International Journal of Sustainable Energy Planning and Management

A Methodology for the Determination of Future Carbon Management Strategies: A case study of Austria

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ABSTRACT

The achievement of global climate targets outlined in the Paris Agreement represents a critical challenge in the coming decades. Certain industry sectors cannot completely avoid all emissions from their processes. In this context, the term unavoidable or Hard-to-abate emissions is used. Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) are recognized as essential components for addressing those emissions to achieve Net Zero Emissions. To identify effective Carbon Management Strategies, balancing future CO_2 sources and possible sinks for achieving long-term climate targets is essential. Especially in Austria hardly any comprehensive studies have been carried out.

This work presents a comprehensive analysis of Austria's CO_2 point sources as well as their projected development until 2050 based on technology-based scenarios. Geological CO_2 storage in Austria is primarily feasible in former hydrocarbon reservoirs and saline aquifers. Future demands for CO_2 as CCU feedstock will arise in the chemical industry.

By 2050, industry will emit approximately 4 Million tons (Mt) of unavoidable CO_2 annually. These emissions must be stored in the long term and correspond to the minimum demand for CCS. Fugitive emissions from agriculture, for example, cannot be captured. Thus, they are not subject of CCU/S measures. Negative emissions are therefore necessary to achieve the climate targets. These negative emissions and the possible use of CO_2 as feedstock are covered by biogenic CO_2.

Keywords

Carbon Capture and Storage (CCS);
Carbon Capture and Utilization (CCU);
Net Zero Emissions;
Bioenergy Carbon Capture and Storage (BECCS);
Bioenergy Carbon Capture and Utilization (BECCU)

http://doi.org/10.54337/ijsepm.8280

1. Introduction

As a result of the Paris Agreement in 2015, the majority of all countries worldwide have committed to limiting global warming to well below 2 °C striving for 1.5 °C compared to pre-industrial levels [1]. The European Union (EU) wants to achieve these targets through the so called European Climate Law, which sets the goal of climate neutrality by 2050 and makes an commitment to negative emissions afterwards [2]. According to the actual Austrian governmental program, climate neutrality is to be achieved as early as 2040 [3].

In 2019 Austria's total greenhouse gas (GHG) emissions accounted for 79.8 Million tons per year (Mt/a) CO_2 equivalent, whereof nearly 70 Mt were CO_2 emissions. Manufacturing industry represents the dominant sector of Austria's GHG emissions with around 34% of total GHG emissions, followed by transport,

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buildings and agriculture and sector energy [4]. Certain industry sectors cannot completely avoid all emissions from their processes. These residual emissions are known as unavoidable or Hard-to-abate emissions. Fugitive emissions that cannot be captured efficiently must be offset through negative emissions. The integration of Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) together with other decarbonization strategies such as fuel switching, enhancing energy efficiency and adopting renewable energy sources, is vital for achieving Net Zero Emissions [5].

In 2020, the global Carbon Capture (CC) capacity was around 50 Mt/a of CO_2. The current project pipeline anticipates a significant increase, projecting a global CC capacity of around 220 Mt/a by 2030. Compared to the target values of 800 Mt/a by the IEA, this is a large gap. Both the IEA and the IPCC emphasize the need for substantial increase, with the IEA assuming the need for CCS of over 2 Giga tons per year (Gt/a) until 2060 to align with the Paris Agreement. The IPCC forecasts that 1,200 Gt of CO_2 will have to be stored by 2100 [6].

In Europe and especially in Austria the support framework for CCU and especially CCS is limited so far and requires significant enhancements to unlock the potential of CCU and CCS for long-term climate goals and develop future Carbon Management Strategies. To achieve this, it is important to evaluate the specific capacities and contributions of these technologies, especially in the case of Austria, where there has been limited in-depth studies in this field because the storage of CO_2 is prohibited up to now. The 2019 evaluation report of the prohibition of geological storage of CO_2 in Austria stated, that further research is needed for permanent geological storage of CO_2. The long-term strategy 2050 of the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology states as well, that a contribution of CCS to climate protection should be met with openness, as it permanently removes CO_2 from the atmosphere [7].

2. State of the Research

There are several studies on the identification of Carbon Capture-relevant CO_2 point sources, the role of CCU and CCS technologies for Carbon Management and the matching of CO_2 sources and sinks.

2.1 CO_2 point sources

CO_2 point sources are defined as stationary sites that emit CO_2 during combustion or as a by-product of production processes [8]. So called energy-related emissions from combustion originate from burning carbonaceous fuels such as coal, natural gas or oil. Process-related emissions are typically a result of chemical reactions required for manufacturing specific products, for example the reduction of iron ore or in the chemical industry [9]. Mineral-bound CO_2 emitted during production processes, as in e.g. cement production, is known as geogenic CO_2. Carbon Capture-relevant point sources in the energy sector comprise power plants, refineries, and gas processing plants. Industrial point sources are cement plants, iron and steel plants and industrial sites where carbon based fuels are used as a feedstock [10].

Flue gas compositions vary as well as the CO_2 concentration [8,9]. Particularly CO_2 concentrations play a significant role because higher purities lead to lower separation efforts and thus lower separation costs [9,10]. The CO_2's origin significantly influences future Carbon Management (CM) Strategies. The CO_2 origin can be distinguished in fossil, biogenic and atmospheric CO_2, as well as CO_2 from waste incineration (mixture of fossil and biogenic carbon) [11].

Billig et al. [12] defined CO_2 point sources with high potential for future CCU activities as sources that have high CO_2 concentrations and are projected to be available until 2050. They analyzed CO_2 point sources in Germany with CO_2 quantities over 100 kt/a. Hansson et al. [13] collected CO_2 point sources with CO_2 quantities over 100 kt/a from industrial process plants, energy generation and biofuels production facilities to determine the potential for CCU in Sweden.

Naims [14] estimated the global supply of CO_2 from point sources to assess the economics of CCU. The cost of CC strongly relies on the quality of the source (CO_2 concentration as well as composition of the exhaust gas). The size of the plant can reduce costs through economies of scale. Therefore, despite the technical feasibility, not all CO_2 sources are economically viable options for CC. If the emitted CO_2 is very pure (e.g. ammonia production), CC requires little additional efforts. For power plants, CO_2 concentrations are generally lower, but economies of scale can contribute significantly to reducing costs of CC. For industrial emitters economies of scale are harder to achieve, because they are often smaller than power plants. According to Naims [14] in total approximately 12.7 Gt of the point sources are capturable, whereof 0.3 Gt are high purity point sources.

Potential CO_2 sources with CO_2 quantities over 1 kt/a in Austria for an utilization within power-to-gas applications has been analyzed by Reiter et al. [15]. According to their results, biofuel production, which accounted for approximately 113 kilotons in 2013, is regarded as the most suitable Austrian source for power-to-gas applications.

2.2 CO_2 sinks

The injection of CO_2 in deep geological formations allows for long-term underground storage. Depleted hydrocarbon reservoirs, saline aquifers, unmineable coal formations and mafic/ultramafic rocks are viable options for geological CO_2 storage [10]. In most areas worldwide geological storage capacities remain unexplored. Currently Asia and North America are the countries with the largest geological storage capacities identified. European CO_2 storage capacities are estimated to 300 Giga tons (Gt). Calculated capacities in the North Sea reach 200 Gt. Overall, the calculated global storage capacity is between 6,800 and 30,000 Gt CO_2 [6].

Considering the Technology Readiness Level (TRL) of the described storage options as well as Austrian geology, depleted hydrocarbon fields are the most likely storage options to be developed in the near future in Austria [16]. In sedimentary basins, saline aquifers usually represent a higher storage potential than hydrocarbon fields, but are generally less well known, as is the case in Austria. CO_2 storage in saline aquifers is associated with greater effort (exploration and characterization) and therefore requires longer development times [17]. Scharf et al. [16] estimated the maximum CO_2 storage capacity in Austrian hydrocarbon fields based on the total hydrocarbon production. According to this study the analyzed hydrocarbon fields have a theoretical capacity for CO_2 storage of 465 Mt. Welkenhuysen et al. [18] used a techno-economic framework through geological, technological and economic simulations to assess practical CO_2 storage capacities in Austrian hydrocarbon reservoirs. The total practical capacities found in this paper account to 118 Mt CO_2.

The use of CO_2 as a feedstock for carbon containing products is a complementary technology to the storage in geological formations and is an option for storage of energy in chemicals, sustainable industrial processes (green chemistry) as well as a potential pathway for the implementation of circularity in industrial systems [11]. CO_2 has currently several industrial uses including the production of chemicals, for example urea, or the direct use of CO_2, in e.g. refrigeration systems, as inert agents or for beverages. Methane or methanol for the production of chemicals and polymers represent possible new process routes [6,10,19,20]. After a specific period, called product lifetime, the CO_2 is released into the atmosphere. Typically CO_2 is considered stored in the product, if its lifetime is lasting for centuries or longer or aligns with geological timescales [21]. An reduction of net CO_2 emissions with the use of CO_2 as a feedstock for products is solely possible, if the compounds produced have a long lifetime before the used CO_2 is re-emitted in the atmosphere [10,17].

Future projections for the demand for industrial CO_2 vary. According to Mikkelsen et al. [20] the large-scale potential for chemical materials is around 200 Mt CO_2 per year, approximately 120 Mt CO_2 per year are currently used, whereof urea accounts for more than half. Aresta et al. [22] projects potentials of 212 Mt/a. The global yearly market as well as the lifetime of current industrial applications of CO_2 is shown in Table 1.

Table 1: Current industrial applications of CO_2, their global yearly market, future expectations in the use and product lifetimes.

Product	Industrial volume [Mt/a] [10]	Industrial volume [Mt/a] [20]	Future expectations in the use of CO_2 [Mt/a] [20]	Lifetime [10]
Urea	90	100	10^2	Months
Methanol	24	40	10^3	Months
Inorganic carbonates	8	80	–	Decades to centuries
Organic carbonates	2.6	2.6	10^2	Decades to centuries
Salicylic acid	–	0.06	10^{-1}	–
Polyurethanes	10	–	–	Decades to centuries
Technological	10	10	–	Days to years
Food	8	8	–	Months to years

In general, fuels and chemicals have relatively short lifetimes from months to decades. Future industrial applications of CO_2 in the chemical industry, such as polymers, or synthetic fuels do not have sufficient binding periods to be considered as CO_2 storage but will be crucial for sustainability in chemical and petrochemical industry [17,21].

2.3 Carbon Management - Zero or Negative Emission routes

Carbon Management covers a range of technologies and strategies for reducing and avoiding CO_2 emissions. It includes activities for the capture, transport, use and storage of CO_2 as well as their integration. This involves various methods such as CCU and CCS technologies for point source emissions and Carbon Dioxide Removal (CDR) approaches such as Bioenergy Carbon Capture and Storage (BECCS) removing CO_2 from the atmosphere [23,24].

Based on possible CO_2 sinks the IPCC [25] distinguishes three process chains: Carbon Capture and Utilization (CCU), Carbon Capture, Utilization and Storage (CCUS) and Carbon Capture and Storage (CCS). As already mentioned in 2.2, the industrial use of CO_2 traps the CO_2 in the product for different time periods depending on the used technology. Fuels and chemicals like urea release the bound carbon after a short period, these process chains are generally referred to as CCU. Other products can last hundreds of years, whereas the geological storage of CO_2 (CCS) may bind CO_2 over geological time scales [10,11]. Process chains from products that store CO_2 are usually referred to as CCUS [25].

Beyond that Carbon Management Strategies can be differentiated according to their potential to mitigate climate change [17]. Based on the CO_2 origin CCU, CCUS and CCS activities enable delaying emissions, reducing emissions (Net Zero Emissions) or balancing emissions (Negative Emissions) [17,24].

CCU can delay climate relevant (fossil or geogenic) CO_2 emissions by replacing existing products with less GHG emissions-intensive alternatives. Net Zero Emissions through the industrial use of CO_2 for products with short lifetimes are solely possible if climate neutral (atmospheric or biogenic) CO_2 is utilized. The utilization of atmospheric CO_2 for products with short lifetimes is called Direct Air Carbon Capture and Utilization (DACCU). Process chains that use biogenic CO_2 are referred to as Bioenergy Carbon Capture and Utilization (BECCU). If climate relevant CO_2 is stored in products over climate relevant periods of time (CCUS), Zero Emission routes are possible. Negative Emissions can be achieved by storing climate neutral emissions in products. These process chains are called Bioenergy Carbon Capture, Utilization and Storage (BECCUS) or Direct Air Carbon Capture, Utilization and Storage (DACCUS). The geological storage of climate relevant CO_2 (CCS) allows Net Zero Emissions. Negative Emissions can be achieved by the geological storage of climate neutral emissions. These Negative Emission routes are called Bioenergy Carbon Capture and Storage (BECCS) or Direct Air Carbon Capture and Storage (DACCS) [17,24,26,27].

The EU and its member states are actively pursuing the implementation of effective Carbon Management Strategies. Austria has similarly committed to unveiling a suitable Carbon Management Strategy by mid-2024, with the decision made in September 2023 [28]. The focus lies on emissions that are difficult to avoid or unavoidable (Hard-to-abate emissions). The primary goal continues to be the decarbonization of the economy by a gradual reduction in the use of fossil fuels. The aim is not to reduce efforts for alternative avoidance options or the extension of fossil business models by using CCU/S [29].

2.4 CO_2 source-to-sink matching

Large-scale applications of CCU/S can be achieved by connecting source clusters with sink clusters via so called trunk lines (backbone). Satellite pipelines enable the connection of individual sources and sinks within a cluster to the main pipeline. This allows CO_2 demands and supply to be coordinated flexibly, like the existing European pipeline network for natural gas. Early CO_2 transport projects are based on point-to-point connections where a single emitter is located at a decent distance from the CO_2 sink (e.g. Alberta Carbon Trunk Line). More recently, hubs and clusters are being developed to bundle CO_2 streams, e.g. around the North Sea (Norway, the Netherlands and the UK) and in Iceland (Equinor, Porthos Project, Carbfix) [30,31].

Through clustering sources and sinks uncertainties associated with the development of capture as well as storage capacities is minimized [32]. Neele et al. [32] analyzed future large-scale CCS networks for Europe based on clusters on a national scale. Optimizing CO_2 source-to-sink matching aims to find the least-cost matching of sources, sinks and operational expenses [33]. Morbee et al. [34] evaluated a least-cost CO_2 transport network for CCS at European scale. Becattini et al. [30] previously developed optimal CO_2 supply chains and their rollout for Switzerland. In this study, CCS of waste incineration plants are considered. For the development of a Bavarian CO_2 transport network the production of cement and lime as well as biomass and waste incineration plants are analyzed [35].

3. Research Need

As shown in Chapter 2, there are several approaches to identify CO_2 sources and sinks. Future demands for CCU as well as CCS resulting from the evolution of the energy system based on technological transformations to reach targeted decarbonization efforts, projected remaining Hard-to-abate emissions and the CO_2 origin (fossil, geogenic, biogenic) has yet not been considered in any studies (cf. 2.3). This paper addresses the following questions based on a Case study on Austria's future Carbon Management Strategies:

- What are possible CO_2 point sources in Austria and how will they develop until 2050?
- What are possible CO_2 sinks in Austria and how will they develop until 2050?
- What Carbon Management Strategies (Zero or Negative Emission routes) can be outlined?
- How to establish a generally valid methodology to determine:
  - Future CCU demands
  - Future (minimal) CCS demands
  - Required additional CO_2 sinks
  - CO_2 source and sink clusters

4. Methodology

The presented methodology in this paper entails a comprehensive assessment of future Carbon Management Strategies based on the following approach (Figure 1).

The assessment includes an analysis of both current and scenario-based future quantity and origin (fossil, geogenic, biogenic) of CO_2 emissions from the evaluated CO_2 point sources. In the second step current and scenario-based future industrial CO_2 demands as well as their CO_2 binding periods and demands for the geological storage of CO_2 are determined. This allows deriving potential Carbon Management Strategies (Zero and Negative Emissions routes).

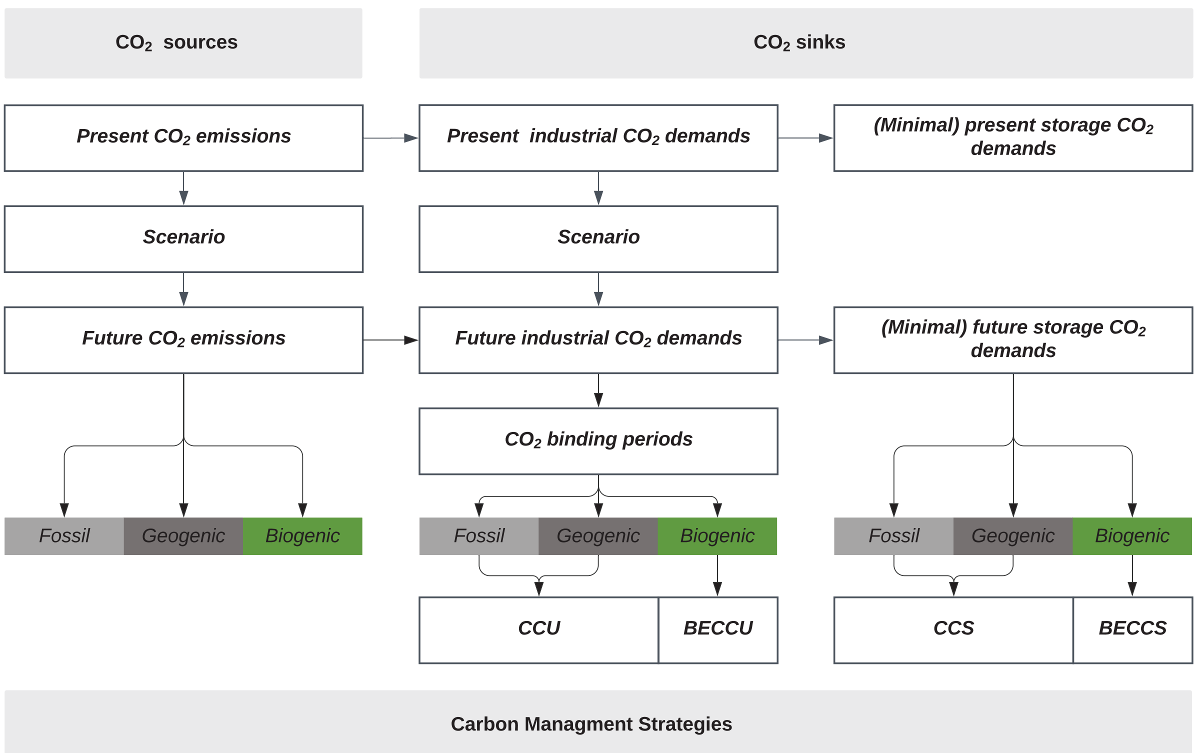

Figure 1: Scheme of the applied methodology to determine future carbon management strategies.

4.1 Quantity and origin (fossil, geogenic, biogenic) of CO_2 sources

To assess the progress in achieving emission reduction goals, Austria reports the trend of GHG emissions on a yearly basis. The latest report [36] was published in 2023 and contains emission data up to 2021. A decline in total emissions from 2019 (80 Mt CO_{2eq}) to 2020 (74 Mt CO_{2eq}) can be observed by comparing total emissions in recent years. In 2021 emissions increase per 4.9% relative to 2020 but still don't meet the level of recent years. The decline of emissions result from a significant slowdown in economic activities in the years 2020 and 2021 due to the spread of COVID-19 [37]. Because of this deviation emission data from 2019 is used as base data.

The EU Emission Trading System (ETS) covers one third of all greenhouse gas emissions in Austria, which accounted for 29.6 Mt CO_{2eq} in 2019. Therefore all emissions from stationary sites subject to the EU ETS are collected to identify relevant CO_2 point sources [4,38]. Emissions from major biomass- and waste incineration plants are equally considered as essential CO_2 point sources. Since biogenic emissions and emissions from the combustion of waste (mixture of fossil and biogenic carbon) aren't covered by the EU ETS, these are taken from Pollutant Release and Transfer Register (PRTR) or calculated using their thermal capacity and corresponding emission factors [39,40]. The capacity threshold for biomass and waste incineration plants is defined in alignment to the EU ETS with 20 MW_{th} of fuel thermal input. The definition of a lower threshold in form of CO_2 quantities is omitted, as efficient and economical CO_2 capture relies not only on CO_2 quantities but also on the CO_2 concentration, the composition as well as the continuity of the exhaust gas stream (cf. 2.1).

Emissions caused by the combustion of carbon-based energy carriers are referred to as energy-related emissions, while process-related emissions originate from industrial transformation processes, such as blast furnaces (BF). Mineral-bound also known as geogenic CO_2 is emitted by the introduction of carbonaceous minerals into the production processes (e.g. $CaCO_3$ for cement production) [41]. Based on the carbon origin, total CO_2 emissions can be characterized in geogenic, fossil and biogenic emissions. This context is illustrated in Figure 2.

The share and origin of energy-related emissions is calculated using specific emission factors. These factors are reported in Austria's National Inventory Report [4]. Table 2 shows specific energy-related emissions of various final energy carriers and their carbon origin.

For the production of Iron and Steel via Blast Furnace-Basic Oxygen Furnace (BF-BOF) route and Crude Oil Refining dedicated energy-related emission factors are reported (Table 3) [4].

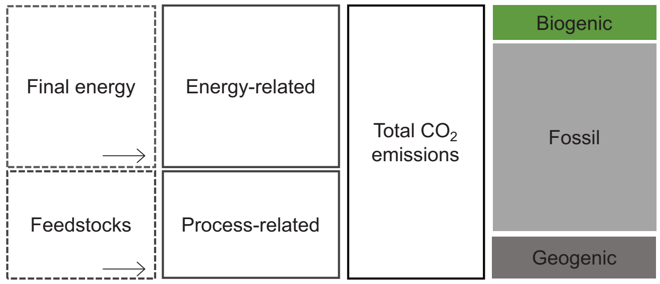

Figure 2: Origin of industrial CO_2 emissions.

Table 2: Specific energy-related emissions in kg CO_2 per TJ.

Carbon origin	**Final energy carrier**	**Energy-related CO_2**	**Reference**
Fossil carbon	Hard coal	95,000	[4]
	Coke	104,000	[4]
	Natural Gas	55,600	[4]
	Fuel Oil	78,000	[4]
Biogenic carbon	Fuel Wood, Wood Waste, Sewage Sludge	112,000	[4]
	Biogas, Sewage Sludge Gas, Landfill Gas	54,600	[4]
Mixture of fossil and biogenic carbon	Municipal Solid Waste	43,450	[4]
	Industrial Waste	75,000	[4]

Table 3: Specific energy-related emissions for Petroleum Refining, Iron and Steel and Cement Production in kg CO_2 per TJ.

Economic sector	**Product**	**Comment**	**Energy-related CO_2**	**Reference**
Energy Supply	Refinery products	Natural Gas, Refinery Gas	2,683	[4]
		Residual Fuel Oil, Gas Oil, Diesel, Petroleum, Jet Gasoline, LPG	3,047	[4]
		Petrol Coke	3,430	[4]
Iron & Steel	Steel	BF-BOF	217	[4]
Non-Metallic Minerals	Cement	Per ton Cement	208	[41]

Production rates as well as specific process-related emissions of each sector are reported in Austria's National Inventory Report [4]. The specific process-related emissions in kg CO_2 per ton product can be found in Table 4.

Energy-related emissions can be avoided by the substitution of fossil fuels. While some process-related emissions can be avoided by the transformation of production processes, process-related geogenic emissions and the share of fossil emissions from the combustion of waste are not completely avoidable and are referred to as Hard-to-abate emissions.

Emissions from agriculture, buildings and transport, waste management as well as fluorinated gases are fugitive and not suitable for Carbon Capture with state-of-the-art technology. These emissions are reported annually by the Environment Agency Austria [4].

The significance of CO_2 concentrations for the capture efficiencies has been discussed in chapter 2.1. In Table 5 typical CO_2 concentrations of the analyzed CO_2 point sources are shown.

CO_2 point sources with high purity require little additional efforts for CC. For the purpose of this work, high purity CO_2 sources are defined as sources with CO_2 concentrations above 50 vol.%. CO_2 sources from ammonia, nitric acid, urea, and fertilizer production as well as bioethanol production and natural gas processing are therefore considered high purity CO_2 point sources.

4.2 Scenario-based future development of the evaluated CO_2 point sources

To project the development of the CO_2 point sources until 2050, technology-based scenarios are used. The innovation network New Energy for Industry (NEFI) developed various scenarios for Austria's pathway to industrial decarbonization. Main decarbonization strategies are the electrification of stationary engines and heat pumps, the use of CO_2-neutral gases like Hydrogen (H_2), biomethane or synthetic methane (CH_4) and the combustion of solid biomass [41,55]. The Environment Agency Austria develops and frequently publishes scenarios to determine future GHG emissions according to the National Energy and Climate Plan (NECP) [56].

To obtain a broader outlook of the future CCU and CCS demands three NEFI scenarios for industry and three scenarios from the Environment Agency Austria for the energy sector and for fugitive emissions were selected. Because Austria's industrial landscape has developed over the last centuries it is assumed that the locations of industrial sites and sites for energy generation will remain the same in the future. Production

Table 4: Specific process-related emissions in kg CO_2 per ton product, *geogenic CO_2 emissions.

Economic sector	Product	Comment	Process-related CO_2	Reference
Chemical & Petrochemical	Ammonia		926.00	[4]
	Nitric Acid		0.72	[4]
	Urea		0.50	[4]
	Fertilizer		40.00	[4]
	Olefine		913.20	[19,41]
	Methanol		554.01	[41,42]
Iron & Steel	Steel	BF/BOF	1,487.00	[4]
		EAF	54.00	[4]
		DRI/EAF (CH_4 reduction)	716.00	[41]
		DRI/EAF (H_2 reduction)	80.00	[41]
Non-Ferrous Metal	Aluminum		0.01	[4]
Non-Metallic Minerals	Brick*		53.00	[4]
	Cement*	Per ton Clinker	517.00	[4]
	Cement*	Per ton Cement	338.43	[41]
	Lime*		746.00	[4]
	Glass*		78.00	[4]
Mining & Quarrying	Magnesia*	Per ton Magnesite	475.00	[4]

Table 5: CO_2 concentrations of potential CO_2 point sources.

Economic sector	Product	Comment	CO_2 concentration [vol.%]	Reference
Chemical & Petrochemical	Ammonia, Nitric Acid, Urea, Fertilizer	H_2 purification	98–100	[9]
	Olefine		7–12	[9]
	Methanol	Steam Reformer off gas	18–20	[43]
Energy Supply	Bioethanol production	Fermentation process	98–99	[9]
	Biogas production		25–50	[44]
	Refinery	Refinery off gas	8–24	[8]
	Natural Gas processing	Acid gas removal	96–99	[9]
	Coal-fired CHP		10–15	[9]
	Biomass CHP		14	[45]
	CH_4 CHP		3–5	[9]
	Oil heating plant		3–8	[9]
	Waste incineration plant		10	[8]
	CH_4 heating plant		7–10	[46]
	CH_4 pipeline compressor station		3–5	[9]
Iron & Steel	Steel	Blend of BF-, BOF- and coke oven gas	23	[47,48]
		EAF off gas	40	[47]
		DRI flue gas	13–18	[49]
Non-Ferrous Metal	Aluminum		3–10	[50]
Non-Metallic Minerals	Brick		1.5–4	[8]
	Cement		14–33	[9]
	Lime		21	[51]
	Glass		13	[52]
Paper, Pulp & Print	Pulp and Paper		7–20	[53,54]

activities are projected using average annual production growth rates of the considered industrial sectors [55].

This approach results in three emission-pathways until 2050. One pathway should serve as a reference pathway, while the others are intended to represent a moderate and a progressive pathway. In the reference pathway technologies currently applied continue, however, fuel switches from ongoing transformation projects are included. The moderate pathway based on stakeholder interviews represents the industry-opinion on technology implementation in the future, while the progressive pathway aims to achieve climate neutrality by 2040 aligning with the Austrian governmental program. *Table* 6 provides an overview of considered technological changes.

Key energy carriers in the moderate and progressive pathway are electricity, renewable gases such as hydrogen and Bio-CH_4 and biomass. Whereas the progressive pathway more strongly relies on the use of hydrogen-based production routes and electrification, in the moderate pathway there is a growing utilization of biogenic fuels (biomass and Bio-CH_4). Future CO_2 emissions are determined by specific CO_2 emission factors from 2.1 based on the substitution of technologies and final energy carriers.

4.3 Determination of potential CO_2 sinks and their development until 2050

Storage sites for save long-term CO_2 storage are known from previous and ongoing exploitation of hydrocarbon fields. CO_2 storage potentials in other types of reservoirs such as saline aquifers may provide substantial storage capacities but have not been sufficiently investigated in Austria up to now.

Storage data presented in this work are preliminary results, taken from an ongoing CCS evaluation in Austria and represent effective storage capacities from a CCS screening in hydrocarbon fields only [57]. Additionally, it should be noted that current underground gas storage sites are also part of the CCS screening, leading to a conflict of use that is not discussed further here. Furthermore, CO_2 storage capacities in Austria might increase dramatically if saline aquifers are taken into account. The total as well as yearly effective capacities for CO_2 storage in hydrocarbon fields with a effective capacity above 2 Mt can be found in Table 7 and are used in this work. The total effective storage capacity in the identified hydrocarbon fields is about 226 Mt.

Potential industrial applications are determined based on current and future CO_2 demands as well as the maturity of the CCU technologies (TRL) (cf. 2.2). Primary global as well as Austrian CO_2 demands currently exist for the production of urea and methanol. Scenarios indicate a significant increase in the demand for methanol for a sustainable production of Olefins (MTO – Methanol to Olefins) and Synthetic Aviation Fuels (SAF) [6]. Specific CO_2 inputs are shown in Table 8.

The evolution of industrial CO_2 demands until 2050 is identified using the described scenarios in a similar manner [41].

4.4 Determination of potential Carbon Management Strategies

Relevant current and future products from CO_2 mentioned in 4.3 do not have sufficient binding periods to be considered permanent sinks [10,11]. Therefore, the CO_2 demand cannot be covered by geogenic or fossil CO_2. Biogenic CO_2 is required to fulfill the future CCU demand (BECCU) in a climate neutral manner. As a result, geogenic and residual fossil emissions have to be stored via CCS in the long term to achieve Net Zero Emissions. Emissions from fugitive sources like agriculture that cannot be captured economically need to be offset via negative emissions. Negative emissions are realized through CCS of biogenic CO_2 (BECCS). The development of future

Table 6: Applied technologies by subsector [55].

Economic sector	Applied technologies	TRL
Chemical & Petrochemical	H_2-based primary production of methanol and olefins	8
	Biomass-based primary production of methanol and olefins	8
	H_2-based ammonia production	8
Iron & Steel	Primary steelmaking by DRI/EAF (CH_4 or H_2 reduction)	7
Paper, Pulp & Print	Extensive heat pump application for temperatures up to 200 °C	7
	Black liquor use in integrated mills with CHP plants	9
All subsectors (selected technologies)	Extensive electrification by low (LT) and high temperature (HT) heat pumps	LT: 9 HT: 7
	Electric engines	9

Table 7: CO_2 storage sites in Austria [57].

Hydrocarbon field no.	Total effective capacity [Mt]	Yearly injectivity (quick-look assessment) [Mt/a]		
		<0.5	0.5-1.5	>1.5
F025	46.2			x
F023	41.2			x
F018	29.1		x	
F008	15.0		x	
F029	11.6		x	
F046	10.0		x	
F026	9.8		x	
F001	7.6		x	
F044	7.4		x	
F038	6.3		x	
F022	6.2		x	
F049	5.9		x	
F012	5.5		x	
F016	5.2	x		
F037	3.8	x		
F043	3.0	x		
F036	2.9	x		
F031	2.8	x		
F047	2.7		x	
F051	2.2		x	
F028	2.1	x		

Table 8: CO_2 receiving processes in chemical industry.

Product	Feed	Feed input [t/t product]	CO_2 input [t CO_2/t product]	Reference
Urea	CO_2	0.73	0.73	[6]
Methanol	CO_2	1.37	1.37	[6]
Olefine (MTO)	Methanol	2.83	3.89	[42]
Kerosene (SAF)	CO_2	2.85	2.85	[6]

BECCS and BECCU demands determines the future demand for biogenic CO_2 to be captured. Capturing of atmospheric CO_2 (DACC) is not analyzed in this paper. Considered Carbon Management Strategies based on the CO_2 origin are shown in Figure 3.

The CO_2 demand for CCU $CO_{2,\mathrm{CCU}}$ is calculated as the sum of the CO_2 demand per specific sink i for products with lifetimes lasting several centuries or longer. Similarly, the CO_2 demand for CCUS $CO_{2,\mathrm{CCUS}}$ is assessed as the sum of the CO_2 demand per specific sink i for products with shorter lifetimes than several centuries. The demand for BECCU $CO_{2,\mathrm{BECCU}}$ results from their differences. These relations are shown in equation (1) to (3).

$$CO_{2,CCU}\left(lifetime\right)=\sum_{i=1}^{i=n}CO_{2,CCU,i} \tag{1}$$

$$CO_{2,CCUS}\left(lifetime\right)=\sum_{i=1}^{i=n}CO_{2,CCUS,i} \tag{2}$$

$$CO_{2,BECCU}=CO_{2,CCU}-CO_{2,CCUS} \tag{3}$$

The demand for CCS $CO_{2,\mathrm{CCS}}$ is calculated from the residual fossil $CO_{2,\mathrm{fossil}}$ and geogenic $CO_{2,\mathrm{geogenic}}$ emissions subtracted from the fossil and geogenic CO_2 demand for CCU $CO_{2,\mathrm{CCU}}$. Fossil and geogenic CO_2 emissions ($CO_{2,\mathrm{fossil}}$, $CO_{2,\mathrm{geogenic}}$) are calculated as the sum of the fossil/geogenic emissions per specific point source j. The demand for BECCS correlates to residual fugitive emissions. The minimal demand for CC of biogenic emissions $CO_{2,\mathrm{biogenic,min}}$ result from the total demand for BECCU and BECCS (equation (4) to (8)).

$$CO_{2,fossil}=\sum_{j=1}^{j=n}CO_{2,fossil,j} \tag{4}$$

$$CO_{2,geogenic}=\sum_{j=1}^{j=n}CO_{2,geogenic,j} \tag{5}$$

$$CO_{2,CCS}=CO_{2,fossil}+CO_{2,geogenic}-CO_{2,CCU} \tag{6}$$

$$CO_{2,BECCS}=CO_{2,fugitive} \tag{7}$$

$$CO_{2,biogenic,min}=CO_{2,BECCU}+CO_{2,BECCS} \tag{8}$$

Geogenic $CO_{2,\mathrm{geogenic}}$ and unavoidable fossil emissions $CO_{2,\mathrm{fossil,min}}$ are Hard-to-abate emissions $CO_{2,\mathrm{Hard\text{-}to\text{-}abate}}$ and represent together with the demand for BECCS the minimal demand for CCS. The minimal demand for CC is calculated by adding the minimal demand for biogenic CO_2 (equation (9) to (11)).

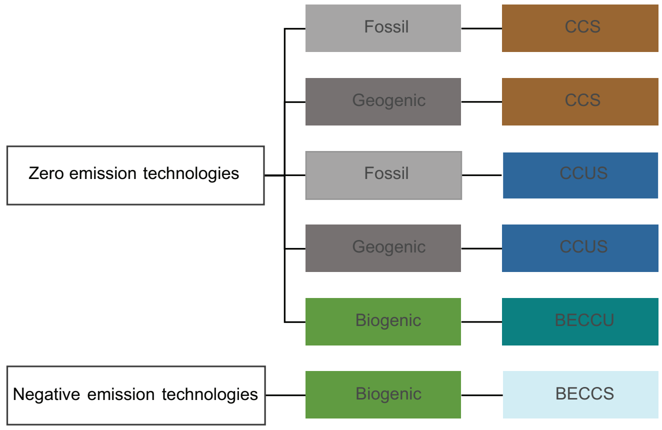

Figure 3: Considered Carbon Management Strategies based on the CO_2 origin.

$$CO_{2,Hard-to-abate}=CO_{2,fossil,min}+CO_{2,geogenic} \tag{9}$$

$$CO_{2,CCS,min}=CO_{2,Hard-to-abate}+CO_{2,BECCS} \tag{10}$$

$$CO_{2,CC,min}=CO_{2,Hard-to-abate}+CO_{2,biogenic,min} \tag{11}$$

5. Results

In total, CO_2 emissions for 109 industrial sites and 77 plants for energy supply are identified and mapped, while the industrial sites are classified in 10 different industrial sub-sectors. The development of the emissions of these sites were calculated for the years 2030, 2040 and 2050. Figure 4 spatially resolves the determined CO_2 emissions of Austria's major point sources in the year 2019.

Austria's federal states with the highest industrialization are Upper Austria with Linz, Lower Austria with Sankt Pölten and Styria with Graz as capital city. Austria's two primary steel production sites are in Upper Austria and Styria, together with the only refinery-site, allocated to energy sector in Lower Austria, these three sites form the top three emitters in Austria, responsible for over 14 Mt/a of CO_2 in 2019. This accounts for around 20% of Austria's total CO_2 emissions and for almost 40% of the emissions from point sources, considered in this study.

Dominant emitters can also be identified in sectors Non-Metallic Minerals, comprising cement production (mostly geogenic emissions), along with Paper, Pulp & Print (mostly biogenic emissions), Chemical & Petrochemical Industry (fossil emissions) and the energy sector (referred as Energy Supply), which includes significant CO_2 point sources such as combined heat and power (CHP) plants with natural gas, waste incineration plants and some smaller biomass plants. The emitters of the energy sector are evenly distributed primary across the three states described and across Austria.

The development of the evaluated emissions based on the determined pathways as well as the share of geogenic, fossil and biogenic emissions is illustrated in Figure 5.

In 2019 point source emissions are predominantly composed of fossil sources. Over 26.9 Mt/a out of a total of around 38.8 Mt/a originate from fossil sources. Around 2.5 Mt/a are geogenic and 9.2 Mt/a are biogenic emissions (due to the description with one decimal place rounding differences may occur). Because of the gradual replacement of fossil energy carriers, total emissions decrease gradually until 2050.

Total point source emissions in the reference pathway in 2050 account for nearly 32.7 Mt/a. In this pathway industry as well as the energy sector still strongly relies on fossil energy carriers with a total of nearly 18.6 Mt/a of fossil CO_2 emissions.

In the moderate pathway remaining emissions from the determined point sources in 2050 are approximately 19.9 Mt/a of CO_2, of which around 2.5 Mt/a are geogenic, 2.0 Mt/a fossil and 15.4 Mt/a biogenic CO_2

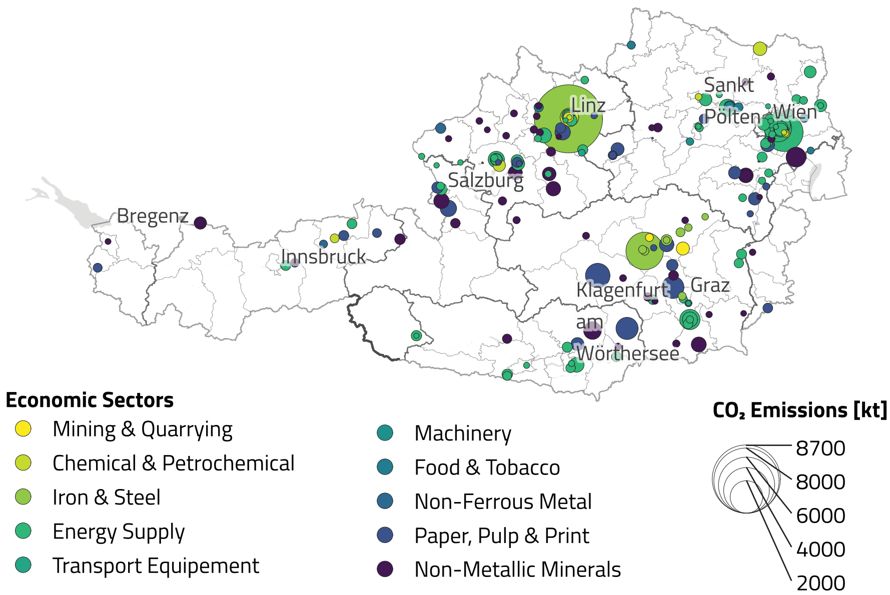

Figure 4: Austria's annual CO_2 point sources in 2019.

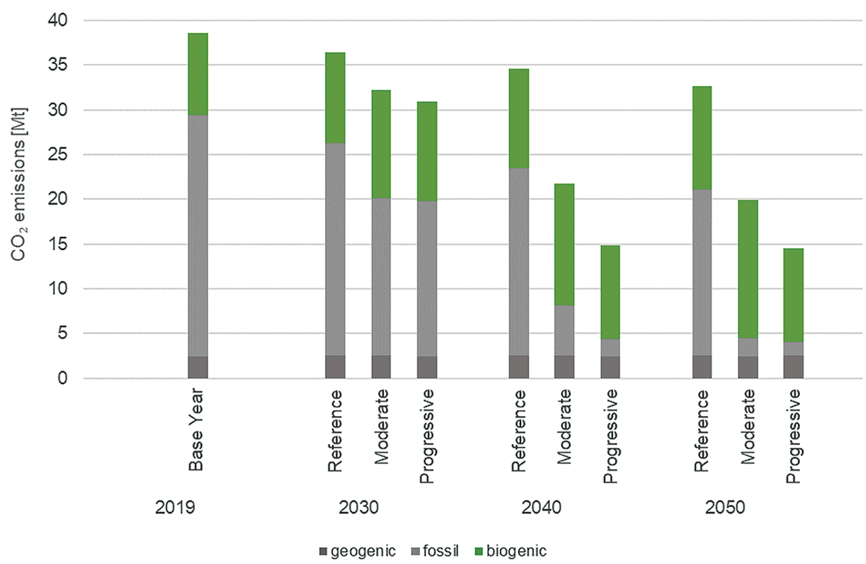

Figure 5: Development of the annual emissions of the determined point sources and share of geogenic, fossil and biogenic CO_2 emissions for the determined pathways.

emissions. Energy-related emissions (nearly 13.3 Mt/a) primarily comprise of biogenic emissions. Residual fossil emissions mainly originate from the combustion of waste. However, this pathway still has residual fossil emissions that are not considered as Hard-to-abate, primarily coming from refinery processes.

In contrast to the moderate pathway, which outlines decarbonization strategies of the industry, the progressive pathway aims to achieve climate neutrality by 2040 aligning with the Austrian governmental program. Therefore, from 2040 ongoing, in the progressive pathway only unavoidable geogenic emissions and emissions from waste incineration remain. Total CO_2 emissions account for approximately 14.8 Mt/a in 2040 and 14.5 Mt/a in 2050. Emissions decrease from 2040 to 2050 due to the reduction in waste incinerated. In 2050 fossil emissions (around 1.5 Mt/a) merely come from waste incineration, while biogenic emissions account for nearly 10.5 Mt/a. In this pathway there are 3.2 Mt/a of process-related CO_2 emissions along with 11.4 Mt/a energy-related of CO_2 emissions remaining.

A spatially resolved scenario comparison for the year 2050 is shown in Figure 6.

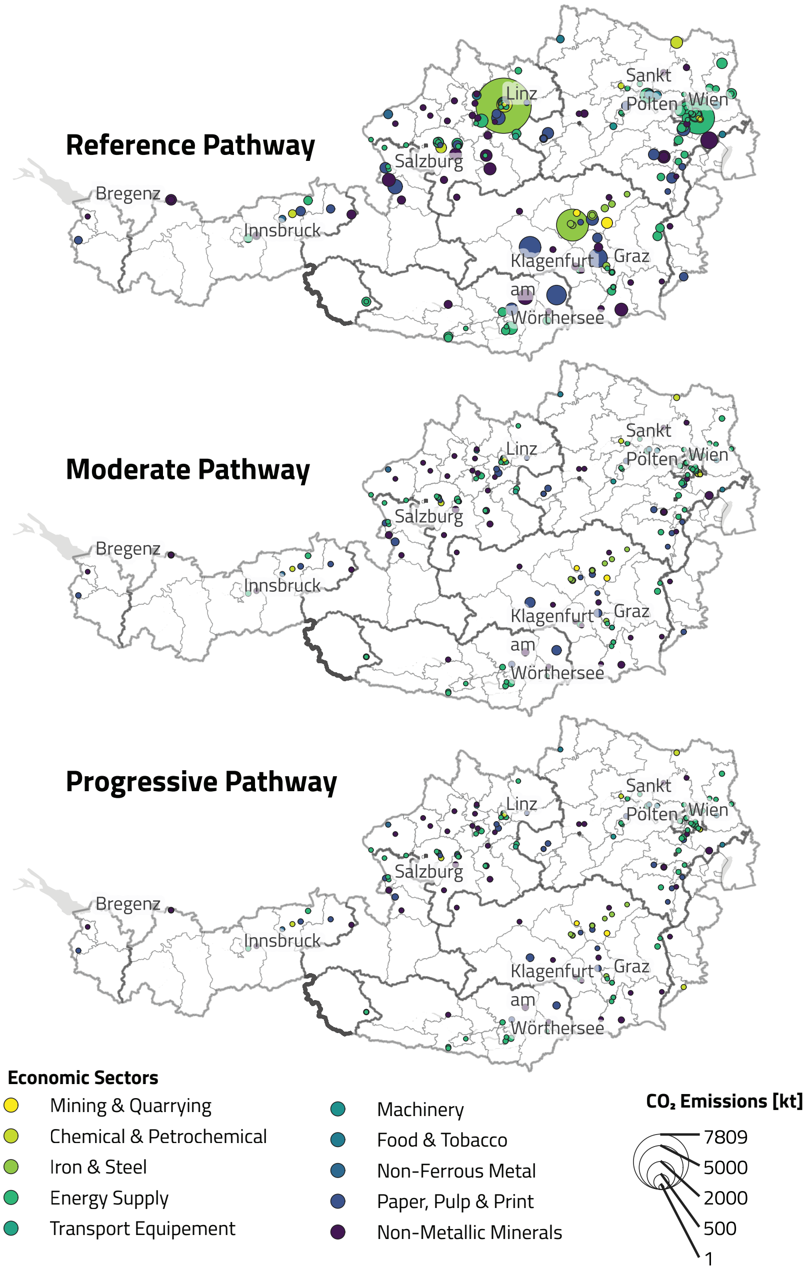

Figure 6: Austria's annual CO_2 point sources in 2050 – Scenario comparison.

Compared to the reference pathway, CO_2 emissions decrease and point sources of comparable quantities are spread within the previously described industrial areas. The sites responsible for the highest CO_2 emissions shift from primary steel production and the refinery to geogenic CO_2 emissions from cement production, biogenic emissions from sector Paper, Pulp & Print and to biomass and waste incineration plants.

In Table 9 the numbers of total and high purity CO_2 point sources in different emission ranges are shown. Most of the analyzed point sources emit less than 50 kt/a post 2050. The largest share of emissions is caused by point sources in the range between 100 and 500 kt/a. Due to economies of scale, the costs of CC can decrease with the size of the plant. For CO_2 sources with high purities CC from small sites (<50 kt/a) may, however, be a viable option.

Because of the insufficient lifetime of chemical products from CCU (paragraph 4.3) it is assumed that urea, methanol and SAF are produced via biogenic CO_2 (BECCU). To achieve Net Zero emissions at least residual geogenic and unavoidable fossil emissions from waste incineration (cf. $CO_{2,\text{Hard-to-abate}}$ from equation (9)) have to be permanently stored via CCS. Residual fossil emissions from point sources that will not be mitigated through the considered substitution of technologies and final energy carriers represent additional demands for CCS. Fossil emissions from fugitive sources that cannot be captured economically must be offset by negative emissions (BECCS). The development of the demand for Carbon Capture $CO_{2,\text{CC}}$ (cf. equation (*6*)) and therefore the development of CCS and BECCS from 2030 until 2050 can be found in Figure 7.

As a result of the substitution of fossil fuels with renewable energy according to the scenarios, emissions decline and hence CCS and BECCS demands decrease until 2050. Depending on the scenario considered, the demand for BECCU is growing due to the implementation of the alternative technologies to produce urea, methanol and aviation fuels.

Without a substantial mitigation of climate relevant emissions in line with the reference pathway, in 2050 a total of 36.1 Mt/a of CO_2 needs to be captured for geological storage (21.1 Mt/a for CCS and 15.0 Mt/a for BECCS). The demands for biogenic CO_2 to offset fugitive emissions exceed the biogenic emissions from the analyzed point sources, leading to a deficit of biogenic CO_2 of 3.4 Mt/a.

In the moderate pathway Hard-to-abate emissions can be reduced from approximately 5.8 Mt/a in 2019 to 4.0 Mt/a by 2050. Fossil emissions from point sources decrease to nearly 0.5 Mt/a by 2050. By 2040 6.3 Mt/a of biogenic CO_2 has to be captured to offset the residual fugitive emissions (BECCS). This can be reduced to 5.2 Mt/a by 2050. This demand for CCS and BECCS results in a total demand for the geological storage of CO_2 of over 9.7 Mt/a in 2050. According to the moderate pathway the demand for biogenic CO_2 for BECCU activities will increase to over 6.0 Mt/a by 2050. A total of 11.2 Mt/a of biogenic CO_2 has to be captured by 2050, which can be covered by biogenic emissions from the analyzed point sources following the moderate pathway.

In the progressive pathway residual fossil emissions from point sources cease from 2040 onwards. Hard-to-abate emissions decrease to 4.0 Mt/a by 2050. Along with the demand for BECCS of 5.2 Mt/a by 2050, there is a resulting demand for the geological storage of CO_2 of 9.2 Mt/a. Compared to the moderate pathway the demand for biogenic CO_2 to cover the industrial use is higher (13.4 Mt/a in 2050). This demand exceeds the biogenic emissions from the analyzed point sources, leading to a deficit in biogenic CO_2 (3.8 Mt/a).

Table 9: Number of point sources and CO_2 emissions in kt/a in different ranges - Scenario comparison for the year 2050.

	Reference pathway				**Moderate pathway**				**Progressive pathway**			
	Number of point sources	CO_2 emissions	Number of high purity point sources	High purity CO_2 emissions	Number of point sources	CO_2 emissions	Number of high purity point sources	High purity CO_2 emissions	Number of point sources	CO_2 emissions	Number of high purity point sources	High purity CO_2 emissions
<50	77	1,257	2	56	68	1,022	2	56	78	1,162	–	–
50-100	28	2,150	–	–	27	2,012	1	70	23	1,750	–	–
100-500	51	11,046	1	120	36	7,400	1	120	37	7,467	1	120
500-1,000	4	2,927	1	523	4	2,724	–	–	3	2,013	–	–
>1,000	5	15,315	–	–	4	6,787	–	–	2	2,123	–	–
∑	165	32,695	4	698	139	19,945	4	246	143	14,515	1	120

There are a total of 60 emitters with Hard-to-abate emissions including 48 plants from sector Non-Metallic-Minerals (geogenic emissions) and 12 waste incineration plants with a fossil share in waste of around 50%. The remaining 50% of the CO_2 emissions from waste incineration plants are of biogenic origin. These CO_2 point sources and sinks are mapped in Figure 8 according to the moderate pathway.

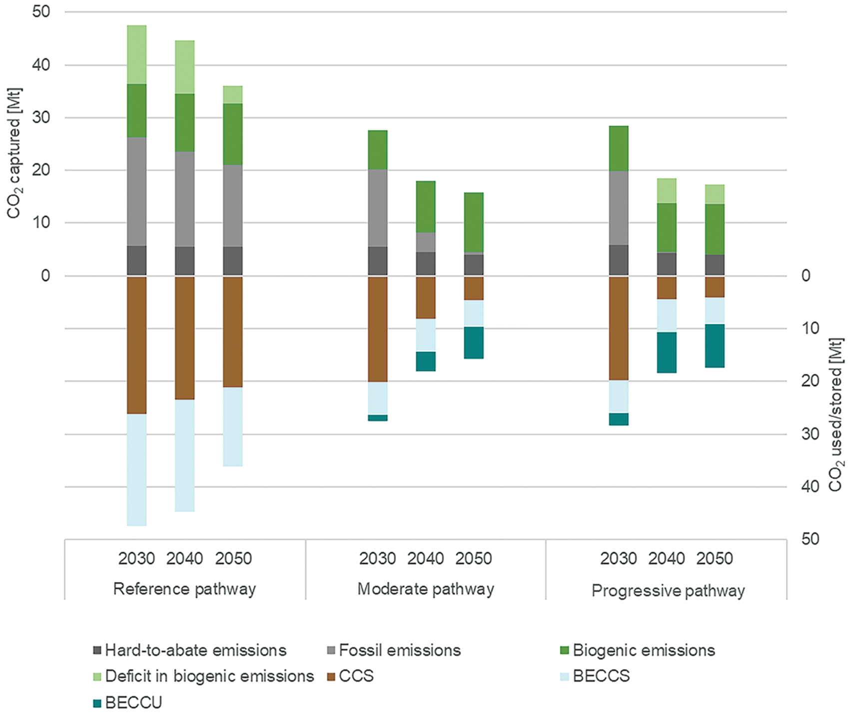

Figure 7: Future annual demands for CC, CCS, BECCS and BECCU based on the captured CO_2 origin – Scenario comparison.

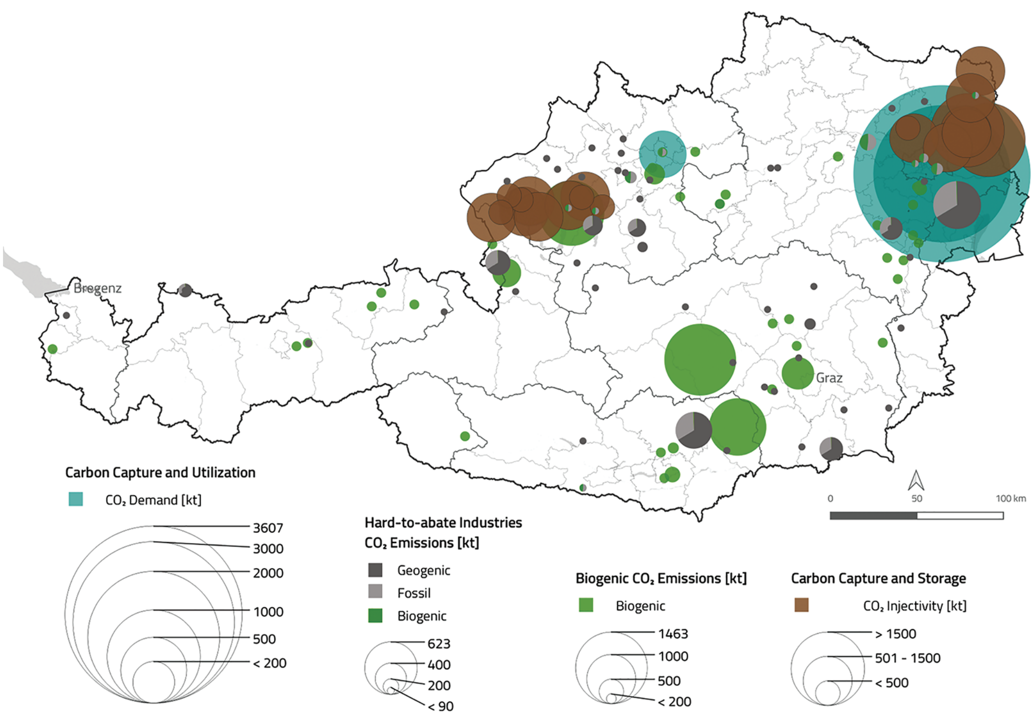

Figure 8: Austria's annual CO_2 point sources (minimal CC demands - Hard-to-abate and biogenic emitters) and CO_2 sinks (yearly CO_2 injectivity of the evaluated storage sites and yearly CO_2 demands of Chemical industry) in 2050 for the moderate pathway.

Until 2050 46 emitters can be identified where all remaining emissions are from biogenic origin, comprising sites of sector Pulp & Paper and Biomass CHP plants. The largest biogenic emitters, with more than 1.0 Mt/a of biogenic CO_2 at certain sites, can be found in sector Pulp & Paper. CO_2 sinks in chemical industry can be determined at three locations.

6. Discussion

Depending on the considered scenario 4.0 to 5.5 Mt of Hard-to-abate emissions and 0.0 to 15.6 Mt of residual fossil emissions per year must be captured in Austria by 2050. To cover the demand for BECCS and BECCU 11.6 to 15.0 Mt/a of biogenic CO_2 is necessary, which results in deficits of 0.0 to 3.8 Mt/a of biogenic CO_2 depending on the scenario. Therefore, a total of over 15.6 to 36.1 Mt/a of CO_2 must be captured by 2050 to achieve Net Zero emissions.

According to the scenarios the minimal demand for the geological storage of CO_2 in Austria declines to 9.2 Mt/a until 2050 (CCS of Hard-to-abate emissions and BECCS). The total effective storage capacity in the identified hydrocarbon fields is about 226 Mt with a minimum yearly injectivity of 9.5 Mt. If all examined storage sites are utilized for CO_2 storage and only Austrian storage sites accommodate the minimal CCS demand, these sites would reach full capacity in approximately 25 years. Therefore, investigating the feasibility of storage in saline aquifers as well as the definition of Austrian storage locations that are best suited due to their geological properties and minimal conflicts of use is essential. Nevertheless, the geological storage of CO_2 abroad cannot be completely avoided. Solely the moderate pathway implies no needs for exports of CO_2 for the geological storage or for imports of biogenic CO_2.

Based on the geographic locations of CO_2 point sources and sinks, clusters of CO_2 sources in Lower Austria, Upper Austria and Styria can be identified. Clusters of CO_2 sinks can be found in Lower and Upper Austria. By clustering sources and sinks, uncertainties in the development of capture, utilization and storage capacities can be minimized. In this way, the flexible coordination of CO_2 demand and supply is possible.

7. Conclusion

This comprehensive evaluation of Austria's CO_2 point sources until 2050 and the determination of their process- and energy-related as well as geogenic, fossil and biogenic share of emissions enables the definition of preferable Carbon Management Strategies with regard of the origin of the carbon emission. Their successful implementation require in-depth analyzes of technical solutions along the entire process chain as well as essential infrastructural developments. Future research efforts have to focus on refining the overall system design especially in terms of optimizing the pipeline design as well as the rollout of CO_2 pipeline networks to ensure the realization of sustainable Carbon Management Strategies.

Acknowledgements

The work presented in this special issue stems from 18th conference on Sustainable Development of Energy, Water and Environment Systems (September 24-29, 2023, Dubrovnik, Croatia). The authors would like to acknowledge participants and organizers.

This work was carried out as part of the project "Austria's climate neutrality: An in-depth evaluation of the potential contribution of CCU and CCS for the Austrian long-term climate goals" with the acronym "CaCTUS - Carbon Capture & Transformation, Utilization and Storage". This project is supported by the Austrian Climate Research Programme (ACRP).

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