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Potential of Carbon Capture Usage Technologies in Austria: A Qualitative Assessment

A Master's Thesis submitted for the degree of
“Master of Science”

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Affidavit

I, **M.SC.LINA MARÍA MEJÍA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "POTENTIAL OF CARBON CAPTURE USAGE TECHNOLOGIES IN AUSTRIA: A QUALITATIVE ASSESSMENT", 104 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

Carbon Capture and Utilization (CCU) is emerging as a transformative technology to combat climate change by capturing carbon dioxide (CO_2) emissions and converting them into valuable products, thereby reducing their environmental impact. This study focuses on the potential of CCU technology in Austria, examining its role in decarbonizing industries and achieving environmental objectives while considering Austria's specific needs, policies, Technology Readiness Level (TRL), and societal acceptance.

Innovative CCU technologies are in the early stages of development and face cost challenges, with CO_2 capture expenses varying widely, ranging from €44 million to over €200 million. These economic hurdles hinder the widespread adoption of CCU in industries such as iron, steel, and cement, primarily due to substantial initial capital expenditures (CAPEX). However, Austria has identified promising pathways for CO_2 utilization that align with its environmental goals. One such pathway involves the mineral carbonation of steel slag, which captures CO_2 while converting it into valuable calcium carbonate for construction materials, reducing carbon emissions and promoting sustainability. Additionally, producing plastics from CO_2 offers another avenue, creating sustainable materials and mitigating climate change. These pathways play a pivotal role in fulfilling Austria's environmental objectives, contributing to reduced carbon footprints and sustainable resource use.

Austria's commitment to achieving a 100% renewable energy mix by 2030 enhances the feasibility and significance of CCU technologies. Nevertheless, several obstacles impede CCU adoption in Austria's industrial sector, including high upfront costs, uncertainty regarding carbon pricing and policies, and the need for technological advancements. To address these challenges and promote CCU adoption, Austria should consider tailored policies, such as subsidies, tax incentives, and carbon pricing mechanisms, while providing regulatory certainty. Fostering research and development efforts to advance CCU technology, improve efficiency, and reduce costs is crucial. Additionally, creating partnerships between the government, academia, and industry can facilitate knowledge sharing and innovation in the CCU sector, ensuring Austria accelerates its transition toward a sustainable industrial landscape.

In essence, CCU offers significant emissions reduction potential through integration with renewables, CO_2 capture from high-emission industries, circular economy principles, carbon pricing, technological advancements, rigorous lifecycle assessments, and sustainable product demand. Effective CCU hinges on secure, long-term fossil CO_2 storage in products while minimizing additional emissions during manufacturing, needing comprehensive LCAs. Key

products for emission reduction via CCU include construction materials, plastics, chemicals, and fossil-based product alternatives. Overall, CCU holds promise in combating climate change, transforming the carbon economy, and promoting sustainability, demanding a thorough evaluation of our transition to a greener future.

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CHAPTER 1

1 INTRODUCTION

Since the outbreak of the industrial revolution, global greenhouse gas (GHG) emissions have risen to unparalleled levels; the average levels of carbon dioxide in the atmosphere have increased considerably, from 172-300 ppm before the last industrial era to 419 ppm in May 2021 (Peres *et al*., 2022). This increase in emissions has led to a rise in the average global temperature by one degree (IPCC, 2015). Many of these emissions, principally carbon dioxide (CO_2), are caused by fossil fuels, deforestation, and agriculture, which significantly contribute to climate change, accounting for an estimated 75% of total GHG emissions (IEA, 2021a).

1.1 Background and motivation

One of civilization's most serious issues is the transition to sustainable energy sources to address climate change because the vast majority of emissions are caused by the world's reliance on fossil fuels and the recent growth in global energy consumption (Ahmad & Zhang, 2020). Despite efforts to include more renewable energy and cut off emissions from economic growth, energy demand is estimated to rise by 5-10% between 2019 and 2030. Transitioning towards low-emission energy systems is imperative (IEA, 2020d).

Austrian industry and the energy sector are responsible for roughly 37% of national GHG emissions. Approximately 110 TWh of energy is needed annually regarding the carbon footprint of all industrial facilities and processes in Austria, accounting for about 27% of the country's total gross domestic product (GDP). In 2019, industrial emissions of GHG reached 27.1 Mt of CO_{2eq}, a 15.8% increase from 1990 levels. To reduce emissions to 10.5 Mt of CO_{2eq} by 2030, a 61% reduction from 2019 levels is necessary (AIT, 2021).

Still, Austrian industries and related services contribute over EUR 75 billion to the country's gross value creation (Statistik Austria, 2021), accounting for 34% of the total value added in Austria. Furthermore, this sector provides jobs for over 960,000 people, almost one in three employees in the country. These contributions demonstrate that a decarbonization strategy that pushes out industrial companies is not a viable solution. Therefore, cost-effective options for decarbonizing these companies must be proposed to avoid the risk of companies leaving (AIT, 2021).

The European Union established an emission trading system (EU-ETS) in 2005, intending to reduce CO_2 emissions by providing incentives by allocating emission allowances. Also, it has implemented political policies and measures such as a higher share of renewable energy and increasing energy efficiency (IEA, 2020a).

The United Nations adopted the Paris Agreement in 2015 to restrict global GHG emissions to prevent global warming from surpassing 2 ºC above pre-industrial levels, aiming to keep it to 1.5 ºC (UNFCCC, 2016). Additionally, the European Union (EU) and its member states have taken action by launching the European Green Deal (EGD), which addresses the challenges posed by climate change and environmental degradation (European Commission, 2020a). The EGD includes the "Fit for 55 package", which commits the EU to become climate neutral by 2050, reaching 40% renewable energy by 2030, and reducing net emissions by 55% in 2030 compared to 1990 levels (European Commission, 2021).

The Austrian federal government has set a goal of eliminating carbon emissions from its energy sector and entire economy by 2040. It is actively working towards this goal as part of its current legislative program (EIA Bioenergy, 2021). The Austrian National Energy and Climate Plan (NECP) for 2021 to 2030 is based on the United Nations Sustainable Development Goals (SDGs), and the climate targets are listed in Table 1.

Table 1. Renewable energy and climate targets in Austria.

Sector	Share of renewables in gross final consumption per sector	GHG reduction target compared to base year 2005
Overall target	46-50% by 2030	36% by 2030 in non-ETS sectors, 100% by 2050
Heating and cooling	Strategy under development	100% by 2050
Electricity	National net annual balance of 100% by 2030	100% by 2050
Transport	Minimum 14% by 2030	100% by 2050

Source: EIA Bioenergy (2021).

As stated before, Austria has set a goal to achieve climate neutrality before 2050, excluding the use of nuclear energy. The country will offset any unavoidable GHG emissions, such as those from agriculture and production, by storing carbon in natural or artificial sinks (EIA Bioenergy, 2021). CCS is the central aim of Austria's 2050 long-term climate strategy; nevertheless, why store the carbon when it can be used?

1.2 Research Problem

Austria is shifting towards a highly efficient and climate-neutral energy, mobility, and economic system that covers every aspect of energy production (generation, transportation, conversion, and consumption) and all related products and services (IEA Bioenergy, 2021). To limit global warming under 2 ºC, annual CO_2 emissions must be reduced to less than 9.5

Gt by 2050, a 73% reduction from 2021 levels (Saidi & Omri, 2020; IEA, 2021b). The International Energy Agency (IEA) notes that the substantial efforts to adopt renewable and fossil-free energy sources will not be enough and that carbon removal methods will be essential in reducing atmospheric CO_2 concentration to meet the goals outlined in the Paris Agreement and 2030 Agenda (IEA, 2016).

Therefore, the idea of Carbon Capture and Utilization (CCU) technology takes relevance since one of the main objectives is to reduce the atmospheric CO_2 levels either by removing it through direct air capture (DAC) or by capturing CO_2 emissions from concentrated point sources (CPS); and then using it in products (Bolland & Nord, 2020). CCU technology cannot only cut CO_2 emissions but also serve as a source of raw materials to support a circular economy and help achieve ambitious environmental goals.

1.3 Aims of the Study

This study aims to perform a qualitative assessment for developing CCU technology in Austria to help decarbonize the industry sector and as a valuable tool to fulfill environmental goals regarding climate change. To achieve this, the study extensively reviewed existing CCU technologies in Europe, with a specific focus on Austria. The review aimed to understand Austria's progress in adopting CCU technologies for sustainable innovation and its alignment with policies. This involved looking into industry requirements, current approaches, policy measures, plans, and rules related to using captured CO_2, as well as societal and political acceptance of implementing this technology.

To give complementary knowledge and to fulfill the purpose of this thesis, one leading and three supplementary research questions were formulated:

Is it possible for Austria to develop CCU technology on a broad scale to meet environmental goals?

The country has a long history of energy and sustainability innovation and research. In addition, the country's strong industrial base, highly skilled workforce, and commitment to sustainability make Austria well-positioned to significantly contribute to developing and deploying CCU technology, helping meet its environmental goals and the global effort to address climate change.

1. **Which paths offer the most significant potential for the utilization of captured CO_2, and what role CCU play in fulfilling Austria's environmental goals?**

It is essential to identify the methods and the market of captured CO_2 for upscaling CCU technology in Austrian industries and which are the current goals and strategies that align with the adoption of this technology.

2. **What is preventing Austria's industrial sector from widespread adoption of CCU technology, and what actions could bring about a change?**

The concept of CCU has been studied and advanced in recent years; however, the future role of CO_2 in society is still being determined. Therefore, understanding the current policies and how plans will impact the demand and supply of captured CO_2 is crucial.

3. **What is CCU technology's technical and economic potential in Austria, and what are the key motivators and obstacles to utilizing captured CO_2?**

Different challenges may arise depending on the methods employed for capturing CO_2 and the utilization of the captured CO_2, including economic, technical, political, and logistical challenges.

1.4 Structure of the document

Chapter 1 introduces the background and motivation for this thesis, the research problem, and the aims of this study.

Chapter 2 focuses mainly on the CCU technology, describing technical aspects and specifications for capturing and using carbon. It also contains data related to the context of this technology in Europe, its status in Austria, and how it helps to fulfill environmental goals.

Chapter 3 contains the methodology used for gathering all information for the qualitative analysis and the framework for assessing the viability of the business cases.

Chapter 4 shows the results and the analysis of the state of CCU technology in Europe and in Austria, and describes the results obtained for each business case.

Chapter 5 contains the discussion and summarizes the findings giving a path for future methods and research directions.

Chapter 6 concludes with the final remarks.

CHAPTER 2

2 CARBON CAPTURE AND UTILIZATION FUNDAMENTALS

Despite the decline in GHG emissions, there will still be processes that produce CO_2. To prevent climate change from exceeding its limits, it is necessary to avoid this unavoidable CO_2 from being released into the atmosphere. CCU technology can effectively address this issue (Haerens, 2017). In 2018, the total global utilization of CO_2 was around 230 Mty (IEA, 2019), a relatively small amount compared to the more than 36,000 Mty of CO_2 emissions generated by human activities (IEA, 2022b).

CCU technology is becoming increasingly significant because it aims to repurpose CO_2 as a raw material, provide the benefits of climate change mitigation, and produce economically viable products. This can be seen in substituting fossil fuels, the chemical industry, or creating new carbon-based materials (Peres *et al.*, 2022).

2.1 Carbon Capture

The challenges of capturing CO_2 vary depending on the industry. For example, power plants with extensive industrial processes produce approximately 50% of global human-caused emissions and tend to have many flue gases concentrated in a few areas, while transportation emissions come from numerous dispersed sources (Goeppert *et al.*, 2012; Ritchie, 2020).

Capture rates can vary greatly depending on the number of point sources at a facility; if emissions are concentrated at one source, capture costs are lower, but high capture rates can be too expensive if emissions are distributed across several sources (Olsson *et al.*, 2020). Carbon capture projects cost around USD 60-110 per ton globally and are expected to drop to around USD 30-50 per ton by 2030 (Peres *et al.*, 2022). The energy efficiency of the capture process and the GHG footprint of the energy used for capture also affect the CO_2 balance of the capture stage. Figure 1 illustrates the significant variation in energy demands of CO_2 capture in different sectors and processes (Olsson *et al.*, 2022).

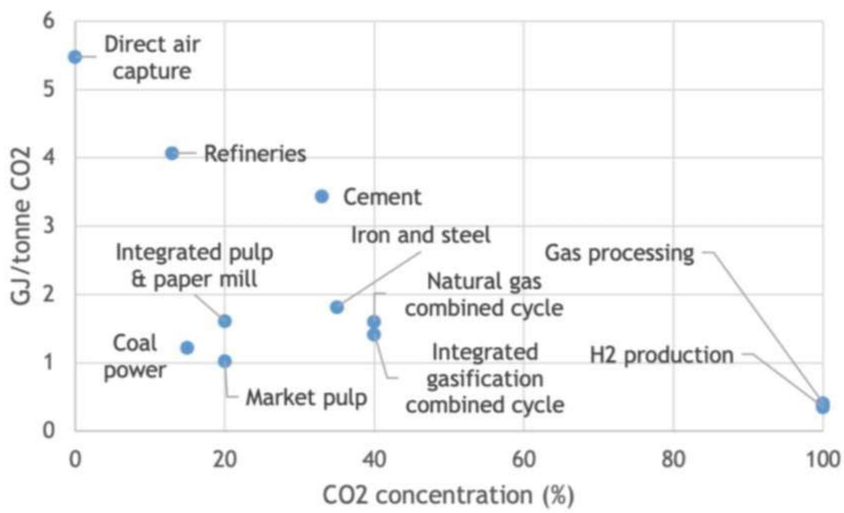


*Figure 1. Energy demands CO_2 capture in different sectors and processes (*Source*: von der Assen et al. (2016)* In *Olsson et al. (2022)*.

The primary methods for capturing CO_2 are direct air capture (DAC) and concentrated point source capture (CPSC). The goal of DAC is to remove the CO_2 already in the atmosphere, while CPSC is used to extract CO_2 from an exhaust or flue gas, preventing CO_2 from being released into the atmosphere (Granér & Johansson, 2022).

2.1.1 Direct Air Capture

This technology is seen as a critical solution to capture CO_2 emissions, particularly from dispersed sources responsible for roughly half of global CO_2 emissions (Goeppert *et al.*, 2012). It primarily employs two techniques: solid sorbent, which uses porous materials to adsorb CO_2, and liquid solvent, involving basic hydroxides to absorb CO_2 directly from the atmosphere (McQueen *et al.*, 2021).

DAC technology is not widely adopted outside of academic research and a few startups because is energy-intensive and involves processing large volumes of air to capture CO_2 due to the low atmospheric CO_2 concentration (0.04%). To ensure sustainability, DAC should use renewable energy sources or waste heat for power (Meylan *et al.*, 2015). The cost of capturing CO_2 via DAC ranges from 200 to 1,000 €$_{2018}$/t CO_2 and about 1,200 kWh to remove a ton of CO_2 (Van Dael, 2018). In regions with abundant renewable energy resources and advanced energy technologies, DAC costs could potentially drop to under USD 100 per ton of CO_2 by 2030 (IEA, 2022a).

2.1.2 Concentrated Point Source Capture

There are three main methods for capturing CO_2 from point sources: pre-combustion, post-combustion, and oxyfuel combustion. Post-combustion is the most widely used globally.

These methods differ in when they extract CO_2 during the combustion process. All methods aim to achieve a higher concentration of CO_2 in the gas stream as this typically reduces the cost of separation (Peres *et al.*, 2022). Flue gases from natural gas-fired power plants typically consist of 8-10% CO_2, 18-20% H_2O, 2-3% O_2, and 67-72% N_2 (Ababneh *et al.*, 2022). The concentration of CO_2 in flue gases from various sources can vary, helping determine the available gas for different industries and assisting in the selection of appropriate carbon capture technologies (Table 2).

Table 2. The concentration of CO_2 of different flue gases.

Flue gas source	CO_2 concentration (%)	P (atm)	CO_2 partial pressure (atm)
Gas turbine	3–4	1	0.03–0.04
Fired boiler of oil refinery and petrochemical plant	~8	1	0.08
Natural gas fired boilers	7–10	1	0.07–0.10
Oil-fired boilers	11–13	1	0.11–0.13
Coal-fired boilers	12–14	1	0.12–0.14
IGCC after combustion	12–14	1	0.12–0.14
Hydrogen production	15–20	22-27	3–5
Steel production (blast furnace)	20–27	1-3	0.2–0.6
Aluminum production	1–2	1	0.01–0.02
Cement process	14–33	1	0.14–0.33

Source: Metz et al. (2005); Husebye et al. (2012); Liguori & Wilcox (2018).

Typical costs of capture at significant point sources are estimated in the range of USD 20-100/t CO_2 (Meylan *et al.*, 2015). According to Lucquiaud *et al.* (2013), the efficiency penalty for a plant, including carbon capture with current solvent technology, is typically between 250-300 kWh/t CO_2. Additionally, compressing the CO_2 requires an estimated 90-120 kWh/t CO_2 of electrical power, which accounts for 30 to 50% of the total energy consumption in the plant. As the technology for capturing CO_2 improves, the energy consumption of the compression process will become increasingly important (Zep, 2011; Jackson & Brodal, 2018; Baroudi *et al.*, 2021).

2.1.2.1 Pre-combustion

Involves converting hydrocarbon-rich fuel into syngas, composed of carbon monoxide (CO) and hydrogen gas (H_2). This process partially oxidizes the fuel, allowing for the separation and utilization of hydrogen while capturing CO_2 as a byproduct. CO_2 separation in pre-combustion methods can be achieved through physical or chemical absorption, with CO_2 concentrations in the flue gas ranging from 15-60% (dry basis) at pressures of 2-7 Mpa (Gazzani *et al.*, 2013; Wang & Song, 2020; Olabi *et al.*, 2022).

Pre-combustion methods offer advantages such as high CO_2 concentration, enabling the use of smaller equipment and different solvents, resulting in lower energy consumption compared to post-combustion techniques. However, the conversion equipment required for fossil fuels in pre-combustion methods comes with high capital costs (Ababneh *et al.*, 2022).

In integrated gasification combined cycle (IGCC) power plants, separating CO_2 from hydrogen incurs an energy penalty. This penalty is lower for physical sorbents because they are regenerated through pressure reduction rather than heat, which is the case for chemical sorbents (Haerens, 2017; Olabi *et al.*, 2022).

2.1.2.2 Post-combustion

Is a method for separating CO_2 from gases generated after combustion, making it adaptable to existing fossil-fuel-powered plants. However, it faces a challenge due to the low concentration of CO_2 in flue gas, typically ranging from 3-20%. Even industrial sources with higher CO_2 concentrations, like cement manufacturing and stainless-steel factories, are still considered post-combustion capture (Feron & Hendricks, 2005; Wang & Song, 2020).

Various techniques are employed in post-combustion CO_2 capture, including absorption in solvents (e.g., monoethanolamine or MEA), solid sorbents, membranes, cryogenic separation, pressure swing adsorption, and vacuum swing adsorption. MEA absorption is the most commonly used method and finds applications in power plants, ethylene oxide, cement, fuels, iron and steel production, and biogas sweetening (Cuéllar & Azapagic, 2015; Haerens, 2017; Mikulčić *et al.*, 2019).

The CO_2 capture process with a 30 wt% aqueous MEA solvent involves absorption and regeneration stages. During absorption, flue gas is exposed to the solvent, allowing for CO_2 absorption and heat release (about 80-100 kJ/mol of CO_2). In the regeneration stage, the CO_2-rich MEA solution is heated in a reboiler to release CO_2 (requiring about 3.1-3.75 MJ/kg of CO_2). The balance between heat release during absorption and heat requirement during regeneration is crucial for optimizing the energy efficiency and economic viability of carbon capture systems (Quang *et al.*, 2013; Jang *et al.*, 2021).

2.1.2.3 Oxyfuel combustion

Involves burning coal or gas in an atmosphere of pure or nearly pure oxygen, producing flue gas with high concentrations of CO_2 and water. Unlike other methods, no chemicals are needed, but the energy required for air-separation processes results in significant environmental impacts (Cuéllar & Azapagic, 2015). While this technology can substantially decrease the cost and energy required for carbon capture, adding an air separation unit to create a carbon-rich environment significantly raises the overall capital cost (Godin *et al.*, 2021; Ababneh *et al.*, 2022).

2.1.2.4 Bioenergy with carbon capture

It is also possible to capture the CO_2 emitted by bioenergy production. The general process is called bioenergy with carbon capture and sequestration (BECCS). However, CO_2 can also be reused for chemical, biological, or physical purposes (bioenergy with carbon capture and utilization, BECCU). For example, the capture of CO_2 produced during ethanol fermentation is very concentrated and cheap, and the utilization of CO_2 results from biogas upgrading (Meylan *et al.*, 2015).

A previous study on the potential of BECCS in Europe found that the capacity for carbon removal could reach 200 MTPA, with the most significant potential in industries such as pulp and paper, incinerators, and bio-power (Rosa *et al.*, 2021).

2.2 Carbon Utilization

While CO_2 can be used and stored in a wide range of products, its time can vary greatly, from days or weeks to centuries. It is vital because CO_2 can be re-released at the end of a product's lifespan. Bennett *et al.* (2014) distinguish between utilizations that result in permanent storage, such as enhanced oil recovery (EOR), and utilizations that lead to subsequent CO_2 emissions, such as short-lived products like fuels and plastics. Storage in materials like cement can last for decades to centuries, whereas products like fuels store carbon for only days or weeks and plastics for years (Figure 2) (Bruhn *et al.*, 2016; Mitchell-Larson & Allen, 2021).

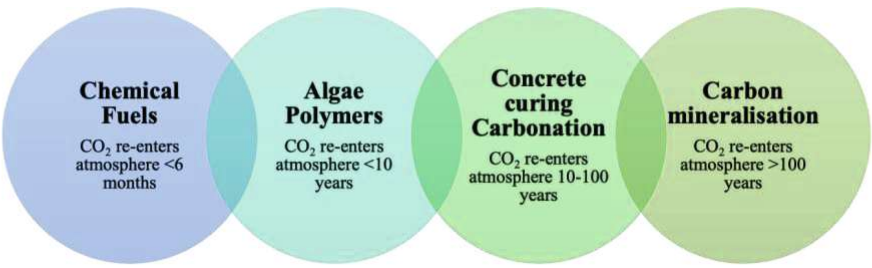


Figure 2. CO_2 storage permanence in CCU products (Source: Serdoner, 2019).

In general, CCU products that do not store carbon for a long time should not be considered negative emission technologies; only CCU products with permanent storage can be seen as direct measures to mitigate climate change. However, Bio-CCU can be regarded as a net-zero-

CO_2 option in terms of the product's carbon content, and it can help phase out fossil energy sources or products. If CCU methods reduce GHG emissions, they can be a crucial step toward a fully decarbonized economy (Gabrielli *et al.*, 2020).

Chemically there are two main ways to use CO_2: carboxylation and reduction. Carboxylation does not break the C=O bonds of the molecule, and it can be used for carbonation, carbon-based chemicals, and polymer production with the advantages of reducing harmful byproducts and storing carbon long-term (von der Assen *et al.*, 2016; Alper & Orhan, 2017). CO_2 reduction breaks one or both C=O bonds, producing several products (methane, methanol, ethanol, carbon monoxide, synthetic gas, formic acid, and acetone) but requires high-energy reactants like hydrogen, heat, electricity, sunlight, or microwaves (Quadrelli *et al.*, 2011; Mikulčić *et al.*, 2019).

Industrially speaking, CO_2 can be divided into two pathways: direct use and conversion. Direct use involves using CO_2 in its gaseous form for carbonating beverages, as a refrigerant, or yield boosting, without any chemical transformation. Conversely, conversion involves transforming CO_2 into other products through various chemical and biological processes (Figure 3) (IEA, 2019).

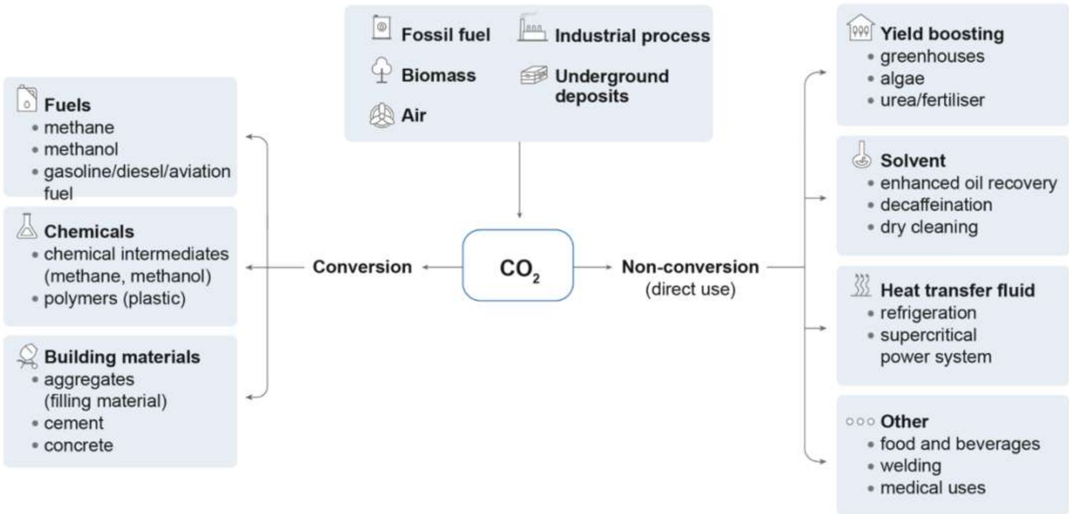


*Figure 3. Industrial pathways for CO_2 utilization (*Source: *IEA, 2019).*

The conversion process offers the potential to mitigate GHG emissions while providing a valuable resource for industry, with applications ranging from producing fuels and chemicals to creating building materials. The pathways for the use of CO_2 are complex and multifaceted, but they offer a promising avenue for a more sustainable future (IEA, 2019; Gulzar *et al.*, 2020).

2.2.1 Direct Utilization

Direct use of CO_2 involves its application without chemical alteration (IEA, 2019). It finds various applications in industries like food and beverage for carbonation, preservation, packaging, and coffee decaffeination (Coffee Review, 2014; Global CCS Institute, 2011). Additionally, it's used in agriculture for enhancing plant growth, as a refrigerant in HVAC systems, fire extinguishers, and dry cleaning (Global CCS Institute, 2011; De Kleijne *et al.*, 2022). In the pharmaceutical sector, it serves specific purposes but requires high-purity CO2 waste streams (Cuéllar & Azapagic, 2015).

Another significant use is in Enhanced Oil and Coal-bed Methane Recovery (EOR and ECBM) for extracting oil and natural gas. This technique involves injecting CO_2 and other agents into reservoirs to release trapped oil (Cuéllar & Azapagic, 2015; De Kleijne *et al.*, 2022). CO_2 in EOR can be used and stored, with 70-80 million tons used in 2017 (IEA, 2019). The potential for storing CO_2 in oil reservoirs is estimated to be 60-360 gigatons in the next 40 years, surpassing the 120 gigatons needed for the IEA's 2 ºC climate target (OECD & IEA, 2015). However, some CO_2 is emitted into the atmosphere due to economic reasons as it returns to the surface with the pumped oil (Cuéllar & Azapagic, 2015).

2.2.2 Conversion of CO_2

Recent years have seen a growing interest in the conversion of CO_2, offering opportunities for CO_2-derived fuels, chemicals, and construction materials. While numerous conversion pathways exist, many are still in early development stages but hold promise for future technical and commercial viability (IEA, 2019).

2.2.2.1 CO_2 to fuels

There are two ways of converting CO_2 into fuels: chemical and biological.

Chemical route

Hydrogenation of CO_2 involves combining CO_2 and H_2 to produce fuels like methanol, dimethyl ether (DME), and ethanol (Klankermayer & Leitner, 2015; De Kleijne *et al.*, 2022). The main challenge is the availability of hydrogen, which can be produced through water electrolysis using renewable energy but can be expensive compared to fossil fuel-based production. Excess renewable energy can be used to generate hydrogen for fuel production (Otto *et al.*, 2015; Christensen, 2020; Vickers *et al.*, 2020).

Dry reforming (Fischer-Tropsch synthesis) involves a reaction between CO_2 and hydrogen to create syngas, which is then processed into synthetic fuels like hydrocarbons and alcohols (De

Kleijne *et al.*, 2022). It has the advantage of using and reducing two primary GHG but requires high temperatures and can face catalyst deactivation issues (Haerens, 2017).

Photo and electrochemical/catalytic conversion use solar energy to reduce CO_2. Photochemical reduction mimics photosynthesis by combining sunlight, water, and CO_2 over a catalyst. Electrochemical conversion uses renewable electrical energy to transform CO_2 into CO and valuable chemicals like methanol. Cost considerations for synthesis materials may influence the viability of these methods for large-scale applications (Hu *et al.*, 2013; Albo *et al.*, 2015; De Kleijne *et al.*, 2022).

Biological route

Plants and microalgae use solar energy to convert CO_2 into glucose through photosynthesis, enabling bio-sequestration and biomass production for potential biofuel production (Cheah *et al.*, 2016; Granér & Johansson, 2022). Microalgae are particularly efficient at this process and can even capture CO_2 from flue gas, making them promising for biofuel production, but challenges like high harvesting energy costs exist (Cuéllar & Azapagic, 2015; Cheah *et al.*, 2016; Haerens, 2017; Granér & Johansson, 2022).

Microbial electrosynthesis offers an alternative method to convert CO_2 into energy-dense liquid fuels using non-photosynthetic organisms, driven by electricity. However, it faces challenges related to microbial physiology, efficiency, specificity, reaction rate, and engineering optimization (Rosenbaum & Franks, 2014; Cheah *et al.*, 2016; Phour *et al.*, 2022). Additionally, anaerobic bacteria can sequester CO_2 under specific conditions, generating compounds like alcohol and biogas that can be used as fuel or raw materials for other products (Mohan *et al.*, 2016).

CO_2 can also enhance crop yields in commercial horticulture when maintained at concentrations of 1,200 ppm, but challenges in logistics and transportation limit its widespread use in greenhouses (IEA, 2019).

2.2.2.2 CO_2 to chemicals

CO_2 can be used to create a range of chemicals, including urea, acrylates, lactones, carboxylic acids, monomeric carbonates, isocyanates, and polymers (Quadrelli *et al.*, 2011; Cuéllar & Azapagic, 2015; Alper & Orhan, 2017).

Urea, a significant product derived from CO_2, is essential in fertilizer production as a nitrogen source. It is produced by combining ammonia and CO_2, with approximately 0.75 tons of CO_2 needed for every ton of urea produced. Globally, around 130 million tons of urea are manufactured annually, primarily for agricultural purposes (Quadrelli *et al*., 2011; Naims, 2016; IEA, 2019; Granér & Johansson, 2022).

Polymers, which have diverse applications, can also be synthesized using captured CO_2, providing a sustainable approach to combat climate change and reduce reliance on fossil fuels. This process can yield polycarbonates, which can contain up to 50% CO_2 while retaining desirable properties like biodegradability and biocompatibility. By 2050, the estimated global potential for CO_2-based polymer production ranges from 10 to 50 million tons annually. The utilization of CO_2 as a feedstock in the chemical and polymer industries is gaining momentum, with an estimated total annual usage of approximately 200 million tons from various sources (Naims, 2016; Hepburn *et al*., 2019).

2.2.2.3 Mineral carbonation

Carbonation is a chemical process that uses CO_2 and metal oxide, such as magnesium or calcium, to create stable carbonates. There are two main types of carbonation: direct and indirect. Direct carbonation occurs in a single step under high-pressure conditions, either in dry or aqueous environments. In contrast, indirect carbonation involves three steps: separating the metal from the mineral, hydrating it, and then reacting it with CO_2 to form a carbonate. This reaction generates heat, making the process self-sustaining, and results in long-term CO_2 storage without the risk of leakage (Cuéllar & Azapagic, 2015; Haerens, 2017).

A variety of industrial residues rich in magnesium or calcium, including steel and blast furnace slags, cement kiln dust (CKD), fly ashes, municipal waste incineration ash, mining wastes, and asbestos, can be used for mineral carbonation to store CO_2. The potential for CO_2 utilization through mineral carbonation is estimated to be around 290 million metric tons annually (Haerens, 2017; Baciocchi & Costa, 2021). Among these materials, steelmaking slag stands out due to its high CO_2 storage capacity of 0.40 kg CO_2/kg slag, with the potential to sequester roughly 21.7 gigatons of CO_2 between 2020 and 2100 (Bobicki *et al*., 2012; Sanna *et al*., 2014; Valluri, 2021). Waste cement and CKD also have substantial storage capacities, although with associated costs (Bobicki *et al*., 2012; Teir *et al*., 2016).

2.3 CCU technology in Europe

In 2005, the IPCC identified CCU as a potential climate mitigation strategy, with the recent 2022 IPCC report reaffirming its importance in reaching climate neutrality by 2050. It's projected that CC technologies must mitigate around 1.5 Gt of CO_2 by 2050. The IEA's "Net Zero by 2050" report predicts capturing 2.4 Gt of CO_2 by 2050, with most being permanently removed and some used for synthetic fuels. However, scaling up CCU is a significant challenge as current capacity is insufficient (IOGP, 2019; Granér &Johansson, 2022; Carbon Capture and Storage Association, 2022).

The European Green Deal and binding climate neutrality goals by 2050 have driven political interest in CCU. The EU is investing in research, development, and pilot projects across industries like cement and chemicals to promote CCU adoption. Funding schemes support CCU, including the Innovation Fund, Connecting Europe Facility, Recovery and Resilience Facility, Just Transition Fund, and Horizon Europe (European Commission, 2020a; Carbon Capture and Storage Association, 2022).

Member States in the EU are required to create National Energy and Climate Plans (NECPs) aligned with Energy Union objectives. Eleven EU countries mentioned CCUS technologies in their 2018 NECPs, with seven implementing strategies or policies supporting CCUS. The CCUS SET-Plan's updated targets increased global project capacity, but Europe delays in commercial projects (IOGP, 2019).

Promising locations for CCU advancements include Rotterdam, Amsterdam, Norway, Ireland, Port of Antwerp (Belgium), Dunkerque (France), and Ravenna (Italy). CCU is in its early stages in Europe and requires competitive renewable energy and low-carbon hydrogen for widespread adoption, offering the potential for a more sustainable, circular economy and reduced emissions (European Commission, 2020a; Carbon Capture and Storage Association, 2022).

CHAPTER 3

3 METHODOLOGY

3.1 Qualitative analysis

This study employs a qualitative research design to assess the feasibility of CCU technologies in Austria. The approach involves gathering information from various sources, including literature, government agencies, and scientific institutions. The goal is to comprehensively analyze the CCU technology landscape in Austria and determine its viability based on diverse and reputable sources.

The research includes an analytical literature review, which aims to identify and examine recent articles and reports on carbon capture and utilization technologies that reduce greenhouse gas emissions and create valuable carbon-based products. The review process follows the Seven-Step Model (Onwuegbuzie & Frels, 2016), involving steps such as exploring topics, conducting searches, organizing information, selecting relevant data, expanding the search, analyzing and summarizing findings, and presenting the research document. Step 3, focused on organizing collected information, is particularly important in the review process (Figure 4).

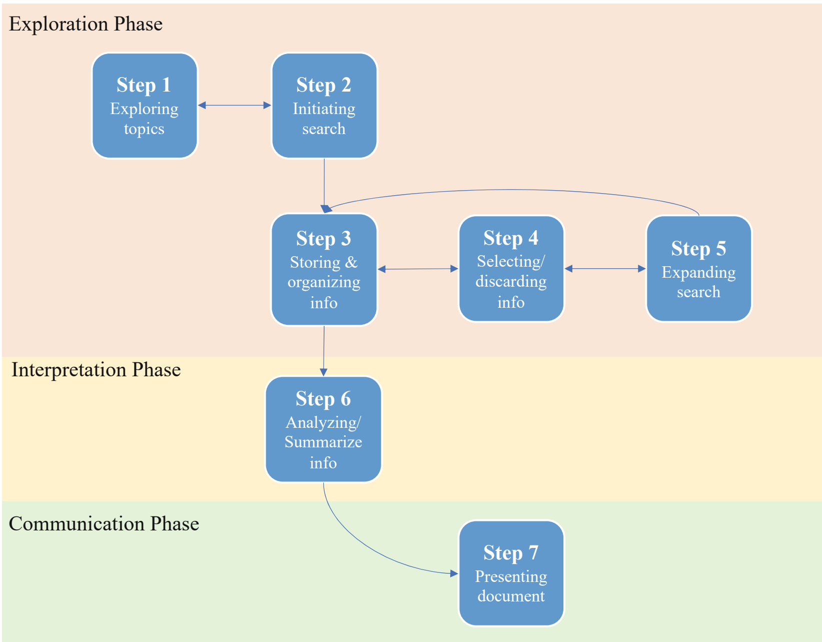


Figure 4. Seven-Step Model for a Qualitative Analysis Based on Literature Review (Source: Modified from (Onwuegbuzie & Frels, 2016).

The research process can be summarized into three phases: Exploration, Interpretation, and Communication.

Exploration Phase

Exploring Topics: This phase begins with defining the research questions and conducting a broad examination of relevant articles and information sources related to CCU in Austria.

Initiating Research: Keyword selection is crucial in this phase, where a list of keywords related to CCU, the environment, CCU products, and location are categorized and used for online searches.

Storing and Organizing Info: A specific folder is created to store all collected documents and information, following a structured naming convention.

Selecting & Discarding Info: A rigorous selection process is employed to narrow down the research materials to those published within the past eight years, written in English, available online, and reviewed by experts. The focus is on the main subject of CCU technologies, particularly the MEA process, mineralization, and the Fischer-Tropsch synthesis of CO_2.

Expanding Search: In this step, additional information sources are explored to provide a more comprehensive understanding of the research topic, ensuring depth and breadth in the analysis.

Interpretation Phase

Analyzing/Summarizing Info: The selected 250 articles are thoroughly examined to address the research questions outlined earlier, and pertinent information is extracted.

Communication Phase

Presenting Document: The final research document is structured and presented, addressing the research questions and providing a clear analysis of the gathered data.

Overall, this research process involves systematically exploring, collecting, organizing, and analyzing information related to CCU technologies in Austria to produce a comprehensive and well-structured research document and answer the three major questions formulated at the beginning of this document.

3.2 Framework for assessing the viability of the business cases

In this study, the business cases were evaluated in a 2030 scenario where Austria has achieved 100% renewable energy in alignment with environmental goals and agreements (IEA Bioenergy, 2021). The primary methodology used for analyzing the implementation of CCU in Austria's industry in 2030 was the "Methodology to assess the business case and economic potential of CCU" published by CarbonNext (2018), funded by the European Commission. Additionally, the study considered case studies conducted in Austria and Sweden by Zauner *et al.* (2022) and Patricio *et al.* (2017), respectively.

To assess the viability of CCU business cases, it was crucial to establish a methodology by first defining the scope and key elements involved in CCU according to CarbonNext (2018). The CCU process comprises three main stages: capturing, transporting, and utilizing CO_2 (Figure 5). While the utilization aspect may vary depending on the chosen CCU pathway, the capture and transport stages are often less impacted by the pathway choice and depend more on factors such as the source of gases (affecting volume, concentration, and pollutant levels) and the transportation distance (impacting the method and associated costs).

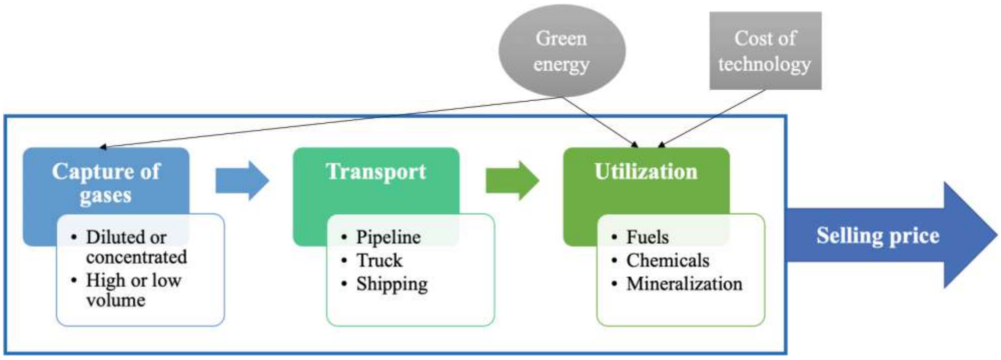


*Figure 5. Scope for a CCU business case (*Source: *CarbonNext, 2018).*

This study identifies several key external factors that influence the viability of a CCU business case. These factors include the availability and cost of green energy, the expenses associated with CCU technology (including catalysts and their effectiveness), and the selling price of CCU products (which is influenced by product volume and competition with traditional products) (CarbonNext, 2018).

For the gas capture stage, a top-down approach was employed, beginning with the compilation of gas sources by industry type in Austria through a literature review. This involved gathering information on the physical and chemical properties of primary gas sources, allowing for their classification (Van Dael, 2018). The transport stage was analyzed by reviewing the literature concerning the costs associated with various transport methods, such as trucks, pipelines, and shipping, along with the main reasons for choosing each method.

In the utilization stage, potential gas-utilizing technologies were assessed through a literature review, taking into account specific process requirements like gas purity levels, quantity, and operational conditions (e.g., temperature, pressure, catalysts). This information was used to identify existing companies or new opportunities for gas reuse. Selection criteria for utilization technologies were based on their Technology Readiness Level (TRL) and the potential market size for resulting gas-containing products. Only technologies with a TRL of 5 or higher were considered, indicating a significant level of development.

To evaluate the business feasibility of CCU, a framework was established, recognizing two categories of factors: pre-conditions and market conditions. Pre-conditions encompass the requirements that must be met for CCU to be a viable alternative, while market conditions impact the costs and pricing of CCU products (Figure 6). These market conditions may or may not depend on the chosen CCU pathways (CarbonNext, 2018).

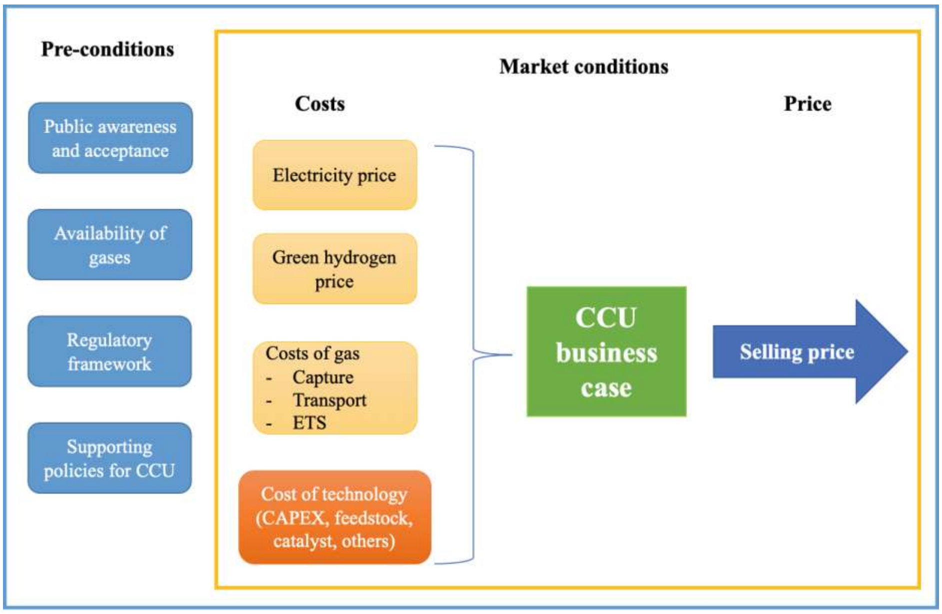


Figure 6. The structure needed to evaluate the business feasibility of CCU (Source: CarbonNext, 2018).

3.2.1 Pre-conditions for a CCU business case

- **Public awareness and acceptance**

The level of public awareness and acceptance of CCU and its importance in carbon emissions reduction plays a crucial role. Effective climate policies can enhance public support for CCU, but there are concerns that it might be seen as a way to justify ongoing pollution in some industries (CarbonNext, 2018). Public opinion regarding the use of CCU in Austria was consulted in various documents, and the results are discussed in Chapter 4.

- **Availability of gases**

The availability of gases like CO and CO_2 is essential for CCU technology development. CO_2 is expected to be more readily available, while CO might be limited due to its use in the steel industry. CO_2 was chosen as the primary raw material for this study (CarbonNext, 2018).

To select a specific industry to evaluate CCU potential, the GHG emissions from the Austrian industry were evaluated and analyzed based on the findings of Diendorfer *et al.* (2021) and verified with the data included in *Umweltbundesamt* Austria's National Inventory Report 2022 (Anderl *et al.*, 2022).

- **Regulatory Framework and Supporting Policies for CCU**

The legal and regulatory framework supporting CCU technology in Austria and the broader European context are significant factors. Strong climate policies and EU measures to achieve carbon neutrality can drive the adoption of CCU (CarbonNext, 2018).

3.2.2 Market conditions for CCU business cases

- **Electricity price**

Electricity cost is a significant expense for CCU pathways. The availability of green electricity and intermittent renewable energy sources can impact the business case. Austria aims to achieve 100% renewable electricity by 2030, affecting electricity prices. (CarbonNext, 2018).

For this study, the Excel Exponential Triple Smoothing Algorithm (ETSA) was employed to predict the electricity price in 2030. The ETSA considers seasonal patterns, trends, and data errors to generate reliable forecasts. The detailed data was obtained from Ember (2023), and the analysis outcomes are presented in Chapter 4.

- **Green hydrogen price**

The cost of hydrogen production is crucial, and it depends on factors like technology advancements, electrolyzer production, and electricity prices (CarbonNext, 2018).

Austria lacks green hydrogen production, but it plans to achieve a capacity of 1 GW for electrolysis-based hydrogen production by 2030 (Gupta, 2022). This will enable the country to produce 4 TWh of green hydrogen annually and align with its recently announced Hydrogen Strategy, which aims to achieve climate neutrality by 2040 (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2022). This study considered the high end of benchmark estimated production costs for water electrolysis using renewable electricity by 2030, with a hydrogen price of 6 €/kg. The estimate was based on Otto *et al.* (2015); Ruf *et al.* (2018); IRENA (2018); Christensen (2020) and Vickers *et al.* (2020).

- **Cost of gas**

This includes the costs of capturing, transporting, and the EU-ETS (Emissions Trading System) for CO_2 in Austria. The cost of CO_2 capture and transport was estimated using research data, and the current price of CO_2 allowances under the EU-ETS was obtained from publicly available data sources, such as the European Energy Exchange (EEX) website and other financial market data providers for up-to-date information.

- **Cost of technology**

Includes evaluating the costs associated with implementing CCU technology to reduce carbon emissions, including equipment purchase, process costs, energy requirements, and maintenance (CarbonNext, 2018).

- **Costs of product**

Considers analyzing the cost of producing CCU products and comparing them to similar products made from fossil fuels. Market demand for CCU products and their competitiveness in terms of pricing are critical.

CHAPTER 4

4 RESULTS

4.1 State of CCU Technology

The role of CCU in achieving net-zero emissions depends on technological advancements. Some CCU technologies are mature and ready for expansion, while others need further development being timely innovation crucial to ensure readiness within the next decade. Despite varying technology maturity, there's a disconnect between where certain CO_2 capture technologies are advanced and where they are most needed, such as in the cement sector. Other sectors, including chemicals, steel, gas-fired power, bioenergy with BECCS, and direct air capture (DAC), also require innovation (IEA, 2020a).

Furthermore, CO_2 transport and storage methods can benefit from ongoing innovation to improve existing techniques and explore new possibilities like large-scale CO_2 shipping and advanced monitoring. Innovations in CO_2 utilization, particularly in synthetic fuels and chemical production, will play a critical role in cost-reduction efforts in the pursuit of net-zero emissions (IEA, 2020a).

4.1.1 Technology Readiness Level (TRL)

The success of CO_2 capture, transport, and utilization as a strategy to reduce its impact depends on having the right technologies at every stage. All the steps in this process must be ready and developed together for CCU to work effectively (IEA, 2020a).

CCU technologies are in various stages of development. Some are already in large-scale use, while others with potential for greater efficiency are still in progress. The TRL scale, initially created by NASA in the 1970s, is widely used to measure technology development. It ranges from 1 to 9 but has been expanded by the IEA to include TRL 10 (market readiness with innovation needs) and TRL 11 (steady growth) (IEA, 2020a).

The TRLs are categorized as follows:

- **Mature (TRL 11):** Widely used technologies requiring minor improvements, such as hydropower and electric trains.
- **Early adoption (TRL 9 or higher):** Technologies that have started selling but need support for further growth, like offshore wind, electric batteries, and heat pumps.
- **Demonstration (TRL 7 or 8):** Technologies being tested, such as carbon capture in cement, hydrogen-based ammonia, and big battery-electric ships.

- **Prototype (at least one design at TRL 5):** Technologies in the testing phase, including ammonia-powered ships, hydrogen-based steel production, and direct air capture.

These TRLs not only describe technology advancement but also usage levels. Many technologies in the early adoption stage are fully developed but not yet widely used, including most CCU applications. These technologies, along with renewables like electric vehicles, onshore wind, and solar panels, are ready for the market but require integration work and supportive policies to grow rapidly (Figure 7) (IEA, 2020a).

Figure 7. TRL of CCU technologies. Source IEA (2020a).

CO_2 capture is crucial in various industries, and there have been technologies available for a long time to capture CO_2 from exhaust gases. The most used technologies are chemical absorption and physical separation. The choice of which technology to use depends on how much CO_2 needs to be captured, the pressure and temperature where it's done, the gas's composition and flow, how well it works with the existing setup, and how much it costs (IEA, 2020a).

4.1.2 Integration of CCU into the energy system

The imperative to achieve climate neutrality by 2050 has led to the recognition that energy-intensive industries must explore alternative methods beyond electrification to reduce carbon emissions effectively (IEA, 2021b). CCU emerges as a crucial solution, offering significant emission reductions and cost-effectiveness. Integrating CCU technologies into the energy system not only aids in emissions reduction but also enhances the flexibility of renewable energy systems by converting variable electricity into fuels and chemicals, thereby improving overall system efficiency (Mikulčić *et al*., 2019).

Two key CC technologies for integration are pre-combustion and post-combustion. Pre-combustion technology, involving gasification, offers flexibility and grid balancing potential. Post-combustion, which removes CO_2 after combustion, is a well-established method. Flexible CC can increase grid reliability, especially in systems with high renewable energy use. Integration of fossil power plants with CC and renewables can boost flexibility and reduce operating costs, particularly when on-site CCU technology eliminates the need for CO_2 transport and storage (Ju & Lee, 2017; Mikulčić *et al*., 2019).

As the future energy system leans toward renewables, dispatchability, and power system operation become critical challenges. Flexible dispatchable technologies like thermal power with CC play a vital role in mitigating the intermittency of renewable energy generation. CCU, especially with suitable electrolysis technology, enhances energy system flexibility, enabling the direct use of hydrogen and the production of various hydrocarbons from syngas (Ridjan *et al*., 2014; Mikulčić *et al*., 2019; Carbon Capture and Storage Association, 2022).

Establishing CO_2 transportation and storage infrastructure is crucial for cost-effective decarbonization and CCU integration. Comprehensive carbon accounting and monitoring are essential components. However, the maturity of CCU technologies varies, with some methods already in widespread use and others under development for improved efficiency and cost-effectiveness (Carbon Capture and Storage Association, 2022).

Integrating CCU into the energy system is complex due to differing TRLs, significant investments, and challenges in identifying the optimal use for captured carbon. Engaging various industrial entities in investing and utilizing CCU technology remains a challenge (Mikulčić *et al*., 2019; IEA, 2020a; Tcvetkov, 2021).

4.1.3 Sectors with CCU potential in Europe

CCU technologies can help Europe achieve climate change targets, promote circular economic systems, enhance energy security, and facilitate the adoption of renewable energy sources by offering storage solutions for renewables (SAPEA, 2018). Synthetic fuels, while controversial, are seen as a viable option for Europe, with estimates suggesting production capacities ranging from 150 to 1,500 million metric tons by 2030. These fuels, particularly those produced using captured CO_2, could play a significant role globally, though they may face competition from cheaper fossil fuels (IEA, 2019).

By 2050, it's estimated that between 1 and 4.2 gigatons of CO_2 could potentially be utilized annually, but the cost of this process could be as high as USD 670 per ton of CO_2 (Alsarhan *et al.*, 2021). Producing methanol and methane from CO_2 is currently more expensive, with costs two to seven times higher than fossil-based counterparts. The major cost factor is electricity, making it essential to have competitive grid electricity prices for CO_2-derived products. However, using low-carbon hydrogen and electricity directly as fuel is a more cost-effective alternative (IEA, 2019).

In contrast, using CO_2 for building materials like mineral carbonation, calcium carbonate, and concrete curing in Europe has the potential to utilize significant amounts of CO_2 at a cost ranging from USD 30 to 70 per ton. These techniques are likely to improve and can mitigate a substantial amount of CO_2 emissions annually, with concrete curing showing the most promise (Alsarhan *et al.*, 2021; Granér & Johansson, 2022).

Less promising but still viable options include microalgae, Bioenergy with Carbon Capture and Storage (BECCS), and CO_2 use in horticulture. Microalgae can absorb large amounts of CO_2 from the atmosphere and potentially use 0.2 to 0.9 gigatons of CO_2 annually by 2050. BECCS technology is expected to use 0.5 to 5 gigatons of CO_2 by 2050. However, the production capacity of CCU materials is expected to remain low in the next decade due to the early stage of technology development (Figure 8; Alsarhan *et al.*, 2021).

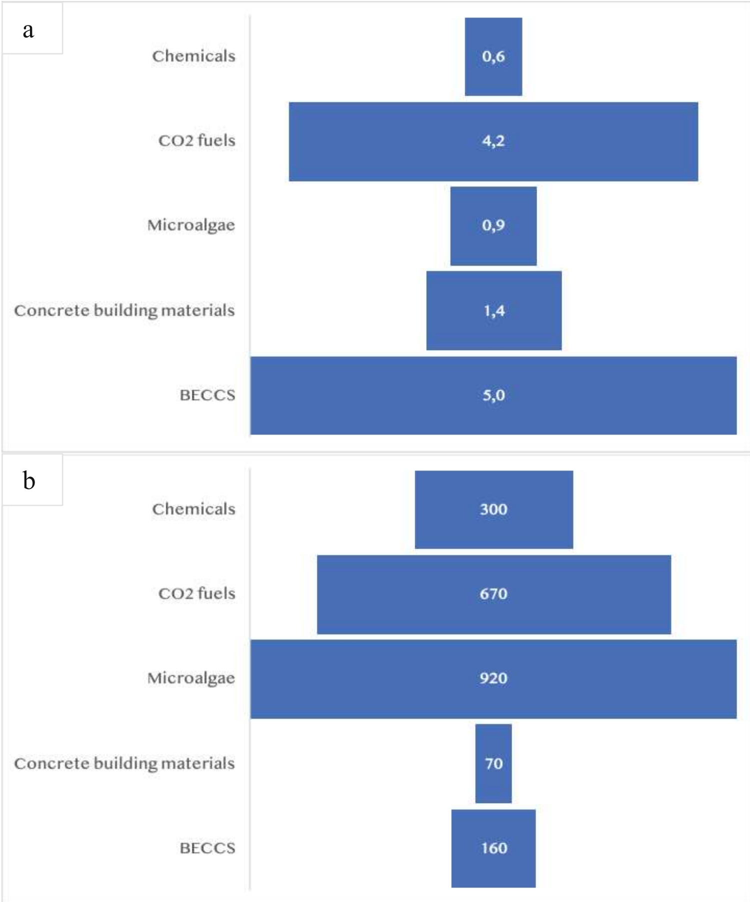


*Figure 8. (a) Maximum expected use of CO_2 (Gt) by field in 2050; (b) Maximum expected cost (USD) of CO_2/ton by field in 2050 (*Source: *Alsarhan et al., 2021).*

Overall, CCU's primary objective until 2030 is to develop products that can replace existing materials and products with competitive pricing and quality. CCU is expected to make a significant contribution to a sustainable energy system only after renewable energy sources have sufficiently replaced fossil fuel-based applications (SAPEA, 2018; Granér & Johansson, 2022).

4.2 State of CCU Technology in Austria

Austria like many countries is actively researching methods to permanently reduce CO_2 emissions, with a focus on energy-efficient processes that use captured CO_2 in industrial applications. While CCU is not a universal solution to emissions reduction, it can play a significant role in overall climate policy strategies (Energy Innovation Austria, 2017).

Austria, aiming for climate neutrality by 2040, faces the challenge of decarbonizing energy-intensive industrial sectors like iron and steel, cement, and chemicals. These sectors are responsible for a substantial portion of global greenhouse gas emissions, but the International

Energy Agency believes up to 60 gigatons of emissions could be saved from these industries by 2050 (Energy Innovation Austria, 2022).

To remain competitive, Austrian manufacturing companies must adopt climate-neutral techniques and production processes, needing an industry transformation. Austria is actively participating in international research and development initiatives, such as the IEA Greenhouse Gas R&D Program, and at the national level, research institutes, and companies are conducting CCU-related projects with support from the Federal Ministry for Transport, Innovation, and Technology and the Climate and Energy Fund. These initiatives involve testing and further developing new CCU solutions in demonstration facilities (Energy Innovation Austria, 2017).

4.2.1 Identification of CCU Innovations and Research Efforts in Austria

According to Energy Innovation Austria, (2017), several studies have been developed in the country, where the following can be highlighted:

ViennaGreenCO_2: New separation process to capture carbon dioxide from exhaust gases

Researchers at TU Wien and the University of Natural Resources and Life Sciences (BOKU) have collaborated on a ViennaGreenCO_2 energy research project, partnering with Shell, to develop an innovative and cost-effective CO_2 separation and capture technology. Unlike current methods that use aqueous amine solvents, this new process utilizes solid amine particles applied to porous particles, creating a fluidized bed system. In this system, exhaust gas and amine-enriched particles move in opposite directions through a multi-stage column, achieving over 90% CO_2 separation. The separated particles are heated in another column, releasing CO_2 for reuse.

Tests at TU Wien have been successful, indicating that this technology could potentially reduce energy consumption by up to 40% and lower separation costs per ton of CO_2 by up to 25%. Moreover, the fluidized-bed system can be built more compactly, potentially at a lower cost than traditional separation facilities. In a pilot project, this technology successfully separated 0.7 tons of CO2 per day from the exhaust gases of the *Wien Energie* biomass power plant in Vienna, Austria.

CO_2USE: Plastic from bioreactors

The "CO_2USE" project focused on developing an environmentally friendly method for producing bioplastics using cyanobacteria and capturing CO_2 in biotechnological processes. Partners including EVN AG, ANDRITZ AG, research institutions, and universities collaborated to create a closed materials cycle for producing PHB (a type of bioplastic) from microorganisms. They converted cyanobacteria residue into biogas through anaerobic processes and recycled nutrients in the cultivation process. The project successfully produced non-toxic, biodegradable PHB as a replacement for fossil plastics.

The follow-up project, "CO_2USE+EPP," aimed to enhance bacterial strains and productivity, along with identifying cost-effective sources of CO_2 for cultivation in a pilot plant. The objective was to increase PHB production from 5-10% of the cell mass to 30-40%, making the process economically viable.

Hydrofinery: Obtaining liquid and gaseous sources of energy from hydrogen and carbon dioxide

The University of Natural Resources and Life Sciences in Vienna conducted the "Hydrofinery" project, aiming to develop ways of utilizing hydrogen and CO_2 to generate gaseous and liquid energy sources. The project introduced a novel approach involving the use of acetate, an intermediate product, to store hydrogen or CO_2. Researchers assessed various microorganisms, including clostridia, homoacetogens, and methanogens, through a screening process to identify the most suitable metabolic pathways.

The project employed a two-stage process: first, homoacetogens converted hydrogen and CO_2 into storable acetate. Subsequently, two different fermentation methods were explored. One method involved the transformation of acetate by archaea to produce biomethane, while the other method used clostridia in the ABE process (acetone-butanol-ethanol fermentation) to mainly produce biobutanol, bioethanol, and acetone. Additionally, the researchers investigated the possibility of directly producing biomethane from hydrogen and CO_2 using hydrogenotrophs.

Oxysteel: New process design for the steel industry

The OxySteel project, led by *Montanuniversitaet Leoben*, focuses on enhancing energy efficiency and reducing CO_2 emissions in electro-steel plants. The project involves using electric arc furnaces to melt steel scrap and employs an innovative process integrating oxyfuel combustion and CO_2 separation. This approach is more energy-efficient and produces lower CO_2 emissions compared to traditional blast furnace methods for converting iron ore to iron.

Oxyfuel combustion is used to pre-heat ladles and for heat treatment, resulting in higher flame temperatures, reduced exhaust gas losses, and lower nitrogen emissions. The Messer Oxipyr oxyfuel burners used in this process are highly energy-efficient and generate flue gas with a high CO_2 concentration.

These new technologies are undergoing testing at the steel mill of *Breitenfeld Edelstahl* AG in Styria. The project aims to replace conventional ladle heaters with three new furnaces equipped with oxygen burners. The CO_2 produced in this process is repurposed for eco-friendly wastewater neutralization within the plant. Researchers anticipate annual energy savings of 12 GWh through the implementation of OxySteel, equivalent to about 10% of the natural gas consumption of a small Styrian town. Furthermore, the project is exploring Demand Side Management in steel production and assessing operational flexibilities to calculate the potential for providing network services (Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology, 2020).

Carbon2Product Austria (C2PAT): Transforming the Green Deal's Aspiration into Reality!

The C2PAT project involves collaboration between Lafarge, Verbund, OMV, and Borealis to address emissions reduction in hard-to-decarbonize industries. Its goal is to establish an industrial-scale cross-sectoral carbon value cycle. The project will capture approximately 700,000 tons of CO_2 emissions generated during cement production and, using green hydrogen, convert this CO_2 into feedstock for high-quality renewable chemicals and environmentally friendly plastics with superior performance and minimal carbon footprint (C2PAT, 2022).

C2PAT will demonstrate the viability of this industrial-scale installation in *Mannersdorf/Schwechat*, Austria, while also developing innovative operational and business models to support industry decarbonization. A key innovation is using cement production CO_2 emissions as raw material for petrochemicals, a novel integrated and cross-sectoral approach. Furthermore, C2PAT exemplifies a circular economy approach in the cement and chemical sectors, as renewable-based plastics can be reused and recycled within various recycling streams. The project partners will assess the market potential for renewable-based products, consider implications for the energy system, and establish models to effectively manage and optimize the overall value cycle holistically (C2PAT, 2022).

4.2.2 The Role of CCU Technology in Fulfilling Environmental Goals

Austria has set ambitious goals to achieve carbon neutrality by 2040, requiring various industries to reduce their GHG emissions and adopt environmentally friendly practices. However, using CO_2 in products or services does not automatically result in emissions reduction, and assessing the potential emissions reductions can be complex, influenced by factors such as location and time (IEA, 2019).

The primary climate benefits of using CO_2 in products or services come from displacing higher life-cycle CO_2 emissions associated with fossil-based fuels, chemicals, or conventional building materials. Five key considerations for assessing the climate benefits of CO_2 use include the source of CO_2, the type of product or service being displaced, the energy required for CO_2 conversion, the carbon retention time, and the scale of CO_2 use opportunities (IEA, 2019).

Carbon retention time varies depending on the product, with some retaining carbon permanently, like building materials, while others release carbon to the atmosphere, like fuels and chemicals. The availability of low-carbon energy is crucial for achieving climate benefits through CO_2 use, and the potential for CO_2 use to contribute to climate goals depends on how quickly and extensively these opportunities can be scaled up. For example, achieving global net-zero emissions requires increased sourcing of CO_2 from biomass or DAC to support carbon-neutral life cycles for certain CO_2 use applications (IEA, 2019).

Various studies have examined the potential reduction of GHG emissions in industrial processes using CCU. For instance, mineral carbonation to produce $MgCO_3$ can reduce GHG emissions by 4% to 48%, depending on capture and allocation methods and heat recovery assumptions. Some studies show that using CO_2 recovered from MEA capture to produce DMC in the urea-based process can reduce GHG emissions by 4.3 times compared to conventional phosgene synthesis of DMC (Khoo *et al*., 2011a; 2011b; Nduagu *et al*., 2012; Cuéllar & Azapagic, 2015).

The Global Warming Potential (GWP) of biodiesel from microalgae varies in different studies, primarily influenced by how waste biomass from microalgae production is managed. Burning waste to generate electricity is often a better option than using biogas from anaerobic digestion due to methane emissions during digestion. The source of CO_2 used in biodiesel production also affects GWP results, with pure CO_2 captured after absorption potentially leading to a GWP increase of 30-60%. Cultivating microalgae in specific ways, such as in flat-plate photobioreactors and using supercritical methanol for lipid extraction, can significantly reduce GWP, even when waste is landfilled. The cultivation stage is the most impactful in biodiesel production, followed by extraction and drying, while harvesting and CO_2 sourcing contribute less to the overall environmental impact (Stephenson *et al*., 2010; Brentner *et al*., 2011; Shirvani *et al*., 2011; Borkowski *et al*., 2012; Zaimes & Khanna, 2013; Cuéllar & Azapagic, 2015).

4.3 Pre-Conditions for a CCU Business Case

- **Public awareness and acceptance of CCU technologies**

Most Europeans are aware of CO_2 and its effects, with those having better knowledge being familiar with carbon capture techniques. However, mineralization remains less known among the public, indicating the need for greater awareness and a more comprehensive scientific approach. Additionally, there's a need to educate people about the benefits of CCU technology, as many holds negative views about its future. European scientific and political leaders should take decisive steps to address these challenges (Carbon Capture & Storage Association, 2021; Koukouzas *et al.*, 2022).

To ensure successful implementation, local governments should provide regulatory guidance for CCU projects and focus on social acceptance, which capacity-building activities for local and regional officials can achieve. Local authorities should also educate the public on CO_2 storage and utilization and their opportunities (Carbon Capture & Storage Association, 2021; Koukouzas *et al.*, 2022).

Engagement with citizens and stakeholders, transparent communication, and opportunities for participation in project development are crucial for community acceptance of CCU projects. Policymakers, companies, trade unions, and environmental NGOs should engage in dialogue to highlight the benefits of CCU projects at various levels of government. Initiatives like the yearly CCUS Forum can help promote understanding and address challenges related to CCU (Carbon Capture & Storage Association, 2021; Koukouzas *et al.*, 2022).

Austria currently opposes nuclear energy and carbon capture and storage (CCS) but supports the EU's goal of reaching climate neutrality by 2050. The country has concerns about the safety and permanence of CCS, which has led to a focus on CCU technologies. Austria has a legal framework that prohibits CO_2 storage in geological structures until at least 2023. The country has limited storage capacity for CO_2, and long-term solutions may involve transporting CO_2 to storage facilities outside Austria. Further research and development work is needed, considering Austria's geological conditions and environmental impact, to determine the feasibility of such projects (Federal Ministry Republic of Austria, 2019).

- **Availability of CO_2**

In 2020, Austria's GHG emissions, excluding land use, land-use change, and forestry, totaled 73.6 Mt CO_{2eq}, which represented a 6.2% decrease from the base year of 1990 and a 7.7% reduction from 2019 (Table 3). The main reason for this decline was the decrease in CO_2

emissions from fuel combustion activities, primarily due to the COVID-19 pandemic (Anderl *et al.*, 2022)

In Austria, CO_2 was the dominant GHG, accounting for 84% of total emissions in 2020. These emissions mainly came from combustion activities, with transportation being the largest contributor within this sector. Methane (CH_4) emissions primarily stemmed from livestock farming and waste disposal, contributing 7.9% to total GHG emissions, while nitrous oxide (N_2O) emissions, primarily from agricultural soils, accounted for 4.8%. The remaining 3.3% of emissions came from fluorinated compounds, primarily associated with refrigeration equipment (Figure 9; Anderl *et al.*, 2022).

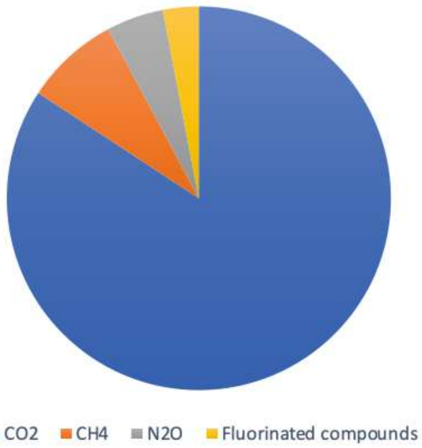


Figure 9. GHG contribution to Austria's emissions (Source: Anderl et al., 2022).

Austria's energy sector was the largest contributor to GHG emissions in 2020, responsible for 68% of total national emissions (Table 3). Within the energy sector, transportation accounted for 42% of emissions, while manufacturing and construction contributed 22%, and the energy industry itself was responsible for 18%. The remaining sectors collectively contributed 18% to total emissions (Anderl *et al.*, 2022).

The industrial processes and other product use (IPPU) sector accounted for 21% of total national emissions in 2020 (Table 3), with the metal and mineral industries being significant contributors. Iron and steel production was particularly noteworthy, with emissions generated from the use of coal, coke, and transformation processes (Anderl *et al.*, 2022).

Table 3. Austria's GHG emissions per sector.

SECTOR	EMISSIONS (kt CO_{2e})		TREND 1990-2020	SHARE (%)	
	1990	2020		1990	2020
Energy	52.805	49.929	-5.4%	67	68
IPPU	13.574	15.489	+14%	17	21

SECTOR	EMISSIONS (kt CO_{2e})		TREND 1990-2020	SHARE (%)	
	1990	2020		1990	2020
Agriculture	8.119	6.964	-14%	10	9.5
Waste	3.926	1.209	-69%	5.0	1.6
TOTAL	**78.423**	**73.592**	**-6.2%**	**100**	**100**

Source: Anderl et al. (2022)

Several major industrial emitters in Austria, including iron and steel production, the mineral industry, chemicals and petrochemicals, and paper products, contributed significantly to GHG emissions. These emitters had individual emissions ranging from 1.432 kt CO_{2eq} to 12.016 kt CO_{2eq} (Diendorfer *et al.*, 2021).

Iron and steel industry

In Austria, iron and steel production plays a significant role in the country's GHG emissions. In 2020, CO_2 emissions from this sector accounted for 12.8% of Austria's total GHG emissions, equivalent to approximately 12 Mt CO_{2eq}, and it consumed about 33 TWh of energy. The iron and steel industry in Austria is concentrated in 52 companies, generating a total gross value of around €2.8 billion. Among these, only one company uses blast furnaces, while others employ electric arc furnaces, contributing around 10% to the nation's total steel production (Diendorfer *et al.*, 2021; Anderl *et al.*, 2022).

The iron and steel sector can be divided into primary and secondary steel production. Primary steel production in Austria relies on blast furnaces, which require over 25 TWh of coal and coke to produce between 6 and 7 million metric tons of steel. The process is a major source of CO_2 emissions in the sector because it involves the use of carbon as a reducing agent to extract iron from oxygen compounds, resulting in CO_2 emissions. Over the past five years, primary steel production has contributed around 12 Mt CO2eq to Austria's GHG emissions, using 7 TWh of fossil energy sources to meet its energy requirements (Diendorfer *et al.*, 2021).

In contrast, secondary steel production employs electric arc furnaces and some gas-powered melters to melt approximately 1 million metric tons of scrap steel, followed by secondary metallurgical treatment. The energy consumption and CO_2 emissions in this process are mainly attributed to the final energy requirements, primarily for providing process heat at high temperatures in iron and steel production (Diendorfer *et al.*, 2021; Statistik Austria, 2021a).

Mineral industry

Austria's mineral sector comprises around 1,300 companies with a total gross value creation of around €2.5 billion. It is responsible for emitting 5.3 Mt CO_{2eq}, making up 20% of the total industrial emissions in Austria and making it the second-most emission-intensive sector. Among the 33 companies listed in the Emissions Trading System (ETS), they generate 4.1 Mt CO_{2eq}, with the cement manufacturing industry being accountable for more than 60% of the emissions reported in the ETS (Diendorfer *et al.*, 2021).

About 63% of the sector's emissions come from process-related sources caused by the conversion of mineral raw materials used in production, such as limestone ($CaCO_3$) being converted into quicklime (CaO) and CO_2 being emitted. This makes the stone, earth, and glass sector challenging for Austria's industry (Diendorfer *et al.*, 2021).

Cement Clinker Production

Cement production in Austria is a significant source of CO_2 emissions, with two-thirds of these emissions stemming from the process of producing clinker, and the remaining third arising from heating the rotary kiln. Austria has adopted modern cement production methods, including utilizing waste heat for preheating and district heating, as well as reusing secondary materials to enhance resource efficiency (Spaun *et al.*, 2021).

There are three main ways to use alternative resources in cement production: alternative raw materials, alternative fuels, and alternative additives to clinker. In Austria, alternative fuels are used at about 80%, replacing conventional fuels like coal and oil through co-processing, which involves recycling materials and recovering energy. Using alternative resources has enabled the Austrian cement industry to achieve a leading global position in reducing CO_2 emissions, with an emission intensity of 0.54 t CO_2/t of cement produced (Spaun *et al.*, 2021).

In 2020, cement production was responsible for 2.5% of all GHG emissions in Austria, including emissions from fuel combustion in cement kilns. Austria has nine cement plants with a total annual production capacity of 4.3 million metric tons of cement clinker. Production levels typically reach 80% to 90% of total capacity. While clinker production initially decreased from 2008 to 2014, it increased to 3.5 million metric tons in 2020 (Anderl *et al.*, 2022).

The energy-related emissions of the cement industry in Austria were 904,000 metric tons of CO_{2eq} in 2018, accounting for only a third of the industry's total emissions. The industry heavily relies on refuse-derived fuels in its energy mix, with significant thermal recovery of plastics and scrap tires. These fuels are used in clinker production in rotary kilns at high temperatures, leading to the release of CO_2 from raw materials and the production of calcium oxide (CaO) for cement. However, this process also generates process-related emissions, similar to other subsectors in the stone, earth, and glass industries (Anderl *et al.*, 2022).

Chemical industry

The chemicals and petrochemicals industry comprises 520 companies that collectively generate a gross value of around €4.8 billion. Out of the ten chemical companies listed in the ETS, they emit a total of 1.8 Mt CO_{2eq}, ranking third in emissions. Approximately 60% of the emissions reported in the ETS (1.1 Mt CO_{2eq}) are associated with producing fertilizers and nitrogen compounds. It should be noted that the international definition includes petroleum processing (such as the S*chwechat* refinery) in the energy field rather than the chemicals and petrochemicals sector (Diendorfer *et al*., 2021; Anderl *et al*., 2022).

In this industry, energy is primarily used to provide process heat above 200 °C, and electrical energy is mainly used for this purpose. Many stationary motors have also been converted to use electricity. Natural gas is the most crucial fossil energy source, primarily for supplying heat, with 3.5 TWh being used for this purpose. Additionally, 2.8 TWh of natural gas is used as a raw material for transformation processes. The sector's process-related emissions amounted to 851 kt CO_{2eq} in 2019 (Diendorfer *et al*., 2021; Anderl *et al*., 2022).

- **Selection of industries for the business cases based on CO_2 availability**

The steel and cement industries, alongside the energy sector, are significant contributors to Austria's annual CO_2 emissions. As a result, they are recognized as major industrial emitters in the country. Considering their prominent role and substantial CO_2 emissions, these industries were selected as the focus of this study, presenting significant potential as business cases.

Case 1: Voestalpine Stahl GmbH

VAS, or Voestalpine Stahl GmbH, is a leading European steel producer and serves as the steel competence center within the Voestalpine Group. VAS operates a fully integrated steel mill located in Linz, Austria, and possesses all the equipment to produce 1.65 Mt of steel annually with 20% of steel slag. The metallurgical plant comprises a coking plant, blast furnace, steelmaking plant, hot-rolling and cold-rolling mill, and galvanizing line. VAS's core business produces flat products, including hot-rolled and refined cold-rolled steel strips and heavy plates. In the 2017/18 business year, VAS generated sales of €3.96 billion and employed approximately 6,800 individuals (Voestalpine, 2021).

In 2020, VAS's crude steel production produced 8.55 million metric tons of CO_2 emissions, with a specific volume of 1,692 tons of CO_2 per ton of crude steel. To achieve a cleaner transition and significant CO_2 emission reduction by 2030, an additional 3 TWh of energy from renewable sources is required (Voestalpine, 2021).

This business scenario involves assessing costs related to capturing CO_2 emissions from the steel industry's flue gas, to utilize these captured emissions in an integrated carbonation process within the plant to produce carbonates ($CaCO_3$), a primary material for cement production. This approach offers advantages such as reducing waste disposal costs and creating marketable products containing CO_2 (IEA, 2019).

The direct aqueous carbonation of steel slag involves mixing the slag with water and CO_2. This results in the extraction of calcium ions from the slag, leading to a calcium-depleted layer within it. Calcium and carbonate ions in the surrounding aqueous solution then combine to form solid calcium carbonate, which precipitates into valuable carbonates with various applications. However, some waste streams may require pre-treatment or extreme operating conditions, and some waste materials may need separation after carbonation, making the process energy-intensive and costly (Figure 10; Gopinath & Mehra, 2016; IEA, 2019)

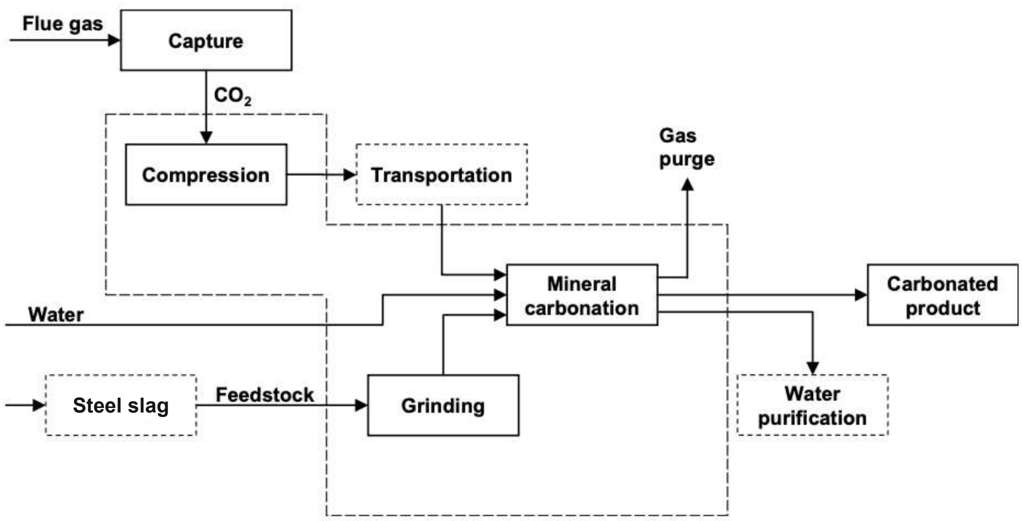


Figure 10. Aqueous carbonation of Steel slag (Source: Modified from Huijgen et al., 2007).

Using CO_2 in the carbonation process offers significant benefits for waste remediation and resource recovery. However, successful implementation requires careful consideration of waste stream properties and process design (IEA, 2019).

Voestalpine is also involved in the SuSteel project, focusing on transforming iron ore into liquid steel using a hydrogen plasma process. This innovative method involves using hydrogen gas and electricity to create a high-temperature stream that melts and reduces iron ore, eliminating the need for pelletizing and making steel production more efficient. Combined with CO2 reuse, this technology offers promising prospects for decarbonizing the iron and steel industry (Seftejani & Schenk, 2018).

Case 2: C2PAT in 2030

In this business scenario, the qualitative assessment will focus on the full-scale plant of the project C2PAT outlined before. By 2030, this plant is expected to capture nearly 100% of the 0.7 Mt of CO_2 emitted annually by Lafarge's cement plant in *Mannersdorf*, Austria. Using green hydrogen generated from renewable sources by Verbund, the captured CO_2 will be converted by the OMV plant into hydrocarbons based on renewable sources. These hydrocarbons can produce renewable-based fuels or serve as a feedstock for making value-added plastics by the Borealis plant (Figure 11).

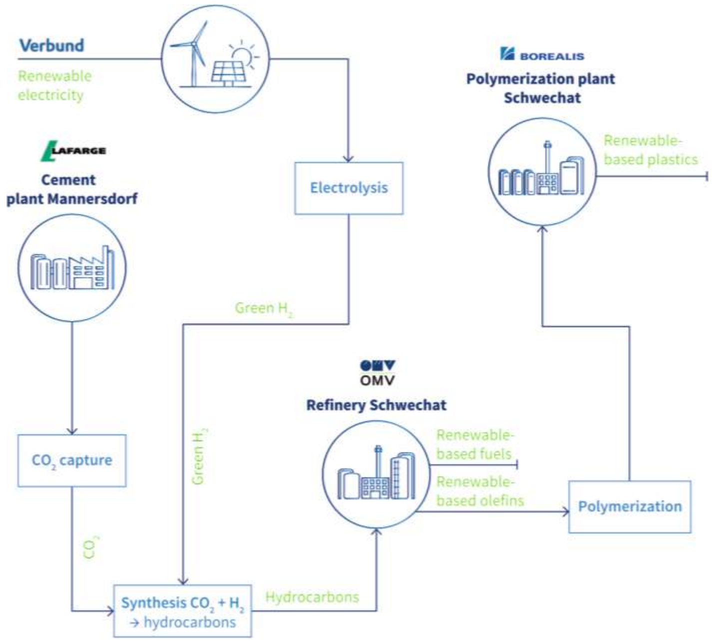


Figure 11. C2PAT – Cross-Sectoral Value Chain (Source: C2PAT, 2022).

Verbund

Verbund is a major energy provider in Austria, specializing in hydroelectric power, which makes up around 95% of its electricity production. In 2019, the company earned approximately €3.9 billion in revenue and had a workforce of 2,800 employees. Verbund is working on a project involving a 44 MWp off-grid PV Park for low-temperature electrolysis, with 10 MW dedicated to converting 10,000 metric tons of CO_2 annually into roughly 2,300 metric tons of Polyolefins (Kitzweger & Haider, 2022; Markowitsch *et al.*, 2022).

Lafarge

Lafarge *Zementwerke*, a subsidiary of *LafargeHolcim*, a global leader in building materials, is actively focused on CCU in Europe. *LafargeHolcim*, with a workforce exceeding 70,000 employees across more than 70 countries, maintains a well-balanced portfolio encompassing both developing and mature markets. One of their Austrian facilities, the *Retznei* plant, is involved in initiatives utilizing Oxyfuel separation technology, currently in advanced testing phases or approaching full demonstration (TRL 5 to 7; IEA, 2020a). Additionally, *LafargeHolcim* manages two cement plants in Austria with a combined annual capacity of around 1.6 million tons of cement. (C2PA, T2022).

OMV Aktiengesellschaft

OMV is a leading Austrian company focusing on sustainability in the oil, gas, energy, and petrochemical sectors. The company is one of Austria's largest listed industrial companies, with sales of €23 billion and approximately 20,000 employees in 2019. OMV has a strong presence in Central and Eastern Europe, the Middle East & Africa, the North Sea, Russia, and Asia-Pacific. It has an average daily production of 487,000 boe/d[1], operates three European refineries, and owns a 15% ADNOC Refining and Trading JV share. OMV also has a 36% participation in Borealis, a leading polyolefin producer. With gas sales volumes of roughly 137 TWh in 2019, the firm operates a gas pipeline network in Austria and gas storage facilities in Austria and Germany. In addition, OMV has set measurable targets for reducing carbon intensity and introducing new energy and petrochemical solutions as part of its commitment to sustainability (C2PA, T2022).

Borealis

Borealis is a top provider of creative solutions in polyolefins, base chemicals, and fertilizers. Its headquarters are in Vienna, Austria, and the corporation is in over 120 countries, employing over 6,900 people. Borealis had a sales revenue of €8.1 billion and a net profit of EUR 872 million in 2019. Mubadala holds a 64% stake in the company through its holding company, while OMV, holds the remaining 36%. Furthermore, Borealis engages with Borouge, a joint venture with the Abu Dhabi National Oil Company (ADNOC), to supply its goods and services to consumers worldwide, and Baystar™, a joint venture with Total in Texas, USA (C2PA, T2022).

- **Regulatory Framework and Supporting Policies for CCU**

Since publishing the first IPCC report in 1990, the EU has implemented numerous policies, strategies, and targets to tackle climate change (Figure 12). These efforts include adopting international agreements such as the UN Framework Convention on Climate Change and the Kyoto Protocol, and implementing various directives such as the Emissions Trading System

[1] Barrels of oil equivalent per day

(ETS), the Renewable Energy Directive, the Effort Sharing Decision, and the 2030 Climate and Energy Framework.

As part of the European Green Deal, the EU recently proposed raising its 2030 GHG emission reduction goal to at least 55% below 1990 levels. Additionally, the EU has enacted the Clean Energy Package, the Paris Agreement, and the European Climate Law, which commits the EU to achieve climate neutrality by 2050 and establish a framework for monitoring and reporting progress (Amanatidis, 2019).

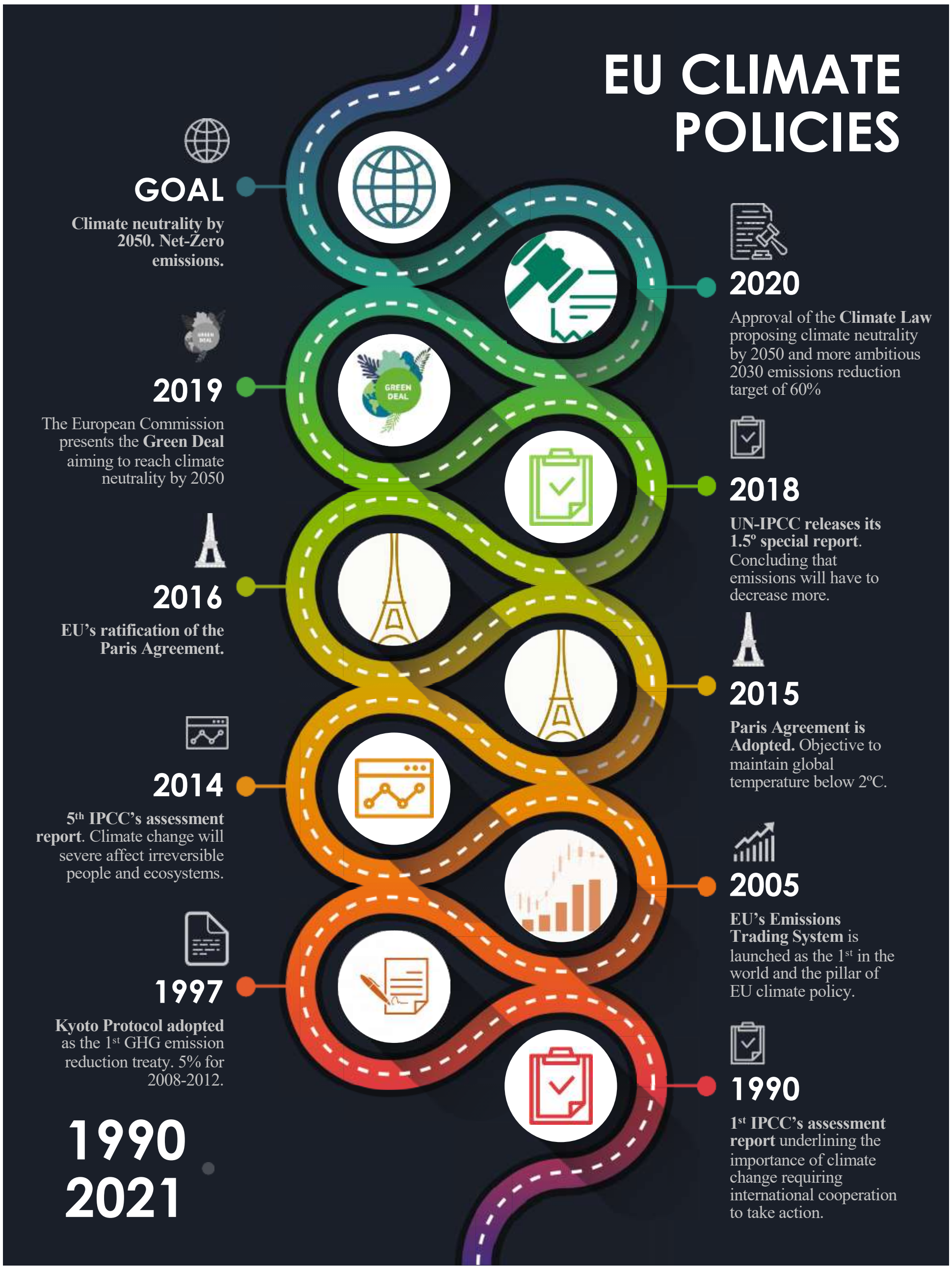


Figure 12. Timeline of the EU climate policies.

The adoption of national climate laws in Europe is increasingly widespread, indicating a solid agreement that countries need to take responsibility for achieving climate neutrality. However, it is not just about passing the laws – the quality of climate governance at the national level is also crucial for achieving these goals (CAN Europe, 2022).

Many EU member countries and some neighbors have enacted national climate laws, creating a unified framework for future policies. Robust climate frameworks showcase government credibility and accountability toward achieving EU climate neutrality goals. While not all nations have implemented such laws, the strength of these regulations varies. Nonetheless, national climate laws promote climate as a top political priority, fostering public awareness and encouraging engagement among citizens, media, and political leaders (CAN Europe, 2022).

European strategies on CCU

The EU has a comprehensive regulatory system for CCU technologies, spanning various policy areas such as trade, environment, energy, innovation, and industry. This system aligns with the EU's objective of achieving climate neutrality by 2050, in accordance with the Paris Agreement and the European Green Deal (EU, 2020; Thielges *et al.*, 2022). To reduce emissions, the European Commission (EC) recognizes the significance of CCU, as outlined in the Energy Roadmap 2050, which aims to cut GHG emissions by at least 80% by 2050. These strategies are influenced by global fossil energy prices and CO_2 costs (García *et al.*, 2021).

The EC also acknowledges the need for substantial investments in CCU to support the transition of European industries. This investment not only helps preserve jobs but also stimulates economic growth and diversifies supply chains into cleaner industries, positioning Europe as a leader in the global clean and competitive economy of the future (Carbon Capture & Storage Association, 2022).

The EU has implemented various policy instruments to advance CCU technologies. These include the CCS Directive, which ensures safe CO_2 capture, transport, and storage, as well as initiatives like Horizon 2020 and the Innovation Fund, which provide economic incentives for CCU research and development. The European Strategic Energy Technology Plan (SET-Plan) aims to reduce costs through coordinated national research efforts and promote cooperation between European countries, companies, and research institutions. These policies can influence the strategies of specific industrial sectors like iron and steel, cement, chemicals, pulp and paper, and aluminum (Carbon Capture & Storage Association, 2021; EU, 2020b).

The European Green Deal explicitly emphasizes the importance of CCU technologies and calls for the promotion of advanced technologies and infrastructure, such as smart grids, hydrogen networks, carbon capture, storage, utilization, and energy storage, to facilitate integration across various sectors (Thielges *et al*., 2022).

The EC recognizes CCU's significance in providing sustainable raw materials, particularly for clean technologies, digital, space, and defense applications. The 2030 Target Plan acknowledges CCU as a means to decarbonize the industrial sector after 2030, especially for industries like aviation and maritime navigation, which have limited decarbonization options. The industrial sector is expected to achieve substantial emission reductions through clean gas technologies, CCS, carbon removals, and CCU technologies. To meet its new 2030 targets, the EC has proposed legislative changes, including revisions to CCU-related policies such as the EU-ETS and the Renewable Energy Directive II, along with the establishment of a new European certification system for renewable and low-carbon fuels (European Commission, 2019; 2020a; 2020d).

The EU has introduced additional strategies to complement the European Green Deal's approach. The EU Strategy for Energy System Integration (European Commission, 2020e) focuses on integrating different energy carriers, infrastructures, and consumer sectors with three main pillars: sector coupling, direct electrification, and the promotion of clean fuels, including renewable hydrogen and synthetic fuels derived from carbon-neutral CO_2 (European Commission, 2020f). Accurate monitoring of CO_2 emissions and removals associated with synthetic fuel production is emphasized to reflect their true carbon footprint (Ramboll, 2019; Thielges *et al*., 2022).

In March 2020, the EU adopted the Circular Economy Action Plan (CEAP) to reduce waste and enhance value throughout the product lifecycle. This plan includes the development of a sustainable product policy framework, incorporating EU-wide criteria for end-of-waste and by-products. The CEAP is relevant to CCU technologies and aims to establish a regulatory framework for certifying carbon removals by 2022, using carbon accounting. This framework will apply to CCU within the context of decarbonization and circular economy initiatives (European Commission, 2020a; 2022).

The Strategic Energy Technology Plan (SET-Plan) provides a comprehensive account of CCU technologies. Its main goal is to promote technological advancement, innovation, and research to facilitate a carbon-neutral energy system. The ninth action of the SET-Plan, the "CCS and CCU Implementation Plan," outlines ten targets for research and innovation in CCUS, with a focus on CCU technologies. These targets include establishing large-scale commercial plants for various CO2 valorization pathways and integrating CCU into Important Projects of Common European Interest (IPCEI) related to hydrogen or low CO_2-emitting industries (Carbon Capture & Storage Association, 2021).

IPCEI projects hold strategic importance as they allow member states to support large-scale transnational projects in Strategic Value Chains (SVC), overcoming State Aid regulations. In 2020, the EU submitted an updated version of its Nationally Determined Contributions (NDC) to the UNFCCC, reflecting the new Green Deal targets for emissions reduction in 2030. However, this document does not explicitly mention CCU (UNCC, 2020; Thielges *et al.*, 2022).

Policy instruments on CCU

The EU employs various methods to endorse CCU, often within broader frameworks related to climate, energy, and environmental concerns. The EU-ETS Directive currently includes only one specific CCU pathway, involving the transfer of CO_2 from the production of precipitated calcium carbonate, to avoid double-counting emissions in regulated sectors. However, a proposed reform as part of the "Fit for 55" package would incentivize CCU by excluding CO_2 emissions that are chemically bound in products from a company's emission allowance (Thielges *et al.*, 2022).

CCU technologies producing recycled carbon fuels and renewable fuels of non-biological origin (RFNBOs) are considered eligible pathways to meet the 2030 climate targets under the Renewable Energy Directive (RED II). To be classified as renewable, these fuels must reduce GHG emissions by 70% (European Commission, 2020d). The Fuel Quality Directive (FQD) aims to reduce GHG emissions per unit of energy supplied, with a focus on RFNBOs. Additionally, the ReFuelEU Aviation Regulation and the FuelEU Maritime Regulation set binding targets for RFNBOs in aviation and reduced GHG emissions from ships, respectively, promoting the development of CCU technologies (European Commission, 2021c; 2021d).

The Industrial Emissions Directive (IED) does not currently consider CCU as Best Available Techniques (BAT) in industry emissions reduction. However, CCU may have potential under other policies like the Regulation on Persistent Organic Pollutants (POPs) and the Regulation on Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH). The Waste Framework Directive (WFD) does not address CO_2 but may establish a framework for captured CO_2 in the future through a certification framework for carbon removals. The Circular Economy Action Plan (CEAP) also mentions CCU, particularly in the context of sustainable building materials and the revision of the Construction Products Regulation (Ramboll, 2019; Thielges *et al.*, 2022).

Politic opportunities for CCU

The EU faces challenges related to oil prices, and it has implemented three market-based policy measures to address these issues within the context of CCU technologies. The EU-ETS, the current emissions trading system, is found to be ineffective in incentivizing CCU adoption due to the significant increase in oil prices required for such motivation. Policymakers are urged to intervene to promote CCU expansion. Subsidies have been proposed to facilitate quicker cost reduction in CCU technologies, encouraging a "learning effect" to advance technology and make CCU more economically viable. Additionally, once CCU costs decrease, the introduction of a carbon tax can incentivize the purchase of sustainable products, steering the industry towards greener practices (Haerens, 2017).

Carbon pricing and public financial support play pivotal roles in decarbonizing industries and fostering investments in CCU. Tradable tax credits, specifically in the capture segment, and the establishment of a market framework for decarbonized products, along with accreditation for low-carbon items, can enhance the attractiveness of CCU and create value across the CCS and CCU value chain. An accreditation scheme for decarbonized products spanning various sectors, such as electricity, hydrogen, steel, chemicals, lime, and cement, could encourage energy-intensive industries to adopt CCU (IOGP, 2019; Bosman, 2021).

Expanding the Guarantees of Origin (GoO) concept, currently used for certifying renewable electricity and other products, is proposed as a potential support mechanism for CCU. Developing tradable certificates for CCU could establish a market and promote cost-effective and favored CCU technologies. However, confidence in the reliability of different techniques and the ability to measure them accurately without double-counting is essential for the success of such a scheme. If CCU can reliably contribute to EU targets and be accurately measured, introducing a GoO or certificate trading scheme could encourage environmental commitment and boost investments and operations in CCU within the European industry (IOGP, 2019).

Economic instruments on CCU

The European Union provides economic incentives and funding opportunities to promote sustainable and low-carbon fuels, including RFNBOs, in air and maritime navigation. The EU's Seven-Year Budget for 2021-2028 allocates one-third of its €1.8 trillion budget to finance the European Green Deal, which includes funding for research and innovation programs such as Horizon Europe and the Innovation Fund. CCUS hubs and clusters are explicitly identified as a strategic goal under Horizon Europe's climate, energy, and mobility work program. The Innovation Fund, which has a budget of €10 billion funded through revenues from the EU-ETS, supports demonstration projects for technologies to decarbonize the energy and industry sectors, including CCU (Amanatidis, 2019; Thielges *et al.*, 2022).

The Commission's proposal for ETS reform seeks to direct funds from the Innovation Fund to carbon contracts for difference (CCDs) that protect investments in innovative climate-friendly technologies. Another funding initiative, the Connecting Europe Facility, funds large cross-border infrastructure projects, including CO_2 transport networks. Overall, the EU is increasing funding for CCU research and development projects and providing new incentives for investments in cost-intensive CCU technologies (Amanatidis, 2019; Thielges *et al.*, 2022).

Relevant regulations related to CCU technology in Austria

Austria's goal to electrify and decarbonize industries by 2040 aligns with its focus on CCU technologies. Several Austrian regulations, policies, and strategies, both directly and indirectly related to CCU, are in line with EU policies. These initiatives collectively support Austria's efforts to reduce GHG emissions and meet environmental targets (IEA, 2019a).

- **National Energy and Climate Plan (NECP):** The NECP is a policy document that outlines Austria's targets and strategies for achieving its climate and energy goals. The plan includes measures to increase the use of renewable energy, reduce GHG emissions, and promote energy efficiency. The NECP also includes a section on CCU technologies, highlighting the potential of CCU to reduce emissions and promote the circular economy.
- **Climate and Energy Strategy 2030:** This strategy is a long-term policy document that outlines Austria's goals and measures for achieving a climate-neutral economy by 2040. The strategy includes measures to promote the use of renewable energy, reduce emissions from transport and buildings, and increase energy efficiency. The strategy also includes a section on CCU, highlighting the potential of CCU to contribute to achieving Austria's climate goals.
- **Austrian Research and Technology Report 2020** comprehensively overviews Austria's research and technology landscape. In addition, the report includes a section on CCU technologies, highlighting the importance of CCU for achieving Austria's climate goals and reducing emissions.
- **Austrian Climate Protection Act:** Adopted in 2011, this law sets out binding targets for reducing GHG emissions in Austria. Austria is required by law to cut emissions by a minimum of 80% by 2050 compared to 1990. CCU technologies are not

mentioned explicitly in the law, but they are considered one of the key measures for achieving emissions reduction targets.

- **Circular Economy Action Plan:** This policy document outlines Austria's transition strategy to a circular economy. The plan includes measures to promote resource efficiency, reduce waste, and increase recycling. CCU technologies are considered an essential part of the circular economy, and the plan includes measures to promote the development and use of CCU technologies.
- **Innovation Strategy Austria:** This policy document outlines Austria's strategy for promoting innovation and research. The strategy includes measures to support research and development in CCU technologies and to promote the development of new technologies and applications.

Overall, Austria has recognized the importance of CCU technologies for achieving its climate goals and promoting a circular economy. Accordingly, the country has adopted a range of policies and strategies to support the development and use of CCU technologies, and this trend will likely continue in the coming years (IEA, 2019a; IEA Bioenergy, 2021).

- **Regulatory requirements for Case 1: Voestalpine**

The EU End of Waste Regulations and similar rules may prevent waste in commercial products, but revising these regulations to allow the use of certain waste materials may be necessary. Stricter waste disposal regulations could also make carbonating waste materials with CO_2 more economically feasible. However, the conservative building sector may be hesitant to accept new building materials, so it may take several years of trials to demonstrate their safety and environmental benefits before they become widely adopted. In the meantime, targeting market segments more open to novel building materials could be a practical approach (IEA, 2019).

- **Regulatory requirements for Case 2: C2PAT**

To be used in industry, chemicals produced from CO_2 must comply with safety regulations and industrial quality standards. In addition, CO_2-derived materials may have different properties than traditionally made chemicals, which could affect downstream processes. Thus, extensive testing and government approval are required before these chemicals can be used in end-use applications (IEA, 2019).

Economic support for CCU in Austria

In addition to direct strategies, there are research focuses and funding programs in Austria that can indirectly benefit CCU technologies. Austria's energy research program, with a budget of

€13.5 million for the 2020 call, aims to bolster the country's position as an innovative hub for clean energy technologies. It focuses on various areas, including energy systems and networks, energy efficiency in industry, storage and conversion technologies, and digitization. Projects under "Sub-topic 2.3 - Cross-sectional technologies for CO_2 reduction in industry" can receive funding for research into bioenergy, such as capturing CO_2 from the atmosphere and binding carbon in biomass. "Sub-topic 3.1 - Storage and conversion technologies" offers funding for efficient production, storage, and conversion of CO_2-neutral chemical energy carriers like power-to-hydrogen, gas, fuel/liquids, and chemicals (IEA Bioenergy, 2021).

Austria also has initiatives like the showcase regions, which promote renewable energy deployment at the regional level with the goal of producing 100% renewable energy from local resources. The *Vorzeigeregion Energ*ie project, supported by a €23 million budget for 2021, focuses on developing and applying domestic energy and transport technologies, establishing Austria as a lead market for innovative energy technologies, and involving users in showcase regions to build trust and acceptance (IEA Bioenergy, 2021).

Furthermore, the *Klima- und Energie-Modellregionen* program supports Austrian regions in utilizing renewable energy resources, promoting energy efficiency, and sustainable business practices. The objectives of the call 2021 are to create new model regions, continue existing model regions, lead projects, and investment projects in areas such as photovoltaic systems, wood heating systems, solar thermal systems, charging points for e-vehicles, renovations of public buildings, large-scale solar systems, and thermal storage for heat (IEA Bioenergy, 2021).

4.4 Market conditions for the CCU business case

- **Electricity price**

The electricity costs for 2030 were estimated by using the monthly wholesale electricity price data from Ember (2023), covering the period from 2015 to the present in Austria. The data was subjected to forecasting using the Exponential Triple Smoothing Algorithm (ETSA), which revealed an upward trend in electricity prices, projecting prices that exceed €350/MWh, with an average value of €232/MWh expected for 2030 (Figure 13).

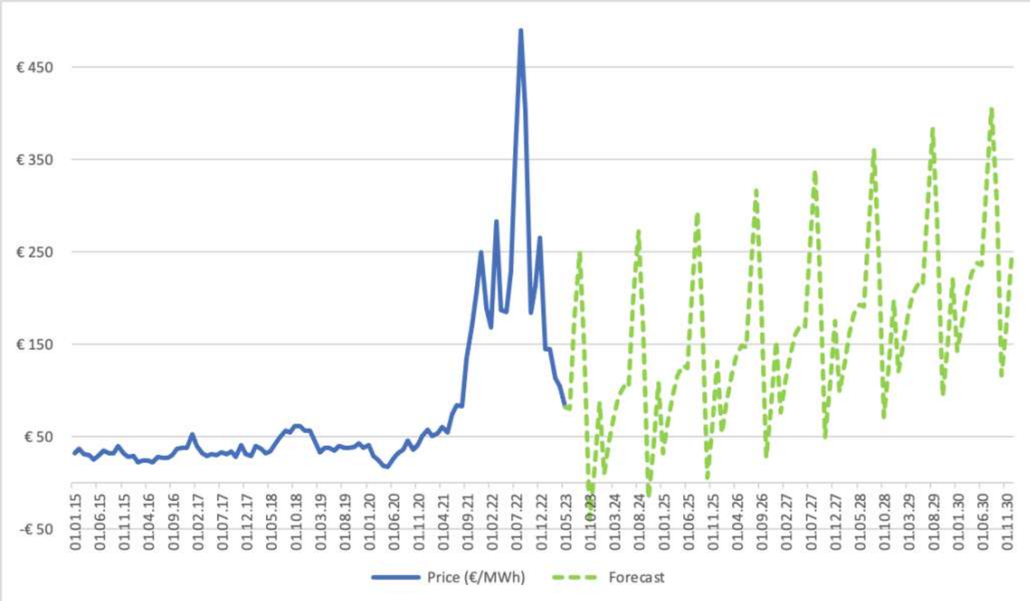


Figure 13. Forecast for Austrian Electricity Price in 2030

In 2030, Austria is expected to experience a rise in electricity costs, with projected prices exceeding €350/MWh. However, the country has set a goal to achieve 100% renewable energy by that year. This shift to renewable sources like wind and solar power has the potential to reduce electricity prices, although the exact impact is uncertain and depends on various factors such as the scale of renewable energy adoption, technological advancements, infrastructure development, and market dynamics (He *et al.*, 2018; Jaeger *et al.*, 2022).

Some reports suggest that reaching the 100% renewable energy target by 2030 could lead to a substantial reduction in electricity costs, potentially lowering them by at least 72%, resulting in a price of €51/MWh (Afman *et al.*, 2017; Federal Ministry of Economic Affairs and Energy, 2017; Jaeger *et al.*, 2022). This aligns with findings from other studies that estimate a similar cost reduction, with an expected levelized cost of electricity (LCOE) of around €50 per MWh in a similar scenario (Bogdanov *et al.*, 2019).

Additionally, it's worth noting that industrial heat costs for 2030 are estimated at €20/MWh, as indicated by predictions in recent research (Fallahnejad *et al.*, 2022) predictions for 2030.

- **Green Hydrogen Price**

The price of hydrogen in 2030 is assumed to be 6 €/kg, highlighting that in 2030 Austria will have 1 GW of electrolysis-based H_2 production, which translates into 4 TWh of green hydrogen (Gupta, 2022).

- **Cost of gas and technology**

Evaluating and comparing technologies involves using performance metrics and benchmarks, which help identify performance gaps and strategies for improvement. In the context of CO_2 capture, factors like investment costs, product expenses, CO_2 capture costs, and CO_2 avoidance costs are considered. These costs can be presented as regular money values (€) or in relation to output (€/metric ton of CO_2 avoided or captured; Roussanaly *et al.*, 2021).

When evaluating CCU, the focus is on the cost of CO_2 capture (€/metric ton of CO_2 captured) and CO_2 emissions avoidance (€/metric ton of CO_2 avoided). The capture cost includes expenses for CO_2 capture system construction and operation at a single site, excluding transport and additional conversions (Naims, 2016; Roussanaly *et al.*, 2021). Conversely, CO_2 avoidance cost is vital in CCU assessment, representing the expense of preventing CO_2 emissions while producing valuable products. This metric facilitates comparisons between CCU systems for more efficient CO_2 reduction. However, capture, compression, and pipeline systems are designed based on captured, not avoided, CO_2 amounts (Roussanaly *et al.*, 2021).

- Capture

Post-combustion technologies are a promising approach for reducing CO_2 emissions, particularly in industries like cement and steel production. Amine absorption, with a TRL of 9, is expected to be the most advanced technology for post-combustion CO_2 capture in 2030 (García-Gutiérrez, 2016; Kazemifar, 2021). This method relies on a chemical reaction between CO_2 and amine within the absorber unit. The flue gas, containing CO_2, contacts liquid amine, forming a weak bond that separates CO_2 from the gas mixture. The amine-containing CO_2 is then taken to the stripper, where heat is applied to release CO_2 from the amine, allowing the solvent to be reused (Figure 14; Kazemifar, 2021).

For CO_2 separation from flue gas with 15-30% CO_2 content at 40°C, using 30% monoethanolamine (MEA) and achieving 90% CO_2 removal, the typical energy required for regenerating the solvent (reboiler duty) ranges from about 3.6 to 4.0 GJ/t CO_2 (approximately 1 to 1.1 MWh/t CO_2). Reboiler duty for different amines, combinations of amines, and concentrations falls within the range of 2.0 to 3.8 GJ/t CO_2 (around 0.6 to 1.1 MWh/t CO_2; Garðarsdóttir *et al.*, 2018, Roussanaly *et al.*, 2021; Kazemifar, 2021).

During the CO_2 amine absorption process, there is a heat release of 80 to 100 kJ/mol of CO_2, and the MEA process typically requires an average electricity input of 0.14 MWh/t CO_2, with a heat release of approximately 0.58 MWh/t CO_2 during absorption (which can be reused) and heat demand of 0.86 MWh/t CO_2 during regeneration (Jang *et al.*, 2021; Morimoto *et al.*, 2021).

Also, the final amount of CO_2 captured must be compressed for storage or transportation with an electricity requirement between 0.09 to 0.14 MWh/t CO_2 (Figure 14; Baroudi *et al.*, 2021).

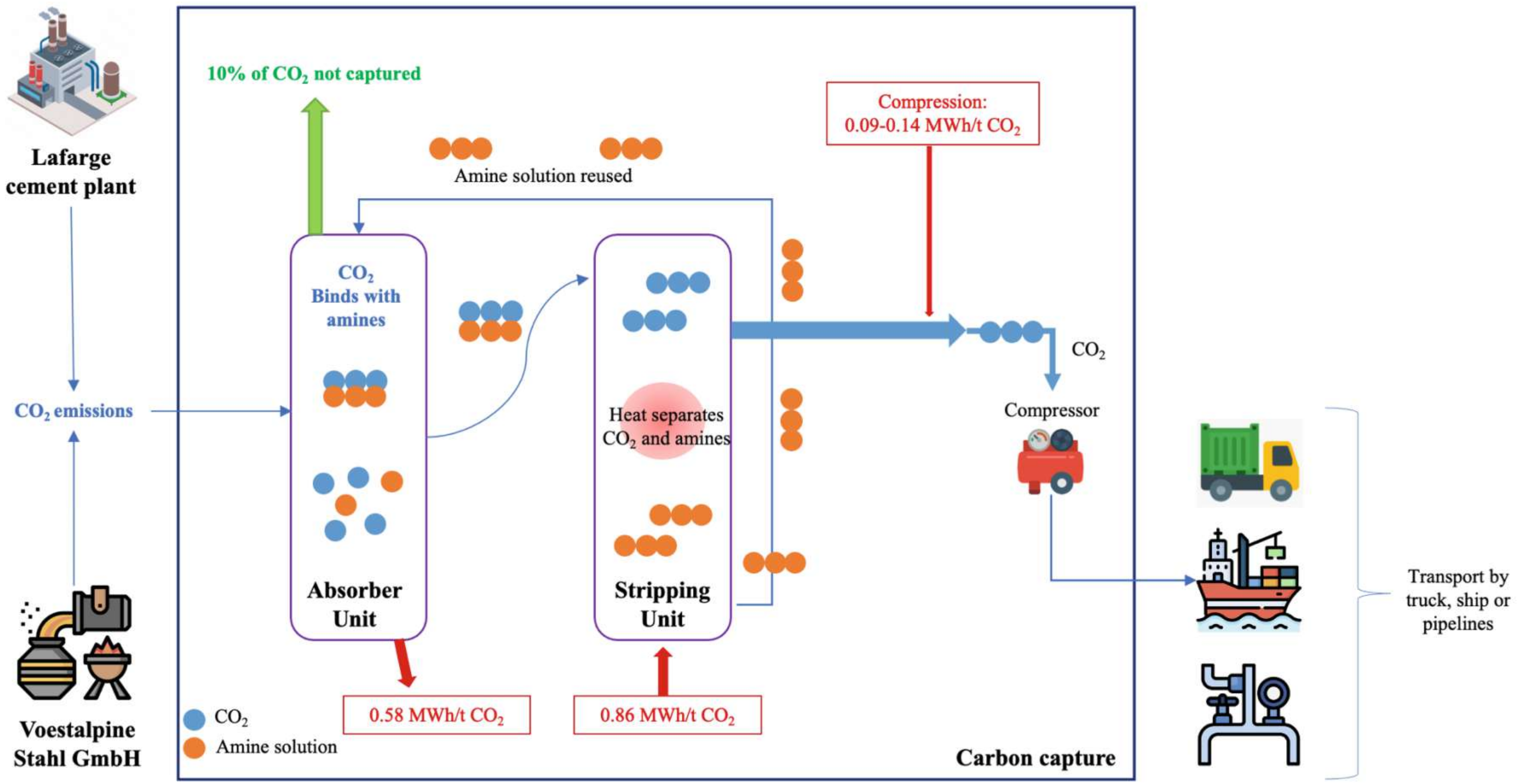


Figure 14. Carbon Capture Methodology with Average Energy Requirements.

In a typical post-combustion CO_2 capture system, approximately 90% of the CO_2 can be separated, meaning that for every ton of CO_2 intended to be captured, around 0.1 tons of CO_2 is still released into the atmosphere (Garðarsdóttir *et al.*, 2018; Van Der Meer *et al.*, 2020; Roussanaly *et al.*, 2021). These systems require thermal energy, often obtained from natural gas, resulting in emissions of about 0.02 tons of CO_2 for every ton of CO_2 intended to be captured. Compressing the captured CO_2 for transportation requires electrical energy, typically sourced from the EU grid, resulting in emissions of approximately 0.03 tons of CO_2 (Van Der Meer *et al.*, 2020).

However, the study is set in the year 2030 when Austria is projected to achieve 100% renewable energy use (IEA Bioenergy, 2021). This means that the heating and electricity needed for the carbon capture process will come from renewable sources, eliminating additional CO_2 emissions, except for the 10% corresponding to the technology's efficiency.

The cost of capturing CO_2 varies based on factors like the energy penalty for separation and compression (resulting in a loss of power generation efficiency), cost penalties for building and operating the facility, the level of CO_2 in the gas stream being captured, plant location, energy and steam supply, and integration with the original facility (Kemp, 2018; Krekel *et al.*, 2018; Ferrari *et al.*, 2019; Kazemifar, 2021). When dealing with less concentrated CO_2 streams, like those from a blast furnace in a steel plant (20-27% CO_2), the expense for CO_2 capture becomes significantly higher. On average, these capture expenses make up about 75% of the total cost of CCU (National Petroleum Council, 2019), with CO_2 capture being the most expensive part due to technology costs and energy requirements (Figure 15; IEA, 2020d; ETC, 2022).

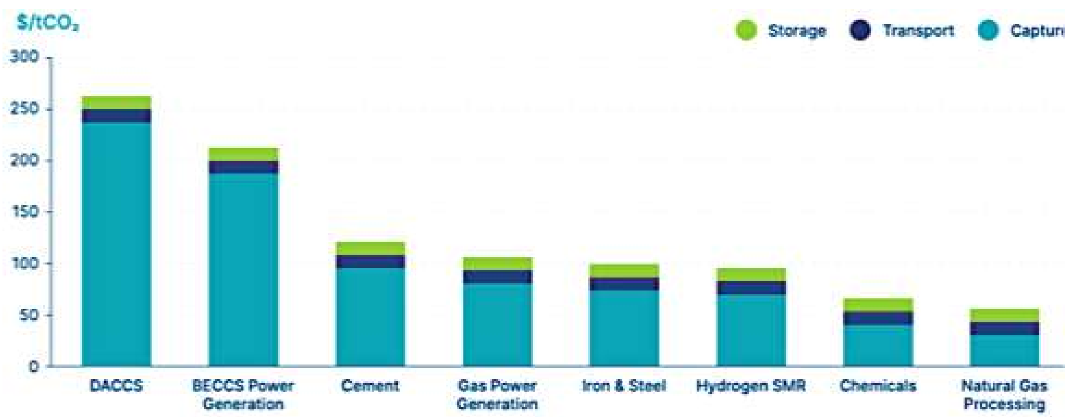


Figure 15. Levelized Cost of Capture, Transport, and Storage by Application. Source: ETC (2022).

In iron and steel plants, the blast furnace is responsible for about 67% of direct CO_2 emissions, with its flue gas containing approximately 27% CO_2. Using amine-based liquid absorption for carbon capture in these plants results in a cost of approximately €70 per ton of CO_2 avoided (James *et al.*, 2019; Kazemifar, 2021). Similarly, top-gas recycling blast furnace technology with post-combustion capture has an average cost of €71 per ton of CO_2 avoided, offering the potential to reduce 65% of total emissions from the plant (Kuramochi *et al.*, 2012; Bui *et al.*, 2018).

While amine liquid absorption technology can be used in cement production as well, it is generally considered to be significantly more expensive due to the need to protect amines from Nox and SO_2 in the flue gas using various treatment methods and increased fuel consumption caused by limited low-grade heat availability (Bui *et al.*, 2018; Kazemifar, 2021). Estimated capture costs for amine scrubbing in cement plants range around €98 per ton of CO_2 avoided (Leeson *et al.*, 2017).

Overall, most researchers agree that introducing carbon capture in the iron and steel sector leads to a cost increase of 31–41%, and in the cement industry, it is expected to result in a cost increase of 68% (Kazemifar, 2021).

In a 2030 projection, considering annual CO_2 emissions of 8,550,000 t for Voestalpine and 700,000 t for Lafarge, assuming 90% capture technology efficiency, approximately 7,695,000 t and 630,000 t of CO_2 could be captured in each case. However, the assumptions for Case 1: Voestalpine are based on a large-scale facility, which is uncommon.

The most significant global carbon sequestration efforts as of 2023 are led by two companies: the Shute Creek Gas Processing Plant in the US, capturing approximately seven million metric tons of CO_2 annually, and the Orca Plant in Iceland, utilizing direct air capture (DAC) to convert carbon into solid stones, with a yearly capacity of 4,000 tons of CO_2 (Global CCS Institute, 2023). Hence, for Case 1: Voestalpine, we consider capturing five million tons of CO_2, assuming it operates similarly to the Shute Creek Gas Processing Plant, marking it as the first of its kind in Europe.

In Case 2: C2PAT, Verbund, a renewable energy company, will launch the project with a 44 MWp PV park. Out of this, 10 MW will be used for low-temperature electrolysis to convert 10,000 tons of CO_2 per year into around 2,300 tons of Polyolefins (Kitzweger & Haider, 2022; Markowitsch *et al.*, 2022). Initially, this captures only 1.5% of the yearly emissions. However, by 2030, it's expected to capture nearly 100% of Lafarge's cement plant's annual emissions, which amounts to approximately 630,000 tons of CO_2 per year.

Based on previous information and distinct carbon capture costs for specific scenarios - capturing from Voestalpine's blast furnace (iron and steel plant) and capturing from Lafarge's flue gas (a cement plant) - estimated costs of €42/t CO_2 captured and €70/t CO_2 captured can be calculated for each case. This calculation takes into account the exchange rate of €0.93, with 41% of the total cost allocated to the iron and steel plant and 68% to the cement plant. Therefore, the annual carbon capture expenses for Case 1: Voestalpine would be approximately **€210 million**, while for Case 2: C2PAT (Lafarge), it would be around **€44.1 million**, reflecting the difference in CO_2 emissions.

Ongoing research and development efforts are focused on improving the energy efficiency of CO_2 capture technologies, including the amine process, to reduce the overall energy and cost burdens associated with large-scale implementation. Today's technologies require about 2-3 MWh/t CO_2 captured, but this could fall to as low as 0.5 MWh/t CO_2 by 2050 or sooner (ETC, 2022).

A common benchmark for post-combustion capture is achieving capture rates of around 90%, as going beyond this level significantly raises costs. While other clean energy technologies like solar PV panels, wind turbines, batteries, and electrolyzers have seen substantial cost reductions over the past decade, carbon capture costs have decreased relatively little (ETC, 2022). This has led to alternative decarbonization strategies becoming more cost-competitive compared to CCU (Figure 16).

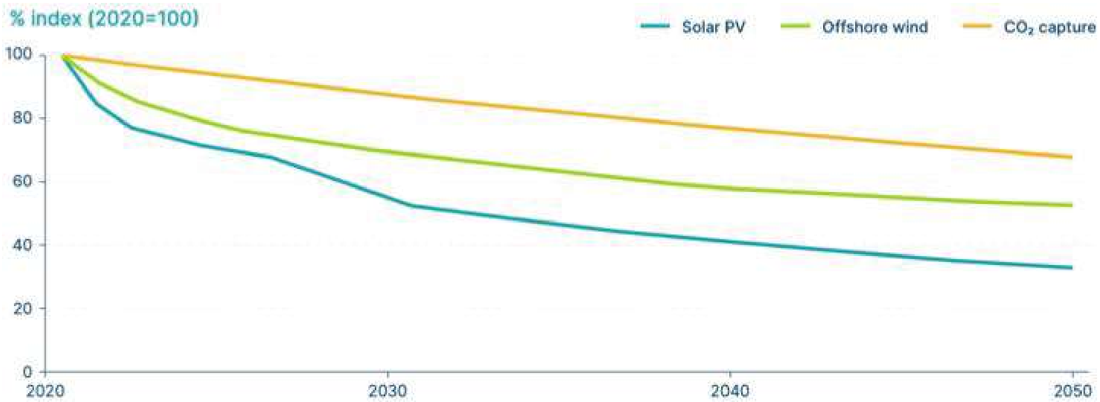


Figure 16. CO_2 Capture and Renewables Costs Outlook. Source: ETC (2022).

Although there's potential for CO_2 capture costs to decrease, this decline may be slower than the remarkable reductions seen in renewables. Slower declines can be attributed to factors like the learning curve and economies of scale, especially if capacity expansions accelerate. However, custom-designed or retrofitted CCU projects could still achieve cost reductions of around 30% by 2050 through multiple incremental improvements, according to the IEA

(2020a; 2021b) analysis. Additionally, revolutionary technological innovations with significantly lower energy input requirements could further reduce costs well below current and anticipated estimates (ETC, 2022).

- Transport

CO_2 transportation is necessary unless it's captured directly at the utilization site. The primary options for CO_2 transport are pipelines, ships, and trucks, with pipelines being the most common for substantial quantities. Ships and trucks are also feasible but not railways (ETC, 2022).

CO_2 captured typically contains water, which must be removed to prevent pipeline and equipment corrosion. This involves dehydrating, compressing CO_2 into a denser or liquid state, and moving it from the capture site to the utilization facility (Kearns *et al.*, 2021; ETC, 2022).

Efficient liquid CO_2 transport is crucial, especially for onshore installations without pipeline access. In North America, there's an extensive CO_2 pipeline network covering over 2,500 km and a total length exceeding 8,000 km, with a transportation capacity of about 50 million Mtpa. In Europe, CO_2 pipelines are mainly found in Norway and The Netherlands, with lengths of 153 km and 85 km, respectively (IOGP, 2019; IEA, 2020a).

- **Pipelines:** CO_2 transportation through pipelines is well-established, especially for large-scale use (IEA, 2020a). It's matured, notably in North America, where a substantial network exists (Olsson *et al.*, 2020). The US alone moves approximately 70 million tons of CO_2 annually via pipelines, mainly for enhanced oil recovery (IOGP, 2019; IEA, 2020a; ETC, 2022).
  Transmission pipelines usually need a minimum volume of about two million tons per year, justifying investments for significant producers or when multiple capture facilities feed into the same pipeline (ETC, 2022). Major CO_2 emitters like power stations, gas processing plants, and industries can independently support cost-effective CO_2 pipelines and serve as core customers for hubs, allowing smaller sources to use the pipeline without incurring higher costs due to lower flow rates (Kearns *et al.*, 2021).
  Pipeline costs vary based on location, population density, and the choice between onshore and offshore routes. Remote and less populated areas have cheaper pipeline construction costs compared to densely populated regions. Offshore pipelines are generally more expensive. Economies of scale are significant, as unit costs decrease

with a larger pipeline capacity. As new projects emerge, pipeline costs will differ across regions (IEA, 2020a).

Repurposing existing offshore oil and gas pipelines for CO_2 transport is cost-effective compared to building new infrastructure. It involves using pipelines that may otherwise become obsolete, yielding financial benefits ranging from 1 to 10% of new construction costs. However, repurposing hydrocarbon pipelines for CO_2 transmission remains challenging and relatively uncommon due to associated complexities (IOGP, 2019; ETC, 2022).

- **Shipping:** Large-scale CO_2 transportation by ships is still in development (TRL 4-7) but offers potential for innovative solutions, especially for unloading at offshore sites and adopting advanced shipping technologies like automation and improved propulsion systems (IEA, 2020a; ETC, 2022).

  The potential for standardizing essential ship components, like connection valves and flanges for ships and storage facilities, holds promise for cost reduction and faster vessel construction. This adaptability in shipping could help establish initial CO_2 capture hubs that might evolve into permanent pipeline networks (IOGP, 2019; IEA, 2020a).

  In Europe, about 1,000 tons of CO_2 are shipped annually from major sources to coastal distribution terminals, and regions like Europe, Japan, and Korea show increasing interest in CO_2 shipping. Ship capacities range from 800 m3 to 1,000 m3, with plans to scale up for industrial use. For instance, the Northern Lights facility in Norway will receive liquefied CO_2 via ships, and as vessel capacities increase, they could potentially reach 50,000 tons in the future, benefiting from economies of scale (ETC, 2022).
- **Trucks:** Offer a practical option for transporting CO_2 over short distances or when CO_2 production is sporadic, making pipelines impractical. They are suitable for cases where CO_2 sources are small and remote, making pipeline investments less feasible. Typically, trucking is more cost-effective for volumes below 1.7 million tons per year. Alternatively, on-site utilization options might also be financially competitive in such cases (ETC, 2022).

According to various sources, the compression of captured CO_2 from atmospheric pressure to 11 Mpa requires around 111 kWh of electrical work/t CO_2. This translates to compression costs of approximately USD_{2020} 11 to USD_{2020} 21/t CO_2 (Figure 17; Baroudi *et al.*, 2021; Kazemifar, 2021; Kearns *et al.*, 2021; ETC, 2022).

The combined cost of compression and pipeline transport averages between USD 9.1 and USD 22.4/t CO_2 avoided, considering a transportation rate of 10 million tons of CO_2/year (Kazemifar, 2021; ETC, 2022).

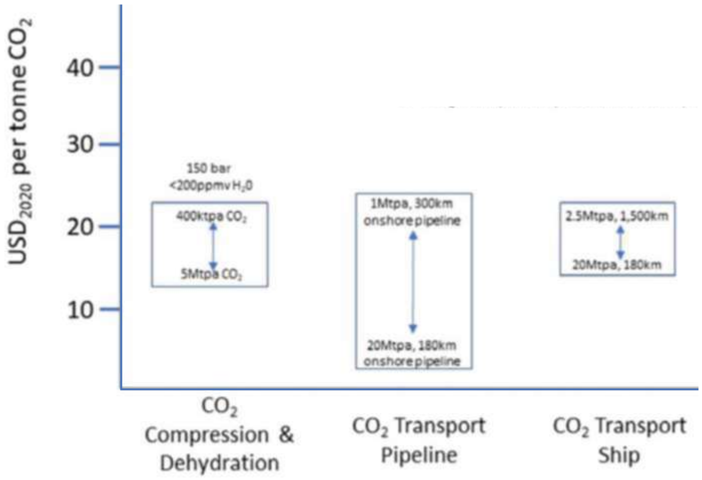


Figure 17. Cost Ranges for Compression and Transportation of CO_2 (excluding capture costs). Source: Modified from Kearns et al. (2021).

In the European context, the expenses associated with offshore CO_2 pipelines fluctuate between €2 to €29/t CO_2, while ship transport costs range between €10 and €20/t CO_2 (Reiter & Lindorfer, 2015; ETC, 2022). This range aligns with Olsson *et al*. (2020) findings, which suggest a cost of €15/t CO_2 for transporting 20 million tons of CO_2 over a distance of 1,200 km via ships and pipelines.

Although CO_2 transport on a large scale is anticipated to be predominantly achieved through pipelines, for capacities below 500 kt CO_2/year, trucking becomes a cost-effective option. Particularly, for capacities below 200-300 kt CO_2/year, trucking is expected to offer a more economical mode of transportation (Kazemifar, 2021).

In Case 1, the quantity of captured CO_2 is substantial, similar to that of a large-scale facility (five million tons of CO_2). Consequently, pipelines appear as the most economically viable transport option due to the significant volume of CO_2. However, since the steel plant covers an area of about 2.08 km^2 (Figure 18), and the gas needs to be transported over a very short distance due to its on-site utilization, truck transportation emerges as the optimal method for moving the gas.

Figure 18. Area of Voestalpine plant in Linz, Austria (Source: Google Earth®).

In Case 2: C2PAT, the Lafarge cement plant is located on the edges of Vienna and needs to transport the CO_2 to the OMV refinery, which is around 25-30 km away (Figure 19). While pipelines seem logical for transporting the gas, the amount of CO_2 (630,000 tons) is insufficient for pipeline usage. Hence, truck transportation also emerges as the most practical and cost-effective solution to transfer the gas over a distance of at least 25 km between these two facilities.

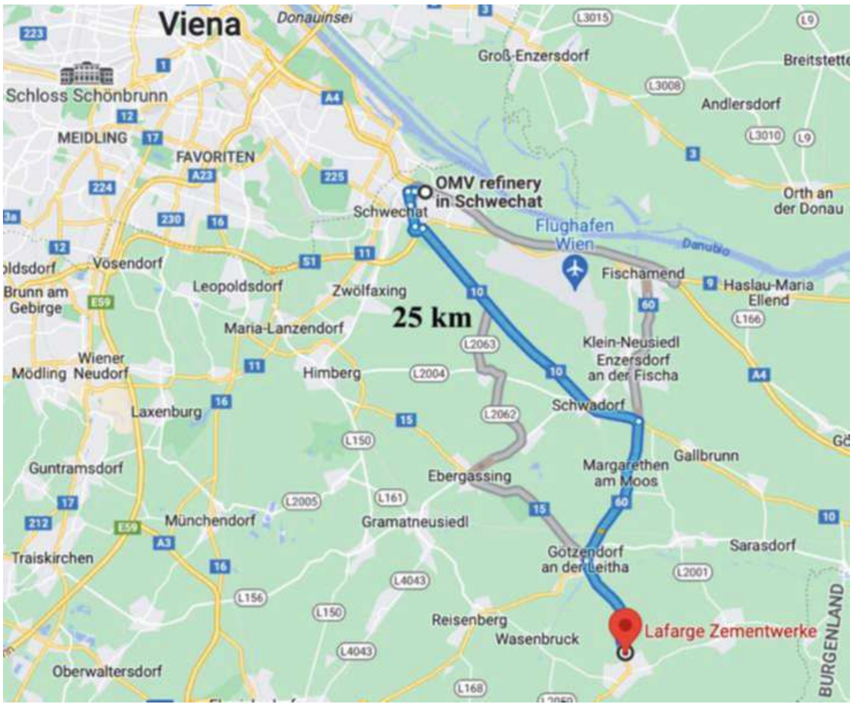


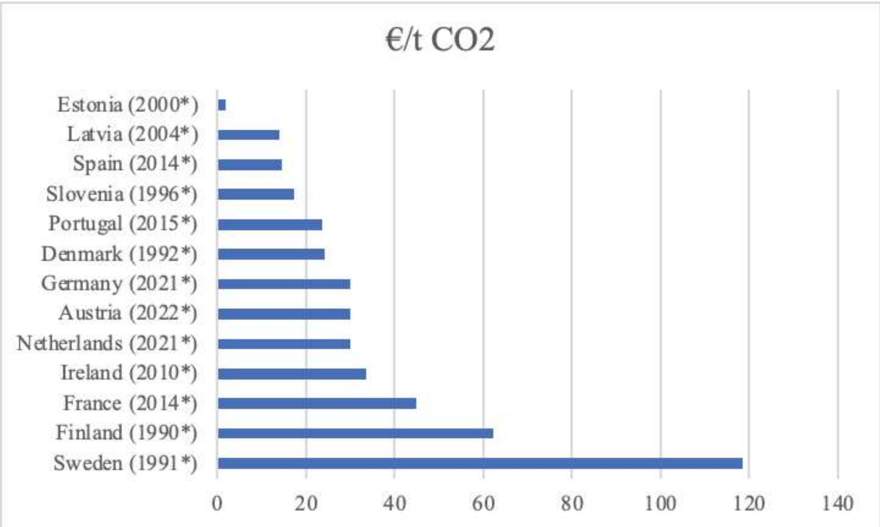
Figure 19. Distance between Lafarge cement plant and OMV refinery in Austria (Source: Google maps®).

Stolaroff *et al.* (2021) reported a cost of about 0.10 €/t/km for truck transportation of CO_2. Assuming an average compression cost of €14.8/t CO_2, as mentioned earlier, case 1: Voestalpine's total expenses for compressing five million tons of CO_2 would be around €74 million. Additionally, transporting this amount over a 2 km distance would incur approximately €1 million, resulting in a combined expense of about **€75 million** for both compression and transportation. Similarly, for Case 2: C2PAT, compressing 630,000 tons of CO_2 would lead to expenses of about €9.3 million, and transporting it across a 25 km distance would add €1.6 million, resulting in a total cost of approximately **€10.9 million** for compression and transportation.

However, CO_2 transportation costs can vary significantly depending on the specific project context. Various factors like capital costs, equipment, labor, energy, and other consumables can differ substantially across different locations (Kearns *et al.*, 2021).

- ETS

Several EU countries have their individual CO_2 pricing systems alongside the European Emissions Trading System (EU-ETS), which primarily targets the energy and industry sectors. These national CO_2 pricing schemes promote environmentally friendly practices in transportation and construction by raising the costs of fossil fuels and heating materials. However, there's substantial diversity in CO_2 prices within the EU. For instance, Sweden boasts the highest price, nearly €120/t, while most other countries typically charge around €30/t (Figure 20). Austria also implemented a €30/t CO_2 price in October 2022 (Wien Energie, 2022).



**First launch date*

Figure 20. National Price of CO_2 in the EU (Source: ISTA, Taxfoundation.org, Carbon Pricing Dashboard, World Bank, 2021).

The EU-ETS is a cap-and-trade system where companies must hold emission permits called European Union Allowances (EUAs). If a company exceeds its allotted emissions, it must purchase extra EUAs to comply with EU-ETS regulations, encouraging emissions reduction and investment in low-carbon technologies (Pahle *et al.*, 2022).

Austria is allocated approximately 43.9 million EUAs annually for the current trading period (2021-2030), subject to annual adjustments by the EU to meet greenhouse gas reduction targets. Voestalpine (2023) reports purchasing emission allowances to cover two-thirds of its emissions in 2021/22. In contrast, Lafarge holds significant CO_2 surplus permits worth millions of euros, covering almost all annual carbon emissions (Cemnet, 2011).

CO_2 allowance prices in the EU-ETS are influenced by factors like emission targets, economic conditions, energy costs, and regulations, making precise 2030 price predictions challenging (Pahle *et al.*, 2022). Forecasts using the ETSA method suggest a rising trend, with a projected peak price of €265/t of CO_2 by December 2030 and an average expected price of about €250/t of CO_2 for 2030 (Figure 21).

Figure 21. Forecast of EU-ETS prices in 2030.

If Voestalpine captures 59% of its annual emissions (5 million tons of CO_2) and Lafarge captures 90% of its emissions (630,000 tons of CO_2), both companies wouldn't need to buy additional permits during the current trading period (2021-2030) because their allocated EUAs would cover their emissions.

- **Cost of technology**

Both plants must adopt carbon capture technology and cover compression and transportation costs, in addition to the energy (electricity and heat) for using captured carbon. In Case 1: Voestalpine, steel slag carbonation is used to produce carbonates ($CaCO_3$), while Case 2:

C2PAT involves hydrocarbon polymerization for recycled plastics from captured CO_2. This section comprises two parts: equipment costs for carbon capture technology, applicable to both cases and encompassing previous expenses for carbon capture, transportation, and EU-ETS, and costs related to carbon utilization technology, which differ for each case.

These costs are based on credible studies that extensively collected information from the CCU literature, including data cited in previous sections.

- Cost of carbon capture technology

This section compares carbon capture costs between two CO_2-emitting industries in Austria. The cost variations primarily hinge on each industry's annual CO_2 emissions, in addition to the expenses related to capturing, compressing, transporting CO_2, and complying with ETS, as outlined before. This section also incorporates costs related to equipment procurement for implementing carbon capture technology in both industries (**Error! Reference source not found.**). The goal is to calculate the initial investment required by each industry to adopt this technology.

Carbon capture technology needs various essential equipment types, including an absorber column or tower, which houses the amine solution capturing CO_2 from flue gas. It is complemented by a reboiler, which heats the saturated amine solution to release CO_2. Another crucial component is the stripping column or tower, responsible for separating CO_2 from the heated amine solution. Cooling the released CO_2 into a liquid state is achieved using a condenser. Storage tanks store the captured CO_2 before transportation. Pumps, valves, and instrumentation play vital roles in controlling flue gas flow, amine solution, and CO2 throughout the capture system. These components constitute the core infrastructure for effective carbon capture technology representing a substantial portion of the investment which usually is directed towards the absorber column, compressor, and heat exchangers (Figure 22).

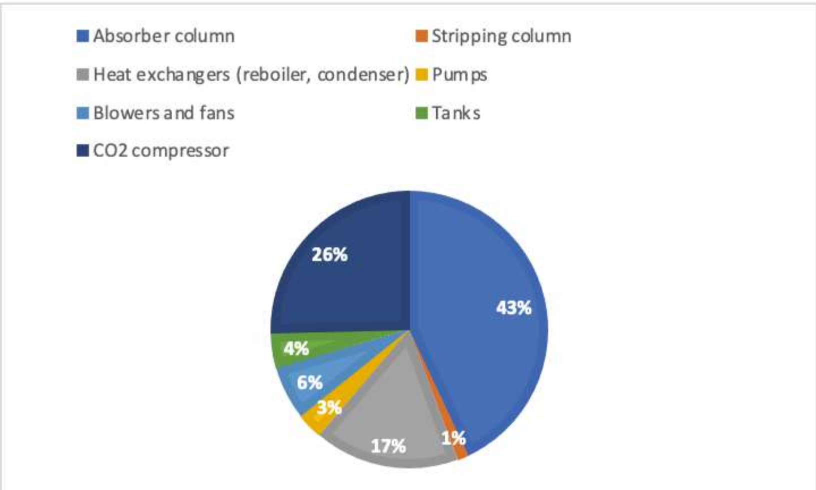


Figure 22. Cost distributions of significant equipment for carbon capture.

Also, according to Roussanaly *et al.* (2017), a carbon capture facility needs approximately 140 employees with a yearly payment of € 60,000 per person. Therefore, annually, the expenses related to labor are about **€8.400.000**.

- Cost of Utilization

CO_2 utilization involves using CO_2 in products rather than storing it underground. It can be cost-effective if CO_2 can replace fossil fuels, enhance products, or be cheaper than storage (Chauvy *et al*., 2019; ETC, 2022). Currently, CO_2 is both a pollutant and a traded commodity, with a global market value of around $8 billion in 2021. Most CO_2 trade occurs in markets with just one buyer, while a smaller portion is openly traded. Investments in CO_2 utilization technology have risen due to the need for carbon capture, with potential scaling linked to product volumes. Different cost scenarios arise depending on CO_2's role as an input, replacement for fossil fuels, or lack of economic value in certain applications (ETC, 2022).

Recent studies have led to the development of various CO_2-based products. However, these products are typically not economically viable because they rely on conventional manufacturing techniques (García *et al*., 2021).

Chauvy *et al*. (2019) classified emerging CO_2-based products based on technical, economic, energetic, environmental, and market considerations. Promising products include methanol, DMC, and methane, which could transition to using CO_2 as a primary input and be ready for commercialization within five years. However, using CO_2 to produce fuel or certain short-lived chemicals prolongs emissions rather than eliminating them.

CO_2 conversion methods are explored not only for the variety of products they can create but also for the value these products hold. Two types of CO_2-based products exist: those with high intrinsic value but limited market demand, such as formic acid, specialized chemicals, and advanced materials, and those with lower intrinsic value but a larger market, such as CO_2-derived fuels and carbonates. Achieving both high intrinsic value and a substantial market volume for these products simultaneously is challenging (Chauvy *et al*., 2019).

Industries like cement, iron, and steel production, which release CO_2 at varying concentrations, are potential candidates for adopting CCU technologies (Chauvy *et al*., 2019). This section outlines the methodology and costs of carbon utilization technologies after capture. The information is sourced from current research and published projects. As different processes are used by each industry, cross-technology and cross-industry evaluations are not presented here. However, a cost comparison for CO_2 utilization within individual industries will be conducted based on the literature.

Case 1: Voestalpine

Mineral carbonation offers an attractive approach to using CO_2 by incorporating it into solid carbonates within construction materials. This process not only reduces CO_2 emissions by storing carbon in a stable mineral form but also repurposes industrial byproducts like steel slag, promoting sustainable waste management practices. Hepburn *et al.* (2019) project that mineral carbonation has the potential to remove, use, and store around 0.1–1.4 gigatons of CO_2 annually by 2050 and potentially up to 3.3 Gt of CO_2 annually by 2100, which could account for about 5% to 12% of projected global CO_2 emissions by 2100 (Renforth, 2019; Di Maria *et al.*, 2020).

Steel slag, in particular, exhibits a CO_2 absorption capacity of 410 kg CO_2/t steel slag, with the potential to sequester 163 Mt CO_2/year (Woodall *et al.*, 2019). Mineral carbonation allows for on-site carbonation of industrial residues, eliminating the need for external waste treatment facilities (Di Maria *et al.*, 2020).

The process of aqueous mineral carbonation involves mixing calcium oxide (CaO)-rich materials like steel slag with water to create a slurry. When CO_2 is introduced into the slurry, it reacts with water to form carbonic acid (H_2CO_3), which then reacts with CaO to produce solid calcium carbonate ($CaCO_3$) as a precipitate. This $CaCO_3$ can be used as a filler in construction materials or as a raw material in cement production (Tu *et al.*, 2015; Chauvy *et al.*, 2019; Voestalpine, 2023a).

For steel slag carbonation, only 20% of the annual steel production is utilized (Voestalpine, 2021), amounting to 330,000 tons. This steel slag must undergo a wet grinding process requiring 4,620 MWh of electricity (Huijgen *et al.*, 2006; Gerdemann *et al.*, 2007).

Mineral carbonation is an exothermic reaction, that generates heat energy (Demirbas, 2007), which varies depending on the minerals and their composition. The exothermic nature of the reaction contributes to minimizing energy and material losses (Wang *et al.*, 2019; Neeraj & Yadav, 2020; Rahmani, 2020; Zhang *et al.*, 2020).
The energy required for aqueous mineral carbonation of steel slag ranges from 980 to 6,300 MJ/t CO_2 captured (Costa *et al.*, 2016; Wang *et al.*, 2018), with variations based on factors like heating, CO_2 compression, and solids-liquid separation. A lower activation energy value of 4.8 kJ/mol has been reported for this process (Tu *et al.*, 2015).

Efficiency of the steel slag carbonation process ranges between 0.264 to 0.289 kg CO_2/t steel slag under specific conditions, with an estimated potential CO_2 sequestration of around 44,550 tons when mixed with five million tons of CO_2.(Chang *et al*., 2012; Tu *et al*., 2015).

Figure 23 shows the process of aqueous mineral carbonation involving steel slag and the associated energy demands.

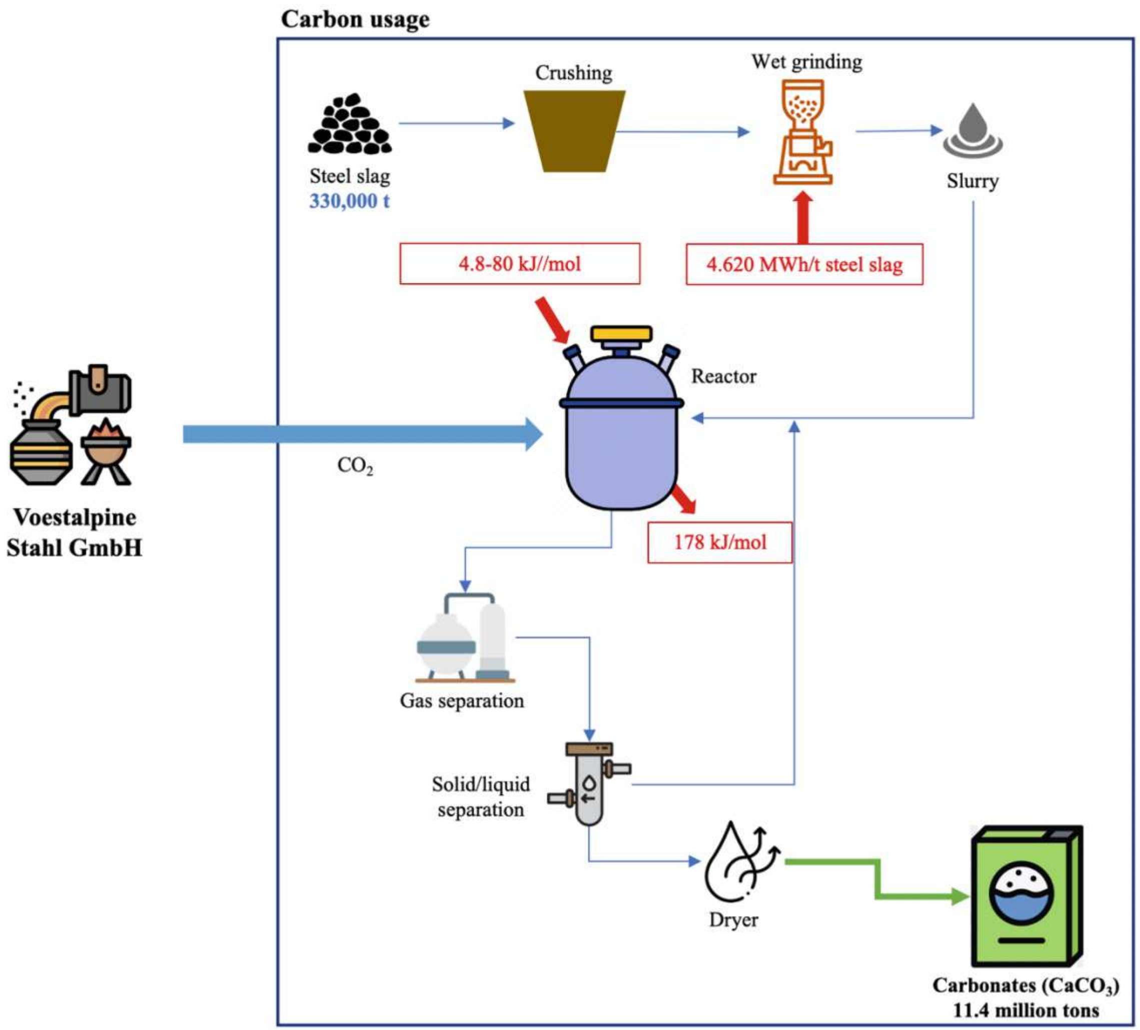


Figure 23. Graphical representation of the carbon usage for Case 1: Voestalpine.

Any unutilized CO_2 produced during the carbonation process is usually released into the atmosphere or sold. This poses a challenge in CCU processes, as not all emitted CO_2 may be captured efficiently. Optimizing the capture and utilization efficiency is crucial for minimizing net CO_2 emissions.

Additionally, the chemical reaction involved in the carbonation of CaO in steel slag results in a portion of the slag retaining reduced CaO content. This residual byproduct contains unreacted CaO and other original components. While its usability may be reduced compared to fresh steel slag with higher CaO content, it can still find applications in various construction and industrial sectors. This byproduct can be sold, generating additional revenue.

Numerous studies over the past decade have assessed the costs associated with the mineral carbonation of steel slag, aiming to find optimal methods for capturing CO_2 within products. These studies have reported costs typically falling within the range of 50-100 USD/t CO_2 captured (Bobicki *et al.*, 2012; Voigt *et al.*, 2018; Neeraj & Yadav, 2020), with some indicating higher costs of 232 USD/t CO_2 (Iizuka *et al.*, 2013), depending on various factors like product value, feedstock expenses, the scale of the sequestration process, depreciation period, and the liquid-to-solid ratio.

Excluding compression costs in mineral carbonation leads to a reduction of 58 €/t CO_2 avoided for steel slag (Huijgen *et al.*, 2007; Sanna *et al.*, 2014). This reduction is due to the absence of investment costs for compressors, electricity expenses for compression, and an improvement in sequestration efficiency. However, even without considering compression, the costs associated with mineral carbonation technologies remain relatively high compared to geological CO_2 capture and storage alternatives. While the secure and inherently safe nature of sequestering CO_2 through mineral carbonation may justify higher costs, further expense reductions are crucial, especially considering current CO_2 emission rights prices in the EU emissions trading scheme.

Regarding the equipment costs for mineral carbonation, Table 4 shows the CO_2 sequestration costs for steel slag carbonation, excluding possible costs for CO_2 capture.

Table 4. Costs for equipment needed for the aqueous carbonation of steel slag.

Equipment for carbon usage	**Costs (€/t CO_2)**	
	Captured	**Avoided**
Compressor, blower, and pump	3	4
Reactor	6	7
Grinding equipment	6	7

Equipment for carbon usage	Costs (€/t CO_2)	
	Captured	Avoided
Heat exchangers	4	4
Other equipment	1	1
Feedstock	0	0
Cooling water	1	1
Grinding	13	15
Staff	5	6
Maintenance	9	10
Other	7	9
Total	**55**	**64**

Source: Modified from Huijgen et al. (2007); Jones (2018), Yang et al. (2011) and Roussanaly et al. (2021)

Assuming an average cost of 75 €/t CO_2 captured, Voestalpine would face an additional annual expenditure of approximately **€3.3 million** to implement mineral carbonation. This calculation doesn't include capital expenditures (CAPEX), other essential operational costs, or potential revenues. Additionally, any unused CO_2 would be released into the atmosphere, incurring penalties associated with ETS prices unless it can be sold to other companies.

Despite the associated expenses, mineral carbonation remains a favored approach for CO_2 sequestration due to the long-term integration of CO_2 into products like construction materials (cement, building blocks, etc.). However, given its high cost, mineral sequestration is more practical for smaller emitters (>2.5 Mt CO_2) as the technology is not yet prepared for large-scale implementation (Neeraj & Yadav, 2020).

Case 2: C2PAT

Four companies (Verbund, Lafarge, OMV, and Borealis) are collaborating to capture CO_2 from the Lafarge cement plant. The captured CO_2 will be combined with hydrogen from Verbund in the OMV refinery. OMV will utilize the Fischer-Tropsch synthesis method to create low-chain olefins, a specific type of hydrocarbon. These olefins can then be further processed into biofuels or recycled carbon plastics through polymerization at Borealis.

According to Kitzweger & Haider (2022) and Markowitsch *et al.* (2022), 10,000 t CO_2/year can yield approximately 2,300 tons of Polyolefins using 10 MW of power. Therefore, it can be reasonably projected that in 2030, 630,000 t CO_2 will result in an annual production of roughly 145,000 tons of Polyolefins, with the use of 630 MW. This projection aligns with the objectives set by Borealis (2023), which aims to achieve a production of 1.82 million tons of renewable-based polymers by 2030.

- **Step 1: Obtaining H_2**

Water electrolysis, driven by electricity through an electrolyzer, splits water into hydrogen and oxygen. It's seen as a promising method for hydrogen production and energy storage, especially when coupled with renewables. Common electrolyzer types include PEM, AWE, AEM, and SOE (Chen & Yu 2018; Lim & Kim 2022; Nasser *et al*., 2022a).

- In **PEM electrolyzers**, use a plastic electrolyte to split water into hydrogen and oxygen. They're quick, and produce very pure hydrogen (up to 99.9%; Buttler & Spliethoff, 2018), but can be expensive due to materials (Bhandari *et al*., 2014; Nasser *et al*., 2022a).
- **Alkaline electrolyzers** move hydroxide ions from the cathode to the anode to generate hydrogen. They're mature, reliable, safe, and suitable for large-scale use (Cao *et al*., 2023).
- **Solid oxide electrolyzers**, use ceramic electrolytes to split water at high temperatures, utilizing waste heat to reduce energy needs. Requires elevated temperatures (700°–800°C) but can efficiently utilize waste heat to reduce the electrical energy needed (Nasser *et al*., 2022a).

In a PV/H_2 system, solar panels connect to an electrolyzer through a power-conditioning unit, optimizing electricity use with a maximum power point tracker (MPPT) and converter(Haider *et al*., 2021; Nasser *et al*., 2022b). Excess solar energy is stored in batteries, offering advantages like DC output, low maintenance, and suitability for PEM electrolyzers, which experts consider ideal for electrolysis, although commercial benefits require more experience (Paul & Andrews 2008; Schmidt *et al*., 2017).

The energy needed per unit of hydrogen relies on electrolysis efficiency, varying with technology and conditions. Ideally, it's about 39 kWh/kg when considering the higher heating value of H_2, but a 60% efficient PEM electrolyzer would demand more energy per unit of hydrogen (Kurrer, 2020; Nasser *et al*., 2022a; Leo, 2023).

$$E\ required\ to\ produce\ 1\ kg\ H_2 = \frac{39\ kWh/kg}{0.60} \approx \mathbf{65\ kWh/kg}$$

As per Markowitsch *et al*. (2022), project simulation, a low-temperature PEM electrolysis operating at 75°C and 30 bar outlet pressure had an overall specific energy consumption of 4.7 kWh/Nm^3 H_2.

PV-powered electrolysis can produce sustainable hydrogen at around $12/kg when solely relying on solar panels, but their efficiency (17% to 26%) and variable electricity production pose challenges. By 2030, costs may drop to about $5.87/kg (Bown *et al.*, 2021). Ultrahigh concentration PV/H2 systems can significantly boost efficiency, producing 0.8 to 1.0 L/min/m_2 of hydrogen (Muhammad-Bashir *et al.*, 2020). Verbund plans to install a 44 MWp PV park for low-temperature electrolysis, assuming 1,200 FLH per year (The World Bank, 2020) and a 25% capacity factor assuming the higher value for their Linz PV Park, between the range 10%-25% reported for solar panels (WNN, 2022).

$$44\ MWp \times 25\% \approx \mathbf{11\ MW}$$
$$Energy = 11\ MW \times 1.200\ h \approx \mathbf{13.2\ GWh}$$

Additionally, the project retains access to green electricity from the power grid as a backup option in case additional energy is required for electrolysis by 2030 (C2PAT, 2022).

Incorporating a battery upfront increases system cost but offers benefits like reducing electrolyzer size and enabling nighttime hydrogen production, resulting in an LCOH range of approximately 6–7 €/kg (Gutiérrez-Martín *et al.*, 2020; Zhang & Wei, 2020; Puranen *et al.*, 2021).

Capital costs for PEM electrolyzer systems range from 800 to 1,950 €/kW (Schmidt *et al.*, 2017) without a significant production scale increase. By 2030, cost reductions are expected to reach 320 to 400 €/kW for large-scale facilities (Reksten *et al.*, 2022). Operating costs usually amount to 1-3% of the initial electrolyzer investment (Glenk & Reichelstein, 2019).

R&D funding can significantly drive cost reductions, with potential savings of 8% to 24% for PEM technology by 2030 (Schmidt *et al.*, 2017). For a 630,000-kW energy requirement to convert CO_2 into polyolefins and an average electrolyzer cost of 350 €/kW (Khouya, 2021; Vartiainen *et al.*, 2021; De León *et al.*, 2023), the electrolyzer cost alone is **€220.5 million**, excluding hydrogen production and operational expenses, which depend on the needed hydrogen quantity for the conversion.

- **Step 2: Combining CO_2 and H_2 to obtain olefins: Reverse Water-Gas Shift Syngas – RWGS and Fischer-Tropsch synthesis – FTS**

The first step involves combining captured CO_2 from the cement plant with green H_2 from Verbund in a Reverse Water-Gas Shift (RWGS) reactor to produce carbon monoxide (CO) and water vapor (H_2O), preparing CO_2 for Fischer-Tropsch synthesis. High temperatures exceeding 900°C are ideal but challenging due to catalyst limitations (Shekari *et al.*, 2023). Solutions involve product separation and recycling or electrochemical CO_2 reduction, increasing operational costs (Tackett *et al.*, 2019; Shekari *et al.*, 2023). The RWGS process initially provides a suitable H_2:CO_2 ratio of 3:1 (Markowitsch *et al.*, 2022) but may exhibit variations. The generated syngas is introduced into a Fischer-Tropsch reactor, producing hydrocarbons. According to Markowitsch *et al.* (2022), the inlet gas stream maintains an H_2:CO ratio of approximately 2:1. Low-temperature Fischer-Tropsch uses Co- or Fe-based catalysts, while high-temperature Fischer-Tropsch favors Fe-based catalysts with catalyst consumption costs of €1.000 per ton at 3w% (Research and Markets, 2019; Kirchner *et al.*, 2020). The hydrocarbons are further processed in a steam cracker to obtain olefins.

Efforts are underway to develop catalysts for converting CO_2 into liquid fuels at lower temperatures, particularly for hydrocarbon production. Fe_2O_3@K_2CO_3, a novel catalyst, has shown promise, achieving a 44.2% CO_2 conversion rate and high olefin selectivity (Ramirez *et al*., 2019). Tandem catalysis, where multiple catalysts work together, holds the potential for cleaner energy sources (Bown *et al*., 2021).

The expenses for syngas and olefin production via RWGS and FTS processes range from €46.4 to €46.7 million in capital expenditures, with operating costs of €13 million/year, primarily driven by H_2 costs (Markowitsch *et al*., 2022; Rezaei & Dzuryk (2019).

- **Step 3: Polymerization to obtain recycled carbon plastics**

The olefins are polymerized to make polyolefins by chemically linking olefin molecules into long polymer chains under specific catalysts and conditions. These polyolefins are further transformed into plastic products.

Figure 24 presents the process for obtaining polymers from captured CO_2, the energy requirements, and the ratios associated with each intermediate process.

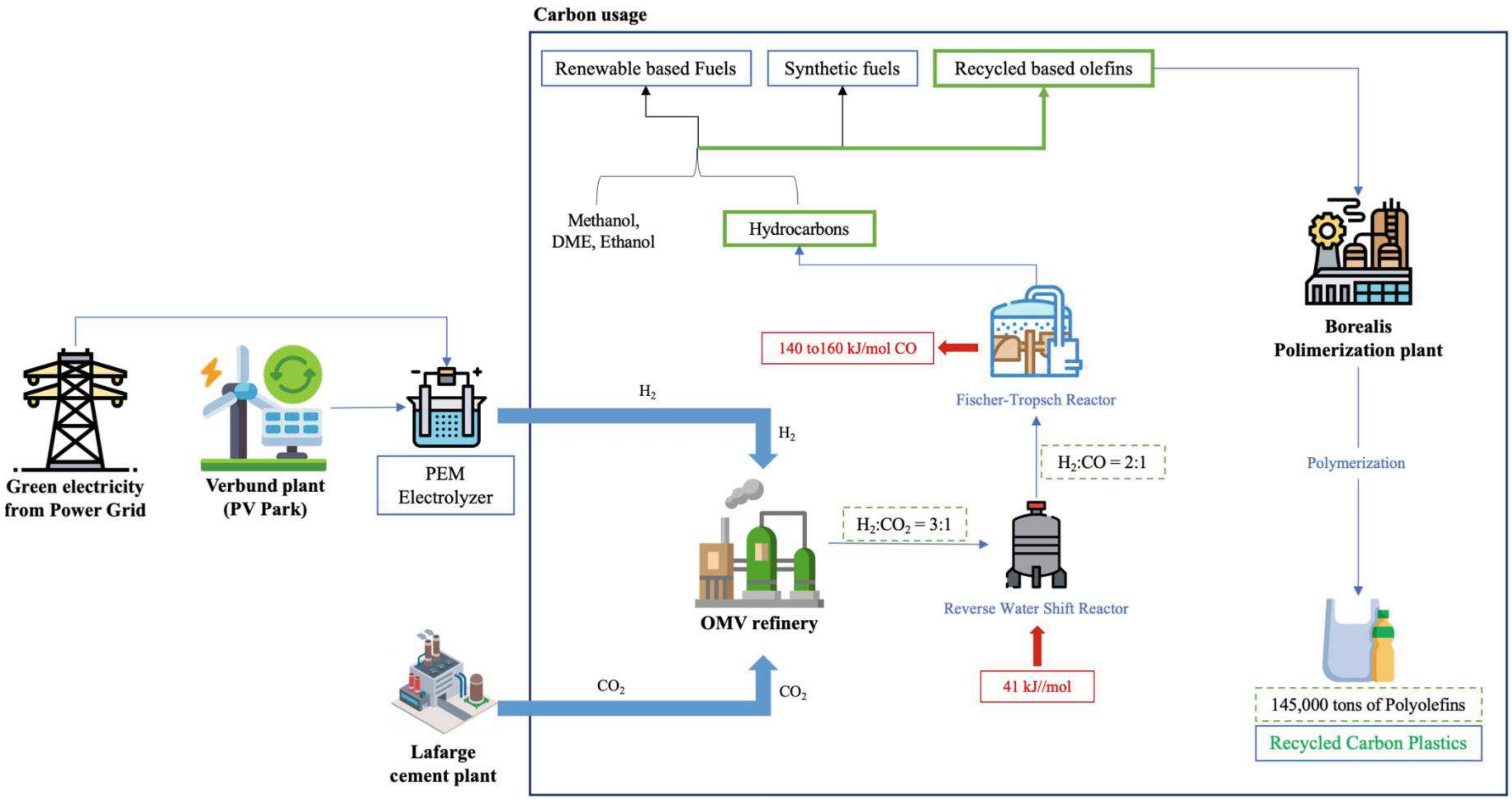


Figure 24. Graphical representation of the process of carbon usage for Case 2: C2PAT

5 DISCUSSION AND RECOMMENDATIONS

The Paris Climate Agreement (2015) and the Glasgow Climate Pact (2021) stress the importance of limiting global warming to 1.5°C or below, requiring a drastic reduction in annual CO_2-equivalent emissions to net-zero by mid-century, with a 40% reduction target by 2030[2] (ETC, 2022). Nevertheless, in 2020, $5.9 trillion supported the fossil fuel industry, while $4 trillion annually is needed for renewable energy investments until 2030 to achieve net-zero emissions by 2050 (Parry *et al.*, 2021).

While clean electrification, hydrogen, and sustainable bioresources help reduce emissions, full net-zero emissions require carbon capture integration, yet this needs thorough evaluation in terms of policies, economics, environmental impact, and feasibility (Desport & Selosse, 2022; ETC, 2022). Several factors currently hinder the widespread adoption of CCU technology in Austria's industrial sector. High upfront costs, lack of specific policies supporting CCU initiatives, and complex economic considerations are among the primary obstacles. To address these challenges and promote CCU adoption, Austria should consider implementing tailored policies that incentivize CCU projects, such as subsidies, tax incentives, and carbon pricing mechanisms. Additionally, fostering research and development efforts to advance CCU technology, improve efficiency, and reduce costs is crucial. Furthermore, creating partnerships between the government, academia, and industry can facilitate knowledge sharing and innovation in the CCU sector. By taking these actions, Austria can overcome the barriers to CCU adoption and accelerate its transition towards a more sustainable industrial landscape.

5.1 Qualitative Techno-economic Assessment

In Austria, CCU technology possesses significant technical and economic potential. The utilization of captured CO_2 in processes like mineral carbonation of steel slag and plastics production offers promising avenues for reducing carbon emissions and creating valuable products. As Austria moves towards a 100% renewable energy mix by 2030, the feasibility of CCU technologies is expected to increase significantly. The key motivators for utilizing captured CO_2 include reducing carbon emissions, enhancing resource efficiency, and aligning with global sustainability goals.

Innovative technologies, such as mineral carbonation of steel slag and CO_2-based plastics production, are in early stages with pilot-scale limitations (Sanna *et al.*, 2014; Lim & Kim, 2022), creating an innovation gap. Bridging this gap is crucial for broader CO_2 utilization

[2] CO_2 equivalence is influenced by the relative Global Warming Potential (GWP) and the selected time frame. For example, methane is roughly 30 times more potent than CO_2 over 100 years and about 80 times more potent over 20 years.

adoption, often focused on bridging the technological gap from fundamental research (TRL 3) to industrial demonstration (TRL 6-7; Centi *et al.*, 2020).

Using CO_2 and fossil fuel-based electricity in CCU isn't practical now but may be feasible as renewables dominate energy, like Austria's 100% renewables target in 2030. Large-scale CCUs need technological advancement and innovation closure to significantly combat climate change (SAPEA, 2018). This involves estimating cost reductions through tech and industrial development, emphasizing technology efficiency and scaling cost reductions.

Despite CCU challenges, its cost-effectiveness and feasibility are evolving, with viable pilot plants (Schiebahn *et al.*, 2015; Bailera *et al.*, 2017; Chwola *et al.*, 2020). However, there's a gap between industrial interest in CCU and CO_2 economics debates, ranging from skepticism to optimism. Environmental assessments, like Life Cycle Assessment (LCA), are conducted alongside economic discussions but yield diverse conclusions using the same data (Centi *et al.*, 2020).

CCU, with potential to cut emissions and boost resource sustainability, faces higher production costs due to investments and process efficiency concerns (Gulzar *et al.*, 2020). Capturing CO_2 at major sources, especially power plants, is vital to curb fossil fuel emissions. Various CO_2 capture technologies, from amines to carbonate looping, are advancing (Sanna *et al.*, 2014). Still, challenges like gas collection, purification, intermittent operation, and the risk of encouraging fossil fuel reliance remain. Integrating CO_2 capture and utilization into existing industries is complex due to stringent environmental regulations (Mikulčić *et al.*, 2019).

The implementation timeframes for CCU technologies in existing plants, as mentioned in this study, range from seven years for emerging environmental tech to 20+ years for mature ones. Given that CAPEX can make up to 70% of CCU production costs, CO_2 cost estimates can be deceptive without proper analysis (Centi *et al.*, 2020).

In CCU technologies, CO_2 capture and purification costs significantly, ranging from €44 million to over €200 million, excluding equipment inversion (over €40 million) and operational expenses, sometimes constituting half the total cost (SAPEA, 2018). This is partly due to the rising expenses of carbon capture infrastructure (Rubin *et al.*, 2015; Naims, 2016). Increasing CO_2 capture rates in power plants can inflate costs up to \$160/ton of CO_2, posing economic challenges for exceeding 95% capture rates, impacting carbon neutrality goals, decarbonization strategies, and CCU project funding (ETC, 2022). Industries like iron, steel, and cement can potentially employ CO_2 innovatively but struggle with economic hurdles.

However, the introduction of carbon taxes and growing carbon capture demand may lower CO_2 costs, potentially revitalizing struggling sectors (Rafiee *et al.*, 2018).

While CCU cost reduction may not match renewable energy's dramatic drops, there's a promise of gradual improvements of up to 30% by 2050, as suggested by the International Energy Agency (IEA, 2021b) and potential breakthrough innovations (ETC, 2022). Scaling processes, a proven practice for efficiency enhancement and cost reduction, is recommended for advancing CCU (Cuéllar-Franca *et al.*, 2015; De Luna *et al.*, 2019), with careful consideration for modeling scenarios, especially concerning hydrogen and electricity performance variations.

Evaluating the economic viability of the CO_2 utilization methods presented here is crucial for their industrial adoption and their impact on CO_2 emissions reduction. When assessing CCU technologies, it's essential to focus on how they replace fossil resources with CO_2 for providing services, beyond merely considering CO_2 storage quantities and durations. Large-scale CCU supports renewable energy utilization and assesses the impact of these CCU pathways (Centi *et al.*, 2020).

In **Case 2: C2PAT**, polymer development matches the progress of CO_2-to-fuels processes. However, interest in CO_2 for polymers leans toward using it as a low-cost carbon source rather than a climate change mitigation technology. In contrast, CO_2-to-fuel processes receive more economic scrutiny and are seen as more directly relevant to greenhouse gas reduction (Centi *et al.*, 2020). Also, in this case, hydrogen plays a dual role as a competitor and co-reactant, as in many CO_2 utilization processes. Therefore, achieving clean and cost-effective hydrogen production is vital for widespread CCU adoption. Access to renewable hydrogen significantly impacts the potential of CO_2-based products, making CO_2-to-chemical processes more feasible with abundant renewable hydrogen (Dutta *et al.*, 2017).

Using CO_2 as a reactant for RWGS, even at €70/ton of captured CO_2, can be cheaper than producing or buying H_2. Carbon tax exemptions can further alleviate CO_2 capture costs. Austria's €30/ton carbon tax partially covers carbon capture expenses, but more stringent policies are needed to fully offset costs by 2030. Hydrogen costs, however, remain higher, exerting a minor influence on overall expenses (Bown *et al.*, 2021).

Green hydrogen in RWGS processes reduces emissions, but efficient CO production and prevention of hydrogen-consuming side reactions are essential for RWGS catalysts. Research in catalysis and materials aims to develop cost-effective RWGS catalysts, lowering hydrogen production expenses. To achieve RWGS commercial viability, reducing green hydrogen costs is key, necessitating research into economical production methods. Decreased hydrogen prices enable CO generation but may not suffice for cost-effective syngas production, highlighting the need for efficient CO2 conversion processes with green hydrogen (SAPEA, 2018; Bown *et al*., 2021).

In chemical processes, CAPEX minimally affects production costs, usually comprising less than 40-50%. For example, analyzing CO_2-to-polymer CAPEX costs reveals over 50% linked to electrolyzers. While electrolyzer efficiency may not improve significantly, costs are tied to industrial scale and nominal power. Electrolyzers dominate hydrogen production due to nascent solar water-splitting technology. Alternative green hydrogen sources, like waste or biomethane through catalytic methane decomposition, are often overlooked but could complement regional green hydrogen production via pipelines (Centi *et al*., 2020).

In **Case 2: C2PAT**, electrolyzer costs depend on factors like scale and expected technological advancements from 2020 to 2050. Technological progress is challenging to estimate, but cost reductions can exceed predictions, akin to PV energy production costs. For instance, PEM electrolyzer costs vary widely, from <€350/kW to >€1,000/kW, significantly impacting overall CO_2 utilization product costs (Centi *et al*., 2020).

Enhancing catalysts, using microreactors, optimizing integration with electrolyzers, and efficient heat integration in **Case 2: C2PAT** can reduce costs by around 15–20% (IRENA, 2020). However, evaluating a reliable state-of-the-art technology as a baseline approach is advisable (Centi *et al*., 2020).

CCU system feasibility extends beyond CO_2 capture costs, considering input materials, energy, hydrogen production, and transportation. Profitability balances these costs with revenues from product and by-product sales. In **Case 1: Voestalpine**, steel slag in mineral carbonation justifies its use as carbonates sequester CO_2 and can be sold for >€70/ton, with by-product steel slag selling at €40/ton (Slag recycling, 2020; Alsarhan *et al*., 2021). In **Case 2: C2PAT**, propylene, and bioplastics market prices are competitive, with expected chemicals from CO_2 costing around USD 300/ton by 2050. CCU's attractiveness depends on carbon allowance prices, profitability offsetting costs, and carbon price fluctuations (Haerens, 2017; Alsarhan *et al*., 2021).

Benchmarking CCU against established power and petrochemical technologies can make CCU appear less competitive. But advanced CCU tech and economies of scale could level the field. Technology maturity and scale must be considered when evaluating CCU against other systems (SAPEA, 2018). Comparing CCU with fossil systems using differing cost benchmarks and ignoring fossil fuel phase-out is flawed. Shift focus to the service of full grid decarbonization provided by CCU, altering conclusions and prompting evaluation against similar services like energy storage, biofuels, BECCS, etc. (SAPEA, 2018).

Peres *et al*. (2022) and Abanades *et al*. (2017) highlight high CO_2 reduction costs in methanol production under various scenarios. Future electricity pricing models and dedicated renewable electricity generation can change economic dynamics (SAPEA, 2018). In both cases, carbon capture costs remain high, and products often don't align with market prices. Comparison with traditional methods and overlooking CCU's importance and benefits make these cases theoretical, and sometimes impractical. Consider economic viability, market demand, energy source, and net carbon emissions for such projects (Gulzar *et al*., 2020).

Evaluating technology economics is complex, with discrepancies between engineering firms and academic researchers due to access to cost databases. CAPEX estimates vary based on experience levels, critical for CO_2 utilization technologies. Emerging CCU technologies require new assessment tools, considering socio-economic trends, market dynamics, competitiveness, sustainability, life-cycle costs, benchmarking, and social impacts beyond traditional methods (Palo *et al*., 2019; Centi *et al*., 2020).

5.2 Qualitative Environmental Assessment

In Austria, several pathways show significant potential for the utilization of captured CO_2. One prominent avenue is the mineral carbonation of steel slag, which not only captures CO_2 but also transforms it into calcium carbonate, a valuable material used in construction. This process aligns with Austria's environmental objectives by reducing carbon emissions and producing low-carbon construction materials. Additionally, the production of plastics from CO_2 is another promising path, offering the opportunity to create sustainable materials while mitigating climate change. These pathways play a crucial role in fulfilling Austria's environmental goals, as they contribute to reducing carbon footprints and promoting sustainable resource utilization.

In **Case 1: Voestalpine**, mineral carbonation is a promising environmental technology that captures CO_2 and transforms it into $CaCO_3$ for construction materials. It stores over 40,000 tons of CO_2, reducing the carbon footprint of these materials by about 200 kg CO_2/kg compared to traditional methods (Mikhelkis & Govindarajan, 2020). Technologies like direct aqueous carbonation, carbonation mixing, and carbonation curing hold the potential for CO_2 emissions reduction, waste utilization, and carbon sequestration in construction materials. This promotes sustainable resource management and potentially carbon-neutral or carbon-negative building materials (Thonemann *et al*., 2022).

Despite its CO_2 sequestration potential, mineral carbonation's current costs hinder widespread adoption, delaying GHG reduction and environmental goals for 2030. In Austria, large-scale CO_2 storage remains cost-prohibitive in 2023 (Federal Ministry Republic of Austria, 2019). Thus, *ex-situ* mineral carbonation, despite costs, remains the better option for Austria, aligning with future emissions reduction goals.

For **Case 2: C2PAT**, CO_2 from a cement plant reacts with hydrogen to produce olefins, which are polymerized into recycled carbon plastics. Energy requirements vary across the process, sometimes releasing heat that can offset heating-related GHG emissions. CCU processes that create products can help mitigate climate change by capturing CO_2 in long-lasting materials. The effectiveness of CCU primarily depends on securely storing fossil CO_2 in products for an extended period, ideally indefinitely, while minimizing additional CO_2 emissions associated with CCU product manufacturing. However, tracking plastic products to prevent disposal issues is a challenge.

Nevertheless, evaluating CCU's impact could also focus on reducing fossil fuel usage rather than just stored CO_2 duration. A shorter cycle can replace more fossil fuels with renewables, aligning with the circular economy concept (Centi *et al*., 2020). In a circular carbon economy, carbon usage should follow a circular pattern, minimizing resource consumption and waste production. This differs from linear carbon storage, which may reduce GHG emissions but doesn't align with circularity. Assessing CO_2 utilization's potential by multiplying product volume by the CO_2 needed can lead to underestimation or overestimation (Hepburn *et al*., 2019).

Recycled carbon plastics offer a sustainable alternative to traditional plastics, reducing waste and resource strain. Power-to-chemical approaches can eventually yield carbon-neutral olefins, but more development and support are needed (Döhler *et al*., 2022; Reznichenko & Harlin, 2022).

Addressing energy demand and resource utilization in regions with limited resources or strict regulations is essential. Further research can enhance energy efficiency and process optimization for recycled carbon plastics (Reznichenko & Harlin, 2022). Considering energy usage and resource consumption alongside CO_2 capture is crucial. Producing plastics from olefins is energy-intensive, but creating polyols from captured CO_2 offers cost savings and reduces environmental impact (Fernández *et al*., 2017).

5.3 Recommendations

CCU faces some specific challenges in the initial scaling-up phase, which Austria must recognize and address. These include the need for coordination across multiple sectors and stakeholders; high capital investment requirements for CO_2 capture and related infrastructure; uncertainty surrounding long-term ownership; untested insurance and finance markets; and public opposition to storage (particularly onshore) in the country (IEA, 2020a).

5.3.1 Recommendations regarding policies

A single standardized policy approach for CCU is not universally applicable. The suitable selection or combination of strategies for each country is contingent upon local market dynamics and institutional variables. These factors encompass the existing state of CCU infrastructure development, emission reduction objectives, domestic energy resources, and the accessibility and cost-effectiveness of alternative methods for reducing emissions (IEA, 2020a).

Governments can have multiple reasons for supporting the development and commercialization of CO_2-derived products and services. While a significant focus has been on mitigating global CO_2 emissions, additional factors like fostering industrial creativity, leading in technology, and supporting circular economy principles also hold importance. The best policy setup remains on the main purpose and goal being targeted (IEA, 2019).

Various customized policies and encouragements can be employed to make investing in CO_2-based products and services more appealing. Regardless of the chosen policy, having a clear and robust system to measure, report, and verify emissions (MRV) is crucial. This is important to ensure that the promised emissions reductions are delivered. However, creating this framework is quite complex due to the diversity of products in different markets and the challenges in accurately assessing emissions reductions for all (IEA, 2019).

• Ensure that CCU technologies and initiatives qualify for public funding programs at different stages of their development, encompassing research and development (R&D), pilot projects, and the initial implementation of infrastructure.
• Ensure that Member States develop specific deployment plans and favorable policies for CCU on both a national level and as part of their National Energy and Climate Plans (NECPs). This is essential for fulfilling the European Union's climate objectives for 2050.

• Ensure that CCU technologies are acknowledged as economic endeavors that contribute to climate change mitigation within the framework of the sustainable finance action plan's taxonomy.
• Encourage the establishment of a market framework for products and services that have been decarbonized. This framework could include Guarantees of Origin or other forms of accreditation schemes, designed to stimulate innovative business models for CCU technologies.
• This framework should acknowledge that the private sector is unlikely to invest in CCU technology without mandatory requirements or the ability to generate profits through the sale of captured CO_2 or by earning credits for emissions reductions within carbon pricing systems.
• Support Member States in their activities to promote the early development of CCU infrastructure, which could involve various strategies such as introducing Contracts for Difference in the power sector, granting tax incentives to incentivize CO_2 usage, allocating funding for the assessment of potential of CO_2 utilization industries, feed-in tariff mechanisms with long-term contracts with low-carbon electricity producers, and mitigating initial value chain risks by offering guarantees for CO_2 supply and off-take.

Modifyed from: *IEA (2019)*

5.3.2 Recommendations regarding the transport of CO_2

A major challenge in integrating CCU into energy systems is the lack of well-defined emission assessment boundaries and policy incentives. Moreover, the absence of energy planning tools impedes effective CCU incorporation, including aligning carbon sources and sinks, planning pipeline routes, and integrating CCU strategies into the larger energy system (Mikulčić *et al.*, 2019).

• Facilitate the involvement of gas infrastructure or other firms, as determined by Member States, in the transportation of CO_2 as either a commercial or regulated operation. This oversight should be carried out by National Regulatory Authorities (NRAs) vested with relevant authority.
• Promote research efforts that assess the suitability of existing transport infrastructure for potential reuse.

Modifyed from: *IEA (2019)*

5.3.3 Recommendations regarding EU-ETS

Carbon pricing is a strategy used to regulate carbon emissions by assigning a monetary value to them. The gradual increase in carbon prices over time reflects the effectiveness of climate policies and commitment to emission reduction plans, demonstrating policymakers' dedication to long-term goals and the reliability of mechanisms like the EU-ETS. Past underestimations of this credibility may explain low carbon prices in the 2010s, as market participants might not have considered targets as reliable indicators of future emission allowance scarcity (Pahle *et al.*, 2022).

Nonetheless, this strategy is currently ineffective in supporting the adoption of newer technologies like CO_2 utilization. Although investing in CCU is vital for promoting a circular economy and partially closing the carbon cycle, the current EU-ETS framework lacks incentives; instead, companies adopting CCU still bear costs for emissions converted into products, leading to higher expenses. Therefore, EU-ETS should be adapted to integrate CCU, encouraging investment. It's anticipated that as the costs of CO_2 conversion decrease over time and carbon prices rise, there might be situations where utilizing CO_2 becomes a financially viable approach (Haerens, 2017; IEA, 2019).

Indirect benefits of CCU, such as increased efficiency or material substitution, can prevent CO_2 emissions, underscoring the importance of including CCU in emissions trading (Naims *et al.*, 2015). Currently, CCU has not been integrated, resulting in companies still having to surrender EUAs even if they transform CO2 into a product, making the EU-ETS primarily effective for CCS, not CCU (Haerens, 2017).

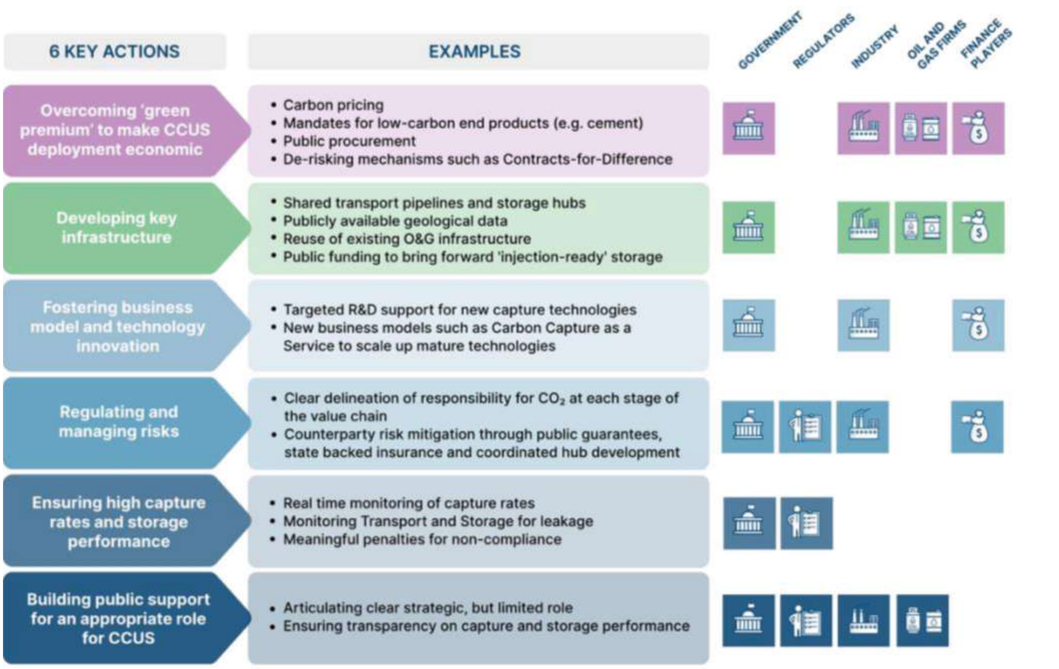
Companies emitting CO_2 may sell the gas to others if the selling price covers capture costs and higher prices could be negotiated if emitters meet quotas through cheaper methods like storage. Recognizing emissions reductions from CO_2 utilization in carbon pricing may result in lower prices and the transfer of emission responsibility. To ensure fairness, the MRV framework must consider factors such as permanent carbon storage, alternative products, and carbon intensity, potentially requiring adjustments for CO_2 utilization due to sector gaps in current pricing systems (IEA, 2019).

• Allow the economic incentives within the EU - ETS to acknowledge and incentivize CCU, contingent upon a comprehensive lifecycle assessment and transparent carbon accounting guidelines.
• Ensure that the transportation of CO_2 via various means, including ships and pipelines, is acknowledged and incentivized within the ETS.

Modifyed from: *IEA (2019)*

It exists varying perspectives regarding the appropriate role of CCU in achieving decarbonization goals. On one hand, certain groups argue that high-emission industries are using the prospect of future carbon capture technologies as a way to justify their continued dependence on fossil fuels in the present, possibly indefinitely. Conversely, industry representatives contend that this crucial and viable technology is unfairly stigmatized due to its association with the fossil fuel sector (IEA, 2020a; ETC, 2022).

Decarbonizing various sectors depends on factors like the readiness of carbon capture technology, economic feasibility of alternatives, and country-specific policies. These factors are uncertain due to evolving technology and costs. Sectoral decarbonization pathways are even more uncertain than 2050 CCU estimates. Publicly available plans and tech assessments support suggested sectoral growth. Global CCU deployment needs to rise from 0.04 Gt/year to about 0.8 Gt/year by 2030 and 4 Gt/year by 2040 (ETC, 2022). Governments, industry, and finance sectors can drive CCU by taking six key actions:



Source: *ETC (2022)*

6 CONCLUSIONS

Challenges for both cases arise from the energy-intensive nature of the process. The energy sources for electricity and heat significantly influence the process's environmental footprint. Additionally, the emissions generated during electricity production and using electricity for CO_2 capture impact the net emissions reduction potential (von der Assen *et al*., 2016). Nevertheless, this studio contemplates a 2030 scenario where Austria will reach 100% renewable sources meaning that all energy and heat required for the initial steps of the process is renewable and clean.

In **Case 1: Voestalpine**, the captured CO_2 will find a longer-lasting application in products like cement, bricks, roads, or construction materials. Conversely, in **Case 2: C2PAT**, ensuring long-term CO_2 capture through recycled carbon plastics needs strict tracking to prevent the product from leaving the recycling loop and ending up in an incinerator liberating the CO_2 again in the atmosphere. However, monitoring the entire lifecycle of plastic products is a challenging task, and this challenge underscores the current issues we face with plastic contamination and the complexities of achieving effective plastic recycling.

Nevertheless, a comprehensive assessment of future possibilities needs moving beyond the often overly narrow approaches currently employed, such as regarding CO_2 utilization merely as a storage choice. Instead, it demands a more expansive perspective regarding the broader system transformation associated with the shift in energy and chemistry paradigms (Centi *et al*., 2020).

The process of making polypropylene from power sources is environmentally beneficial. This method absorbs more CO_2 from the air than it releases during production, effectively reducing its impact on global warming. While it doesn't use much more water than traditional polypropylene production, it might require more land, especially if renewable power is used. This shows that producing polypropylene this way could change it from adding to carbon emissions to actually reducing them, which could significantly help fight climate change. If polypropylene is used in long-lasting materials used in buildings and infrastructure and isn't burned, it could be used for long-term carbon storage, further aiding the environment (Kuusela *et al*., 2021).

The positive development is a growing interest in CCU. This trend encourages advanced research into using captured CO_2 in sustainable industries, which, needless to say, is both sustainable and environmentally friendly in more ways than one. Of course, proper governance and regulations are crucial to enable the implementation of these innovative technologies (Fernández *et al.*, 2017).

The effectiveness of CCU in mitigating GHG emissions relies on a set of vital framework conditions. Integrating CCU into a comprehensive carbon management strategy centered on emissions reduction and sustainability is paramount. Key conditions for realizing substantial GHG emissions reductions through CCU include:

Energy Source: The choice of energy for CCU processes is critical. Optimal emissions savings are achieved when CCU operations are powered by renewable and low-carbon energy sources like wind, solar, and hydropower. A transition to green energy minimizes the carbon footprint associated with CCU.

Carbon Source: The effectiveness of CCU is heightened when it captures CO_2 emissions from high-volume industrial sources such as power plants and cement factories. These sources offer significant potential for emissions reductions.

Circular Economy Approach: Implementing a circular economy model is pivotal. It needs efficient use and recycling of products generated by CCU, be it plastics, construction materials, or chemicals. This approach curtails emissions linked to the production of equivalent items from fossil resources.

Carbon Pricing: Carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, serve as incentives for industries to embrace CCU technologies by elevating the cost of carbon emissions. When the price of carbon emissions is sufficiently high, CCU becomes economically competitive, further fostering emissions reductions.

Regulatory Support: Supportive and transparent regulations create an enabling environment for CCU. Governments can stimulate CCU adoption by offering financial incentives, subsidies, and favorable policies that advance research, development, and commercialization of CCU technologies.

Technological Advancements: Continuous progress in CCU technologies is vital for enhanced efficiency and cost reduction. Investment in research and development to refine CCU processes and scale them up is indispensable for realizing emissions savings.

Lifecycle Assessment: Thorough life cycle assessments (LCAs) should be conducted to evaluate the overall emissions reduction potential of CCU processes. These assessments scrutinize the carbon footprint from CO_2 capture to utilization, ensuring a significant net reduction in emissions.

Market Demand: The demand for CCU-derived products in the market is pivotal. The economic viability of CCU is contingent on the demand for sustainable materials and chemicals. A robust market demand attracts investments and incentivizes industries to adopt CCU as a GHG emissions reduction strategy.

In summary, CCU effectively reduces GHG emissions when it aligns with key factors: renewable energy use, capturing CO_2 from high-emission industries, adhering to circular economy principles, benefiting from carbon pricing and supportive regulations, advancing technology, conducting comprehensive lifecycle assessments, and meeting market demand for sustainability. In this context, CCU becomes a powerful tool in mitigating climate change, cutting emissions, and fostering resource efficiency.

ABBREVIATIONS

AP	Acidification Potential
BAT	Best Available Techniques
BECCS	Bioenergy Carbon Capture and Sequestration
BECCU	Bioenergy Carbon Capture and Utilization
CC	Carbon Capture
CCS	Carbon Capture Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Use and Storage
CEAP	Circular Economy Action Plan
CKD	Cement Kiln Dust
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
CPS	Concentrated Point Sources
CPSC	Concentrated Point Source Capture
CS	Crude Steel
DAC	Direct Air Capture
DACCS	Direct Air Capture Carbon Storage
DMC	Dimethylcarbonate
DME	Dimethyl ether
EC	European Commission
ECBM	Enhanced coal-bed methane
EGD	European Green Deal
EOR	Enhanced oil recovery
ESR	Effort Sharing Regulation
ETS	Emission Trading System
ETSA	Exponential Triple Smoothing Algorithm
EU	European Union
FLH	Full Load Hours
FQD	Fuel Quality Directive
FTS	Fischer-Tropsch Synthesis
GCCSI	Global CCS Institute
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GoO	Guarantees of Origin
Gt	Gigatons
GWP	Global Warming Potential

HDPE	High Density Polyethylene
IEA	International Energy Agency
IED	Industrial Emissions Directive
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Projects of Common European Interest
IPPU	Industrial Processes and other Product Use
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LPG	Liquefied Petroleum Gas
MEA	Monoethanolamine
MJ	Megajoule
MPa	Mega Pascal
Mt	Million tons
MTPA	Metric Tons Per Annum
Mty	Million tons per year
NECPs	National Energy and Climate Plans
NGCC	Natural Gas-fired Combined Cycles
PC	Pulverized Coal-fired simple cycles
PCC	Precipitated Calcium Carbonate
PEM	Proton Exchange Membrane
POPs	Persistent Organic Pollutants
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
RED	Renewable Energy Directive
RFNBOs	Renewable Fuels of Non-Biological Origin
RWGS	Reverse Water-Gas Shift
SDGs	Sustainable Development Goals
Sm^3/h	Standard cubic meters per hour
SMR	Steam Methane Reforming
SVC	Strategic Value Chains
TEA	Techno-economic Assessment
TRL	Technology Readiness Level
TWh	Tera Watts hour
UNFCCC	United Nations Framework Convention on Climate Change
VAS	Voestalpine Stahl
WFD	Waste Framework Directive

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