino M, Popielak P, Panowski M, et al (2022) The Environmental Impacts of Carbon Capture Utilization and Storage on the Electricity Sector: A Life Cycle Assessment Comparison between Italy and Poland. Energies 15:6809. https://doi.org/10.3390/en15186809

Falco MD, Natrella G, Popielak P, Capocelli M (2022) Methodologies for CCU technologies environmental analysis. In: The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies. CRC Press

Farinha C, Brito J de, Veiga MD (2021) Chapter 8 - Life cycle assessment. In: Farinha C, Brito J de, Veiga MD (eds) Eco-Efficient Rendering Mortars. Woodhead Publishing, pp 205–234

Fernández-Dacosta C, van der Spek M, Hung CR, et al (2017) Prospective techno-economic and environmental assessment of carbon capture at a refinery and CO2 utilisation in polyol synthesis. Journal of CO2 Utilization 21:405–422. https://doi.org/10.1016/j.jcou.2017.08.005

Finkbeiner M, Inaba A, Tan R, et al (2006) The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. Int J Life Cycle Assessment 11:80–85. https://doi.org/10.1065/lca2006.02.002

Fortin C, Gianfolcaro N, Gonzalez R, et al (2020) Dimethyl ether, A review of production processes and a modeling of the indirect route. 20

Furre A-K, Eiken O, Alnes H, et al (2017) 20 Years of Monitoring CO2-injection at Sleipner. Energy Procedia 114:3916–3926. https://doi.org/10.1016/j.egypro.2017.03.1523

Garcia-Garcia G, Fernandez MC, Armstrong K, et al (2021) Analytical Review of Life-Cycle Environmental Impacts of Carbon Capture and Utilization Technologies. ChemSusChem 14:995–1015. https://doi.org/10.1002/cssc.202002126

Gładysz P, Sowiżdżał A, Miecznik M, Pająk L (2020) Carbon dioxide-enhanced geothermal systems for heat and electricity production: Energy and economic analyses for central Poland. Energy Conversion and Management 220:113142. https://doi.org/10.1016/j.enconman.2020.113142

Gładysz P, Ziębik A (2015a) Life cycle assessment of an integrated oxy-fuel combustion power plant with CO2 capture, transport and storage – Poland case study. Energy 92:328–340. https://doi.org/10.1016/j.energy.2015.07.052

Gładysz P, Ziębik A (2015b) Life cycle assessment of an integrated oxy-fuel combustion power plant with CO2 capture, transport and storage – Poland case study. Energy 92:328–340. https://doi.org/10.1016/j.energy.2015.07.052

Global CCS Institute (2019) Global status of CCS - Targeting climate change

Global CCS Institute (ed) (2021) Global Status of CCS 2021. CCS accelerating to net zero. Global CCS Institute Publications

Global CCS Institute B (2016) The global status of CCS 2016. Global CCS Institute

Global CCS Institute, Parsons Brinckerhoff (2011) Accelerating the uptake of CCS: industrial use of captured carbon dioxide

Guinée JB (2002) Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards. Kluwer Academic Publishers, Netherlands

Gulf Coast Carbon Centre (2018) Testing Offshore Monitoring Technologies near Tomakomai, Japan | Gulf Coast Carbon Center. In: Gulf Coast Carbon Centre. https://gccc.beg.utexas.edu/research/tomakomai-UHR3D. Accessed 25 May 2024

Halland E, Johansen WT, Riis F (2011) CO2 storage atlas - Norwegian North Sea

Harding FC, James AT, Robertson HE (2018) The engineering challenges of $CO_2$ storage. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 232:17–26. https://doi.org/10.1177/0957650918756542

Hasan MMF, Zantye MS, Kazi M-K (2022) Challenges and opportunities in carbon capture, utilization and storage: A process systems engineering perspective. Computers & Chemical Engineering 166:107925. https://doi.org/10.1016/j.compchemeng.2022.107925

Hendriks C, Crijns-Graus W, Bergen F (2004) Global Carbon Dioxide Storage Potential and Costs

Herold A, Monni S, Erda L, et al (2010) Methodological choice and identification of key categories. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change

Herold J, Ruester S, Von Hirschhausen C (2011) Carbon Capture; Transport and Storage in Europe: A Problematic Energy Bridge to Nowhere? SSRN Journal. https://doi.org/10.2139/ssrn.1736496

Ho H-J, Iizuka A, Shibata E (2019) Carbon Capture and Utilization Technology without Carbon Dioxide Purification and Pressurization: A Review on Its Necessity and Available Technologies. Ind Eng Chem Res 58:8941–8954. https://doi.org/10.1021/acs.iecr.9b01213

Höller S, Viebahn P (2011) Assessment of CO2 storage capacity in geological formations of Germany and Northern Europe. Energy Procedia 4:4897–4904. https://doi.org/10.1016/j.egypro.2011.02.458

Holloway S (2009) Storage capacity and containment issues for carbon dioxide capture and geological storage on the UK continental shelf. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 223:239–248. https://doi.org/10.1243/09576509JPE650

Hong WY (2022) A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO2 emissions future. Carbon Capture Science & Technology 3:100044. https://doi.org/10.1016/j.ccst.2022.100044

Hosseini S, Aslani A, Kasaeian A (2023) Life cycle cost and environmental assessment of CO2 utilization in the beverage industry: A natural gas-fired power plant equipped with post-combustion CO2 capture. Energy Reports 9:414–436. https://doi.org/10.1016/j.egyr.2022.11.200

Hotta A (2010) Foster Wheeler's Solutions for Large Scale CFB Boiler Technology: Features and Operational Performance of Łagisza 460 MWe CFB Boiler. In: Yue G, Zhang H, Zhao C, Luo Z (eds) Proceedings of the 20th International Conference on Fluidized Bed Combustion. Springer, Berlin, Heidelberg, pp 59–70

Hotta A, Psik Rafał (2013) Testing and simulation in Turow Unit 3 and the application of the results on the Lagisza 460 MWe OT CFB

Hussain D, Dzombak DA, Jaramillo P, Lowry GV (2013) Comparative lifecycle inventory (LCI) of greenhouse gas (GHG) emissions of enhanced oil recovery (EOR) methods using different CO2 sources. International Journal of Greenhouse Gas Control 16:129–144. https://doi.org/10.1016/j.ijggc.2013.03.006

IEA (2024) Capacity of large-scale CO2 capture projects, current and planned vs. the Net Zero Scenario, 2020-2030 – Charts – Data & Statistics. In: IEA. https://www.iea.org/data-and-statistics/charts/capacity-of-large-scale-co2-

capture-projects-current-and-planned-vs-the-net-zero-scenario-2020-2030. Accessed 16 Jun 2024

IEA (2017a) IEA GHG Technical Review: CCS Industry build-out rates - comparison with industry analogues. In: IEAGHG Document Manager. https://documents.ieaghg.org/index.php/s/ZYF3XPcXBFpscpV. Accessed 23 May 2024

IEA (2020) Innovation needs in the Sustainable Development Scenario – Clean Energy Innovation – Analysis. In: IEA. https://www.iea.org/reports/clean-energy-innovation/innovation-needs-in-the-sustainable-development-scenario. Accessed 26 Jun 2024

IEA (2018) US budget bill may help carbon capture get back on track – Analysis. IEA

IEA (2017b) Energy Technology Perspectives 2017 – Catalysing Energy Technology Transformations. International Energy Agency, Paris

Igliński B, Piechota G, Kiełkowska U, et al (2022) The assessment of solar photovoltaic in Poland: the photovoltaics potential, perspectives and development. Clean Techn Environ Policy. https://doi.org/10.1007/s10098-022-02403-0

Intergovernmental Panel on Climate Change, Metz B, Davidson O, et al (eds) (2005) IPCC special report on carbon dioxide capture and storage. Cambridge University Press, for the Intergovernmental Panel on Climate Change, Cambridge

International Energy Agency (2021) Poland. In: IEA. https://www.iea.org/countries/poland. Accessed 17 Apr 2023

International Organization for Standardization (2014) ISO 14040:2006. In: ISO. https://www.iso.org/standard/37456.html. Accessed 9 May 2023

IOGP (2019) The potential for CCS and CCU in Europe

IRENA and Methanol Institute (2021) Innovation Outlook: Renewable Methanol. International Renewable Energy Agency, Abu Dhabi

Jackson S, Brodal E (2018) A comparison of the energy consumption for $CO_2$ compression process alternatives. IOP Conf Ser: Earth Environ Sci 167:012031. https://doi.org/10.1088/1755-1315/167/1/012031

Japan CCS Homepage (2024) Tomakomai CCS demonstration project. In: Japan CCS. https://www.japanccs.com/en/business/demonstration/index.php. Accessed 25 May 2024

Jensen MD, Azzolina ND, Schlasner SM, et al (2018) A screening-level life cycle greenhouse gas analysis of CO2 enhanced oil recovery with CO2 sourced from the Shute Creek natural gas-processing facility. International Journal of

Greenhouse Gas Control 78:236–243. https://doi.org/10.1016/j.ijggc.2018.08.010

Jiang K, Ashworth P, Zhang S, et al (2020) China's carbon capture, utilization and storage (CCUS) policy: A critical review. Renewable and Sustainable Energy Reviews 119:109601. https://doi.org/10.1016/j.rser.2019.109601

Jiang Y, Lei Y, Yang Y, Wang F (2018) Life Cycle CO2 Emission Estimation of CCS-EOR System Using Different CO2 Sources. Pol J Environ Stud 27:2573–2583. https://doi.org/10.15244/pjoes/80897

Kang Z, Liao Q, Zhang Z, Zhang Y (2022) Carbon neutrality orientates the reform of the steel industry. Nat Mater 21:1094–1098. https://doi.org/10.1038/s41563-022-01370-7

Kearns J, Teletzke G, Palmer J, et al (2017) Developing a Consistent Database for Regional Geologic CO2 Storage Capacity Worldwide. Energy Procedia 114:4697–4709. https://doi.org/10.1016/j.egypro.2017.03.1603

Khetkorn W, Rastogi RP, Incharoensakdi A, et al (2017) Microalgal hydrogen production – A review. Bioresource Technology 243:1194–1206. https://doi.org/10.1016/j.biortech.2017.07.085

Kim HJ, Suh HK, Park SH, Lee CS (2008) An Experimental and Numerical Investigation of Atomization Characteristics of Biodiesel, Dimethyl Ether, and Biodiesel−Ethanol Blended Fuel. Energy Fuels 22:2091–2098. https://doi.org/10.1021/ef700692w

Kolster C, Masnadi MS, Krevor S, et al (2017) CO2 enhanced oil recovery: a catalyst for gigatonne-scale carbon capture and storage deployment? Energy Environ Sci 10:2594–2608. https://doi.org/10.1039/C7EE02102J

Koytsoumpa EI, Bergins C, Kakaras E (2018a) The CO2 economy: Review of CO2 capture and reuse technologies. The Journal of Supercritical Fluids 132:3–16. https://doi.org/10.1016/j.supflu.2017.07.029

Koytsoumpa EI, Bergins C, Kakaras E (2018b) The CO2 economy: Review of CO2 capture and reuse technologies. The Journal of Supercritical Fluids 132:3–16. https://doi.org/10.1016/j.supflu.2017.07.029

Krzywanski J, Czakiert T, Blaszczuk A, et al (2015) A generalized model of SO2 emissions from large- and small-scale CFB boilers by artificial neural network approach. Fuel Processing Technology 137:66–74. https://doi.org/10.1016/j.fuproc.2015.04.012

Lelek L, Kulczycka J, Lewandowska A, Zarebska J (2016) Life cycle assessment of energy generation in Poland. Int J Life Cycle Assess 21:1–14. https://doi.org/10.1007/s11367-015-0979-3

Leonzio G, Bogle IDL, Ugo Foscolo P (2023) Life cycle assessment of a carbon capture utilization and storage supply chain in Italy and Germany: Comparison between carbon dioxide storage and utilization systems. Sustainable Energy Technologies and Assessments 55:102743. https://doi.org/10.1016/j.seta.2022.102743

Leung DYC, Caramanna G, Maroto-Valer MM (2014) An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews 39:426–443. https://doi.org/10.1016/j.rser.2014.07.093

Li W, Xu D, Ding S, Dong L (2023) Sustainability assessment of CCS technologies by combining multi-criteria decision making with life cycle assessment. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-023-02155-z

Ling J, Ntiamoah A, Xiao P, et al (2014) Overview of CO2 capture from flue gas streams by vacuum pressure swing adsorption technology. Austin J Chem Eng 1:1–7

Liu M, Wen H, Fan S, et al (2022) Experimental Study of CO2-ECBM by Injection Liquid CO2. Minerals 12:297. https://doi.org/10.3390/min12030297

Majchrzak-Kucęba I (2022) CO2: A useful reactant. In: The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies. CRC Press

Majchrzak-Kucęba I, Wawrzyńczak D, Ściubidło A, et al (2019) Stability and regenerability of acivated carbon used for CO2 removal in pilot DR-VPSA unit in real power plant conditions. Journal of CO2 Utilization 29:1–11. https://doi.org/10.1016/j.jcou.2018.11.003

Majchrzak-Kucęba I, Wawrzyńczak D, Zdeb J, et al (2021) Treatment of Flue Gas in a CO2 Capture Pilot Plant for a Commercial CFB Boiler. Energies 14:2458. https://doi.org/10.3390/en14092458

Makoś P, Słupek E, Sobczak J, et al (2019) Dimethyl ether (DME) as potential environmental friendly fuel. E3S Web Conf 116:00048. https://doi.org/10.1051/e3sconf/201911600048

Marchi B, Zanoni S, Pasetti M (2018) Industrial Symbiosis for Greener Horticulture Practices: The CO2 Enrichment from Energy Intensive Industrial Processes. Procedia CIRP 69:562–567. https://doi.org/10.1016/j.procir.2017.11.117

Marks-Bielska R, Bielski S, Pik K, Kurowska K (2020) The Importance of Renewable Energy Sources in Poland's Energy Mix. Energies 13:4624. https://doi.org/10.3390/en13184624

McQueen N, Gomes KV, McCormick C, et al (2021) A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Prog Energy 3:032001. https://doi.org/10.1088/2516-1083/abf1ce

Melo F, Morlanés N (2005) Naphtha steam reforming for hydrogen production. Catalysis Today 107–108:458–466. https://doi.org/10.1016/j.cattod.2005.07.028

Mika-Brysk M, Wróblewska E (2015) Polskie podejście do CCS w świetle aktualnego statusu rozwoju tej technologii. Przegląd Geologiczny 63:4

Mikunda T, Brunner L, Skylogianni E, et al (2021) Carbon capture and storage and the sustainable development goals. International Journal of Greenhouse Gas Control 108:103318. https://doi.org/10.1016/j.ijggc.2021.103318

Ministerstwo Klimatu i Środowiska (2023) Projekt ustawy o Prawo geologiczne przyjęty przez Radę Ministrów - Portal Gov.pl. In: Ministerstwo Klimatu i Środowiska. https://www.gov.pl/web/klimat/projekt-ustawy-o-prawo-geologiczne-przyjety-przez-rade-ministrow2. Accessed 16 May 2023

Ministry of Climate and Environment (2021) Energy Policy of Poland until 2040 (EPP2040) - Ministry of Climate and Environment. In: Ministry of Climate and Environment. https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040. Accessed 20 Jan 2023

Mirek P (2019) Experimental investigation of the flow characteristics of low-pressure drop air nozzles working with CFB boilers. E3S Web Conf 82:01013. https://doi.org/10.1051/e3sconf/20198201013

Modahl IS, Askham C, Lyng K-A, Brekke A (2012) Weighting of environmental trade-offs in CCS—an LCA case study of electricity from a fossil gas power plant with post-combustion CO2 capture, transport and storage. Int J Life Cycle Assess 17:932–943. https://doi.org/10.1007/s11367-012-0421-z

Monitor Polski (2021) Obwieszczenie Ministra Klimatu i Środowiska z dnia 2 marca 2021 r. w sprawie polityki energetycznej państwa do 2040 r.

Monteiro J, Roussanaly S (2022) CCUS scenarios for the cement industry: Is CO2 utilization feasible? Journal of CO2 Utilization 61:102015. https://doi.org/10.1016/j.jcou.2022.102015

Morales Mora MA, Pretelín Vergara FC, Martínez Delgadillo SA, Leiva MA (2017) Comparison of carbon balance measuring tools in an enhanced oil recovery project based on the carbon dioxide from the ammonia production process streams. Journal of Cleaner Production 144:540–552. https://doi.org/10.1016/j.jclepro.2016.12.114

Morales Mora MA, Vergara CP, Leiva MA, et al (2016) Life cycle assessment of carbon capture and utilization from ammonia process in Mexico. Journal of Environmental Management 183:998–1008. https://doi.org/10.1016/j.jenvman.2016.09.048

Morales-Mora MA, Pretelìn-Vergara CF, Martínez-Delgadillo SA, et al (2019) Environmental assessment of a combined heat and power plant configuration

proposal with post-combustion CO2 capture for the Mexican oil and gas industry. Clean Techn Environ Policy 21:213–226. https://doi.org/10.1007/s10098-018-1630-3

Mostafa M, Antonicelli C, Varela C, et al (2022) Capturing CO2 from the atmosphere: Design and analysis of a large-scale DAC facility. Carbon Capture Science & Technology 4:100060. https://doi.org/10.1016/j.ccst.2022.100060

Müller L, Kätelhön A, Bringezu S, et al (2020a) The carbon footprint of the carbon feedstock CO2. Energy & Environmental Science 13:. https://doi.org/10.1039/D0EE01530J

Müller LJ, Kätelhön A, Bachmann M, et al (2020b) A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. Frontiers in Energy Research 8:

Müller M, Hübsch U (2000) Dimethyl Ether. In: Wiley-VCH Verlag GmbH & Co. KGaA (ed) Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, p a08_541

Neele F, Hendriks C, Brandsma R, Blomen E (2006) EU GeoCapacity Assessing European Capacity for Geological Storage of Carbon Dioxide. Geological Survey of the Netherlands

NEPIS (2006) US EPA Life Cycle Assessment: Principles and Practice

Nijborg DM (2022) The difference between the public acceptance of CCUS and CCS in the Netherlands

Nikas A, Elia A, Boitier B, et al (2021) Where is the EU headed given its current climate policy? A stakeholder-driven model inter-comparison. Science of The Total Environment 793:148549. https://doi.org/10.1016/j.scitotenv.2021.148549

Nogueira R, Silva A, Bogas JA (2022) Strategies for carbon capture in concrete production. In: The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies. CRC Press

Nowak W, Mirek P (2013) Circulating fluidized bed combustion (CFBC). In: Fluidized Bed Technologies for Near-Zero Emission Combustion and Gasification. Elsevier, pp 701–764

Nuñez-Lopez V, Gil-Egui R, Hosseini S (2019a) CO2-EOR and GCS Co-Optimization with Carbon Lifecycle Analysis Considerations

Núñez-López V, Gil-Egui R, Hosseini SA (2019) Environmental and Operational Performance of CO2-EOR as a CCUS Technology: A Cranfield Example with Dynamic LCA Considerations. Energies 12:448. https://doi.org/10.3390/en12030448

Nuñez-Lopez V, Gil-Egui R, Hosseininoosheri P, et al (2019b) Carbon Life Cycle Analysis of CO2-EOR for Net Carbon Negative Oil (NCNO) Classification (Final Report). Univ. of Texas, Austin, TX (United States)

Okoye-Chine CG, Otun K, Shiba N, et al (2022) Conversion of carbon dioxide into fuels—A review. Journal of CO2 Utilization 62:102099. https://doi.org/10.1016/j.jcou.2022.102099

Olecka A, Bebkiewicz K, Chłopek Z, et al (2021) Krajowy raport inwentaryzacyjny 2021 Inwentaryzacja gazów cieplarnianych w Polsce dla lat 1988-2019

Ott J, Gronemann V, Pontzen F, et al (2012) Methanol. In: Wiley-VCH Verlag GmbH & Co. KGaA (ed) Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, p a16_465.pub3

Otto D, Pfeiffer M, de Brito MM, Groß M (2022) Fixed Amidst Change: 20 Years of Media Coverage on Carbon Capture and Storage in Germany. Sustainability 14:. https://doi.org/10.3390/su14127342

Pan S-Y, Chang EE, Chiang P-C (2012) CO2 Capture by Accelerated Carbonation of Alkaline Wastes: A Review on Its Principles and Applications. Aerosol Air Qual Res 12:770–791. https://doi.org/10.4209/aaqr.2012.06.0149

Parker ME, Meyer JP, Meadows SR (2009) Carbon Dioxide Enhanced Oil Recovery Injection Operations Technologies. Energy Procedia 1:3141–3148. https://doi.org/10.1016/j.egypro.2009.02.096

Parliament of the Republic of Poland (2011) Mining and Geological Law

Patricio J, Angelis-Dimakis A, Castillo-Castillo A, et al (2017) Method to identify opportunities for CCU at regional level — Matching sources and receivers. Journal of CO2 Utilization 22:330–345. https://doi.org/10.1016/j.jcou.2017.10.009

PGE Systemy S.A Ochrona środowiska - CCS demonstration plant. https://pgegiek.pl/ochrona-srodowiska/ccs/ccs-demonstration-plant2. Accessed 21 Jun 2024

Pietrzak MB, Igliński B, Kujawski W, Iwański P (2021) Energy Transition in Poland—Assessment of the Renewable Energy Sector. Energies 14:2046. https://doi.org/10.3390/en14082046

Popielak P, Majchrzak-Kucęba I, Wawrzyńczak D (2024) Climate change mitigation with CCUS - A case study with benchmarking for selected countries in adapting the European Union's Green Deal. International Journal of Greenhouse Gas Control 132:104057. https://doi.org/10.1016/j.ijggc.2023.104057

Przybojewska I (2018) Legal possibilities of carbon capture and storage in Poland. Law and Administration in Post-Soviet Europe 5:18–27. https://doi.org/10.2478/lape-2018-0003

PubChem Methane. https://pubchem.ncbi.nlm.nih.gov/compound/297. Accessed 22 Jun 2024

Raadal HL, Modahl IS (2022) Guidelines for Life Cycle Assessment (LCA) of CCU systems

Raadal HL, Modahl IS (2021) Life Cycle Assessment of CCS (carbon capture and storage) and CCU (carbon capture and utilization)

Ray RL, Singh VP, Singh SK, et al (2022) What is the impact of COVID-19 pandemic on global carbon emissions? Science of The Total Environment 816:151503. https://doi.org/10.1016/j.scitotenv.2021.151503

Read A, Tillema O, Ros M, et al (2014) Update on the ROAD Project and Lessons Learnt. Energy Procedia 63:6079–6095. https://doi.org/10.1016/j.egypro.2014.11.640

Roode-Gutzmer QI, Kaiser D, Bertau M (2019) Renewable Methanol Synthesis. ChemBioEng Reviews 6:209–236. https://doi.org/10.1002/cben.201900012

Rubinsin NJ, Karim NA, Timmiati SN, et al (2024) An overview of the enhanced biomass gasification for hydrogen production. International Journal of Hydrogen Energy 49:1139–1164. https://doi.org/10.1016/j.ijhydene.2023.09.043

Rumayor M, Dominguez-Ramos A, Irabien A (2019) Innovative alternatives to methanol manufacture: Carbon footprint assessment. Journal of Cleaner Production 225:426–434. https://doi.org/10.1016/j.jclepro.2019.03.015

Saastamoinen H, Leino T (2019) Fuel Staging and Air Staging To Reduce Nitrogen Emission in the CFB Combustion of Bark and Coal. Energy Fuels 33:5732–5739. https://doi.org/10.1021/acs.energyfuels.9b00850

Sala S, Wolf M-A, Pant R (2012) Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and supporting information

Sathre R, Masanet E, Cain J, Chester M (2011) The role of Life Cycle Assessment in identifying and reducing environmental impacts of CCS. Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States)

Scrase JI, Watson J (2009) Strategies for the deployment of CCS technologies in the UK: a critical review. Energy Procedia 1:4535–4542. https://doi.org/10.1016/j.egypro.2009.02.272

Shirley P, Myles P (2019) Quality Guidelines for Energy System Studies: $CO_2$ Impurity Design Parameters

Simons A, Bauer C (2011) Life cycle assessment of hydrogen production. In: Wokaun A, Wilhelm E (eds) Transition to Hydrogen: Pathways toward Clean Transportation. Cambridge University Press, Cambridge, pp 13–57

Skone TJ (2016) Is net carbon negative crude achievable with CO2 enhanced oil recovery? National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV (United States)

Skone TJ, Schivley G, Jamieson M, et al (2018) Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plants

Solomon S, Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change (eds) (2007) Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge ; New York

Sowiżdżał A, Starczewska M, Papiernik B (2022) Future Technology Mix—Enhanced Geothermal System (EGS) and Carbon Capture, Utilization, and Storage (CCUS)—An Overview of Selected Projects as an Example for Future Investments in Poland. Energies 15:3505. https://doi.org/10.3390/en15103505

Stec M, Tatarczuk A, Więcław-Solny L, et al (2015) Pilot plant results for advanced CO2 capture process using amine scrubbing at the Jaworzno II Power Plant in Poland. Fuel 151:. https://doi.org/10.1016/j.fuel.2015.01.014

Stewart RJ, Haszeldine RS (2015) Can Producing Oil Store Carbon? Greenhouse Gas Footprint of CO2EOR, Offshore North Sea. Environ Sci Technol 49:5788–5795. https://doi.org/10.1021/es504600q

Sun Y, Zhao Y, Yuan L (2018) CO2-ECBM in coal nanostructure: Modelling and simulation. Journal of Natural Gas Science and Engineering 54:202–215. https://doi.org/10.1016/j.jngse.2018.04.007

Talapatra A (2020) A study on the carbon dioxide injection into coal seam aiming at enhancing coal bed methane (ECBM) recovery. J Petrol Explor Prod Technol 10:1965–1981. https://doi.org/10.1007/s13202-020-00847-y

Tang D, Tan G-L, Li G-W, et al (2023) State-of-the-art hydrogen generation techniques and storage methods: A critical review. Journal of Energy Storage 64:107196. https://doi.org/10.1016/j.est.2023.107196

Tang L, Yokoyama T, Kubota H, Shimota A (2014) Life Cycle Assessment of a Pulverized Coal-fired Power Plant with CCS Technology in Japan. Energy Procedia 63:7437–7443. https://doi.org/10.1016/j.egypro.2014.11.780

Tarkowski R, Uliasz-Misiak B (2019) Prospects for the use of carbon dioxide in enhanced geothermal systems in Poland. Journal of Cleaner Production 229:1189–1197. https://doi.org/10.1016/j.jclepro.2019.05.036

Tatarczuk A, Więcław-Solny L, Stec M, et al (2013) First Polish Pilot Plant for CO2 Post Combustion Capture

The UK Government (2019) UK becomes first major economy to pass net zero emissions law. In: GOV.UK. https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law. Accessed 23 Dec 2022

The UK Government (2022) CCUS Investor Roadmap, 1st edn. UK Department for International Trade, London

The UK Government (2021) Carbon Capture, Usage and Storage: An update on the business model for industrial Carbon Capture

Theo WL, Lim JS, Hashim H, et al (2016) Review of pre-combustion capture and ionic liquid in carbon capture and storage. Applied Energy 183:1633–1663. https://doi.org/10.1016/j.apenergy.2016.09.103

Tomatis M, Mahmud Parvez A, Afzal MT, et al (2019) Utilization of CO2 in renewable DME fuel production: A life cycle analysis (LCA)-based case study in China. Fuel 254:115627. https://doi.org/10.1016/j.fuel.2019.115627

Tucker O, Tinios L (2017) Experience in Developing the Goldeneye Storage Permit Application. Energy Procedia 114:7466–7479. https://doi.org/10.1016/j.egypro.2017.03.1880

Turgut O, Bjerketvedt VS, Tomasgard A, Roussanaly S (2021) An integrated analysis of carbon capture and storage strategies for power and industry in Europe. Journal of Cleaner Production 329:129427. https://doi.org/10.1016/j.jclepro.2021.129427

U.S. Energy Information Administration (2016) International Energy Outlook 2016

van der Giesen C, Meinrenken CJ, Kleijn R, et al (2017) A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO2 versus MEA-Based Postcombustion Capture. Environ Sci Technol 51:1024–1034. https://doi.org/10.1021/acs.est.6b05028

Van Peteghem L, Sakarika M, Matassa S, et al (2022) Towards new carbon–neutral food systems: Combining carbon capture and utilization with microbial protein production. Bioresource Technology 349:126853. https://doi.org/10.1016/j.biortech.2022.126853

Vangkilde-Pedersen, Alier, Anghe, et al (2009a) WP2 Report – Storage capacity. EU GeoCapacity project – Assessing European Capacity for Geological Storage of Carbon Dioxide.

Vangkilde-Pedersen T, Kirk K, Smith N, et al (2009b) Assessing European Capacity for Geological Storage of Carbon Dioxide. GeoCapacity, Denmark

Vidas L, Castro R (2021) Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis. Applied Sciences 11:11363. https://doi.org/10.3390/app112311363

Vögele S, Rübbelke D, Mayer P, Kuckshinrichs W (2018) Germany's "No" to carbon capture and storage: Just a question of lacking acceptance? Applied Energy 214:205–218. https://doi.org/10.1016/j.apenergy.2018.01.077

Volkart K, Bauer C, Boulet C (2013) Life cycle assessment of carbon capture and storage in power generation and industry in Europe. International Journal of Greenhouse Gas Control 16:91–106. https://doi.org/10.1016/j.ijggc.2013.03.003

von der Assen N, Jung J, Bardow A (2013) Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls. Energy Environ Sci 6:2721. https://doi.org/10.1039/c3ee41151f

Wakeham VVA, Olchowya GA, Watson JTR (1990) The Transport Properties of Carbon Dioxide. J Phys Chem Ref Data 19:

Wawrzyńczak D, Majchrzak-Kucęba I, Pevida C, et al (eds) (2022a) The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies: A Case Study. CRC Press, Boca Raton

Wawrzyńczak D, Majchrzak-Kucęba I, Pevida C, et al (eds) (2022b) The Carbon Chain in Carbon Dioxide Industrial Utilization Technologies: A Case Study. CRC Press, Boca Raton

Wawrzyńczak D, Majchrzak-Kucęba I, Srokosz K, et al (2018) The pilot dual-reflux vacuum pressure swing adsorption unit for CO 2 capture from flue gas. Separation and Purification Technology 209:. https://doi.org/10.1016/j.seppur.2018.07.079

Wildbolz C (2007) Life Cycle Assessment of Selected Technologies for CO2 Transport and Sequestration. Institute of Environmental Engineering (IfU)

Wilkins R, Menefee AH, Clarens AF (2016) Environmental Life Cycle Analysis of Water and CO2-Based Fracturing Fluids Used in Unconventional Gas Production. Environ Sci Technol 50:13134–13141. https://doi.org/10.1021/acs.est.6b02913

Wójcicki A (2013) Rozpoznanie formacji i struktur do bezpiecznego geologicznego składowania CO2 wraz z ich programem monitorowania. Państwowy Instytut Geologiczny, Warszawa

Yadav S, Mondal SS (2022) A review on the progress and prospects of oxy-fuel carbon capture and sequestration (CCS) technology. Fuel 308:122057. https://doi.org/10.1016/j.fuel.2021.122057

Young B, Krynock M, Carlson D, et al (2019) Comparative environmental life cycle assessment of carbon capture for petroleum refining, ammonia production, and thermoelectric power generation in the United States. International Journal of Greenhouse Gas Control 91:102821. https://doi.org/10.1016/j.ijggc.2019.102821

Zahasky C, Krevor S (2020) Global geologic carbon storage requirements of climate change mitigation scenarios. Energy & Environmental Science 13:. https://doi.org/10.1039/D0EE00674B

Zero Emission Platform (2019) CO2 Storage Safety in the North Sea: Implications of the CO2 Storage Directive

Zero-Emission Platform CCS/CCU projects. In: Zero Emissions Platform. https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/. Accessed 23 Nov 2022

Zhang J, Webley PA, Xiao P (2008) Effect of process parameters on power requirements of vacuum swing adsorption technology for CO2 capture from flue gas. Energy Conversion and Management 49:346–356. https://doi.org/10.1016/j.enconman.2007.06.007

Zhang X, Schwarze M, Schomäcker R, et al (2023) Life cycle net energy assessment of sustainable H2 production and hydrogenation of chemicals in a coupled photoelectrochemical device. Nat Commun 14:991. https://doi.org/10.1038/s41467-023-36574-1

Zhang Y, Zhang S, Benson T (2015) A conceptual design by integrating dimethyl ether (DME) production with tri-reforming process for CO2 emission reduction. Fuel Processing Technology 131:7–13. https://doi.org/10.1016/j.fuproc.2014.11.006

Zimmermann A, Müller LJ, Marxen A, et al (2018) Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO2 Utilization

20 Years of Carbon Capture and Storage - Accelerating Future Deployment. Carbon Capture

(2015) Diesel fuel. In: Handbook of Petroleum Product Analysis. John Wiley & Sons, Inc, Hoboken, NJ, pp 155–168