ConsenCUS

# Report on cluster analysis and sector coupling

ConsenCUS deliverable 8.5

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## 1. Inhoud

# 1 Report on cluster analysis and sector coupling

## 1.1 Task description and scope of this report

This report is the output of deliverable **D8.5 “Report on Cluster Analysis and Sector Coupling”** in WP8, Task 8.4.

We first summarize the tasks conducted within this report and then explain how those tasks were realized. In the following sections, the detailed study, analysis, and results are presented.

Summary of the tasks conducted:

Based on tasks 8.1, 8.2, and 8.3 and input from all participants in this WP, a cluster analysis was carried out by RUG. The value chain design included an in-depth industrial symbiosis analysis, taking into account the specific demand and supply conditions (such as different $CO_2$ purity levels) required by each entity in the cluster. Various cluster configurations were studied through the network optimization framework. This was used to rank alternative solutions and analyze a range of the most feasible cluster configurations.
The value chain integrated the $CO_2$ capture, $CO_2$ transport, $CO_2$ storage, and $CO_2$ utilization components. A portfolio of $CO_2$ cluster structures was generated, including the possibility for flexible and varying production based on weather conditions and potential seasonal temporal $CO_2$ storage. This time-dependent operation was vital in creating industrial symbiosis under varying availability of electricity and hydrogen, or other similar resources, influenced by weather conditions and seasonal energy flows. A multi-period analysis was used to optimize $CO_2$ chains, considering GHG emissions across different development paths over time, with the goal of reaching net-zero by 2050. This task connected WP8 with WP7 (task 7.3), where the community narratives and public perception of the same cluster components were studied.

**Description of How These Tasks Were Realized:**
In this task, a value chain optimization framework was developed to analyze how location, size, and timing of investments are affected by alternative technologies and infrastructures using mathematical models. Various cluster configurations such as with the consideration of different emission sources and the end uses as followed upon ConsenCUS techology  were studied through the network optimization framework. This was used to rank alternative solutions and

analyze a range of the most feasible cluster configurations. The input data for emission sources, end uses and storage sites was linked with the deliverables 8.1 and 8.2.

First, we developed the methodological framework (founded upon Deliverable 8.4) for the value chain optimization. The framework integrates various supply chain components of the $CO_2$ clusters, considering the capture of $CO_2$ and its delivery for various end uses. A set of configurations was considered to address uncertainties inherent in such networks, such as variability in supply and demand.

The optimization framework was then tailored to applications in Europe to analyze specific conditions for clusters. For example, in **Appendix I, Section 3.3**, we present a mixed-integer linear programming model to determine the least-cost approach for capturing and storing/utilizing a predefined amount of $CO_2$ emissions. We addressed key decisions, such as how much $CO_2$ should be captured at each node and which storage or utilization site should be targeted. The model supports multiple transit modes, allowing for seamless transitions.

Likewise, in **Appendix II, Section 3.2**, we detail the mathematical model used to design optimal cross-border $CO_2$ supply chains for sustainable aviation fuel (SAF) production from formic acid, as per the ConsenCUS project's conversion unit.

This value chain framework integrates $CO_2$ capture, transport, storage, and utilization components. For example, as shown in **Tables 6, 7, and 8** and the constraint sets that follow in **Appendix I**, capture nodes were connected to storage and utilization nodes via arcs allowing for $CO_2$ transportation through different modes.

Our approach enabled multi-period assessments using scenario analysis and forecasting models based on regression analysis to study various future projections. This included the possibility for flexible production based on weather conditions and seasonal $CO_2$ storage. This time-dependent operation was essential in fostering industrial symbiosis under variable electricity and hydrogen availability, or similar weather-dependent resources.

For instance, in **Section 4 of Appendix I**, we show how scenarios were designed to analyze different 30-year implementation pathways. We considered projections involving potential storage capabilities, favorable weather, and availability of hydrogen and electricity for $CO_2$ processing. These factors affected $CO_2$ capture costs, which are analyzed in **Section 3.2.1 of Appendix I**.

The cost breakdown vividly underscores the considerable impact of energy prices on the economics of carbon capture. Accordingly, the use of renewable energy sources with lower marginal costs would not only reduce the cost of capturing $CO_2$ but also yield the greatest environmental benefitWe categorized these varying parameters into two main scenario types: *restricted* and *ample*, to evaluate their strategic impact. This led to a portfolio of $CO_2$ structures based on projected variations in storage or production availability.  For example, in **Section 4.1 of Appendix I**, we report the cluster configurations for Romania under both restricted and ample scenarios. We broadened the perspective by analyzing $CO_2$ market economics, particularly the impact of the EU Emissions Trading Scheme (ETS), using a dummy storage node to represent excess $CO_2$ requiring carbon tax payments or allowance purchases.

In **Section 3.1.3 of Appendix II**, we detail our demand estimation for SAF produced from captured $CO_2$ in 2030, using an ARMA model with a trend component applied to historical jet fuel consumption data. This time-dependent analysis captured demand variations, such as those caused by the COVID-19 pandemic, which led to significant reductions in 2020 and 2021, followed by recovery in 2022–2023.

The value chain design also included an in-depth industrial symbiosis analysis, accounting for specific demand and supply conditions (e.g., different $CO_2$ purity levels) of each cluster entity. Various configurations were again studied and ranked using the network optimization framework. We adopted a case study research methodology, involving in-depth exploration within a specific context to draw broader insights into $CO_2$ cluster configurations.

For instance, we analyzed CCUS opportunities in Bulgaria, Greece, Romania, and Croatia by cost-estimating and optimizing CCUS value chains incorporating emitters from various industries and utilization forms. We considered different $CO_2$ purity levels, as shown in **Table 4 in Appendix I** and **Table 5 in Appendix II**.

We evaluated industrial symbiosis based on regional industrial development and availability. Specifically, we focused on four emitter categories likely to adopt $CO_2$ capture technologies: oil and gas refineries, fertilizer plants, iron and steel producers, and cement manufacturers (see **Section 3.1.1 in Appendix I**). The captured $CO_2$ was then used in sectors such as sugar production, greenhouses, and hydrogen production (see **Section 3.1.3 in Appendix I**).

We report our cluster configurations and related analysis in **Section 4 of Appendix I**, with per-country configurations in **Section 4.1**, followed by an analysis of shared infrastructure among countries. Another set of configuration analyses is found in **Section 4 of Appendix II**, where clusters are ranked and assessed based on cost parameters.

The results from these configurations were then generalized through scenario generation and sensitivity analysis to gain insights applicable to other regions and time periods. An example is found in **Section 4.1.2 of Appendix II**, where we analyze the effects of conversion yields and costs related to capture, conversion, and transport.

We also further explored cluster configurations based on the use of formic acid, central to the ConsenCUS project, focusing on conversion to high value-added products. Specifically, formic acid was examined for its role in producing fatty acids, used as feedstock for SAF synthesis via the HEFA (hydroprocessing of esters and fatty acids) pathway. The network covers $CO_2$ capture, FA and fatty acid conversion, SAF synthesis, and transportation of feedstock and fuel. Our goal was to understand cost interactions across the value chain and assess the economic feasibility of forming such clusters under the project's technological assumptions.

A key finding is that cross-border SAF supply chains can offer significant economic benefits, especially for regions lacking sufficient domestic $CO_2$ point sources. While SAF produced via 7

CCU remains expensive, its cost approaches that of HEFA when low-cost, high-purity $CO_2$ is available through international cooperation. Direct air capture (DAC) reduces dependence on emitters but remains economically unviable in the near term due to high energy requirements and costs. Point source capture is currently the more feasible option. Ultimately, the viability of SAF production depends strongly on technological progress in fuel conversion. If conversion costs decline, transport and supply chain logistics will play a larger role in overall system costs. This makes infrastructure decisions more complex and dependent on long-term developments in capture technologies.In sparsely industrialised areas, cross-border networks make sense today, but may become redundant if DAC becomes viable in the future. Flexible transport options may therefore be more robust than fixed infrastructure. The framework developed here supports decision-making by highlighting trade-offs across technology, logistics, and policy in SAF value chains.

This task also links to **WP7**, where regional analysis and local narratives are studied .

We refer to **Section 5 in Appendix I** as to how we explain these connections. Additionally, for sector-specific analysis related to the target end product, we conducted expert interviews, as described in **Section 3 of Appendix II**.
We refer the reader to the following appendices for the full studies:

1. **Appendix I – A Practical Assessment of CCUS Opportunities in the Southeast European Industrial Sector**
2. **Appendix II- From $CO_2$ Emissions to Jet Fuel: Analysis of Potential Sustainable Aviation Fuel Supply Chains in Europe**

# A Practical Assesment of CCUS Opportunities in the Southeast European Industrial Sector - Bulgaria, Croatia, Greece, Romania

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**Abstract**

Carbon capture, storage, and utilization (CCUS) stands out as a promising tool to advance the achievement of industrial decarbonization objectives. Nonetheless, persistent uncertainties surrounding technical and commercial parameters have hindered its widespread adoption. This paper aims to shed light on the CCUS prospects within Southeast European countries, namely Bulgaria, Croatia, Greece, and Romania. It does so by estimating costs and optimizing CCUS value chains that encompass emitters from the fertilizer, oil refining, iron and steel, and cement industries. Our analysis, coupled with consultations with industry experts, reveals that the implementation of CCUS has the potential to reduce overall industrial CO2 emissions in the region by up to 25%. In some countries, the formation of CCUS clusters emerges as a straightforward decarbonization strategy, whereas in others, the presence of widely spaced emission sources and sinks necessitates coordinated development of pipeline infrastructure and crosscountry collaboration. This potential is further bolstered by supranational programs. However, it is worth noting that the current EU Emission Trading System (ETS) scheme does not seem to sufficiently incentivize investments in carbon capture. The availability of free ETS allowances still covers a significant portion of capturable CO2 emissions, potentially discouraging individual plants from pursuing expensive carbon capture initiatives.

*Keywords:* Carbon Capture Usage and Storage, Southeast Europe, value chain analysis, optimization, modelling

## 1. Introduction

With the European Commission steadfastly committed to achieving net-zero greenhouse gas emissions by 2050 in alignment with the goals of the Paris Agreement [1], substantial investments are in the pipeline to enable the advancement of Carbon Capture, Utilization, and Storage (CCUS) technologies. Nevertheless, a multitude of concerns and uncertainties loom over the domains of demand, trade, transportation, and utilization, all of which exert considerable influence on the successful implementation of these technologies. Within this context, two primary challenges stand out in relation to the adoption of CCUS.

The first of these challenges revolves around the necessity for robust strategies for reducing CO2 emissions effectively. The second challenge pertains to the efficient and cost-effective supply and distribution of CO2, both of which are integral to the CCUS framework. Notably, the industrial sector, which relies significantly on fossil fuels as feedstock, stands out as a formidable hurdle in the journey to decarbonize [2]. CCUS technologies, as a focal point, concentrate on capturing emissions originating from industrial processes. This captured CO2 can be either securely sequestered in controlled geological storage sites, a practice known as Carbon Capture and Storage (CCS), or channeled into other industries as a valuable feedstock, termed Carbon Capture and Utilization (CCU).

Although CCUS initiatives are burgeoning across Europe, a majority of them are currently concentrated in Western and Northern European nations. In the Southeast European region, there are limited examples, such as the CO2 EOR Project [3] in Croatia, where CO2 sourced from local natural gas processing facilities enhances oil recovery at the Ivanić and Žutica fields. Croatia is also in the early stages of planning a similar project, iCORD, which aims to capture CO2 emissions from fertilizer and concrete production plants, storing them in oil fields in Moslavina and Pannonia [4]. Within the framework of the EU-sponsored project ConsenCUS, CO2 emissions from industrial sites, including an oil refinery in Romania and a magnesite production plant in Greece, are earmarked for transformation into valuable end uses.

While a growing number of individual demonstration projects provide evidence of the technological feasibility of CCUS, the high associated costs and a lack of clear commercial guidelines restrict its widespread adoption across eligible industries. Consequently, a burgeoning body of literature has arisen, exploring the technological prospects and constraints of carbon capture, transport, utilization, and storage. This includes distributed case studies and in-depth cost evaluations that focus on the financial aspects of CCUS deployment. However, a critical research gap remains in the form of region-specific analyses, offering a comprehensive view of the CCUS value chain, encompassing production through to end use.

In this paper, our objective is to make a valuable contribution to the existing literature. To this end, we systematically identify and evaluate opportunities for Carbon Capture, Utilization, and Storage in four Southeast European countries: Romania, Bulgaria, Greece, and Croatia. These countries are characterized by their collective consideration of Carbon Capture, Utilization, and Storage as an option in their carbon reduction strategies. They have expressed an interest in exploring and implementing CCUS technologies, recognizing their potential to mitigate carbon emissions and play a crucial role in achieving climate goals as supported by projects such as ConsenCUS [5] and CO2 EOR [3]. We embark on this endeavor by initially pinpointing the industrial sources of CO2 emissions, geological sites suitable for storage, and potential utilization sites in the region. Additionally, we compile a comprehensive database of the most promising potential sites. Subsequently, we delve into the analysis of capture, storage, and transportation costs. We then proceed to develop a tailored mixed-integer linear programming model, which allows us to determine the cost-optimal CO2 source-sink pairs and the most efficient transportation methods. Finally, we present the findings of our analysis and engage in discussions with experts in the field. Our results underscore the substantial potential of CCUS in reducing industrial CO2 emissions by up to 25% in the region. Furthermore, our research indicates a compelling need for adjustments within the European Union Emissions Trading System (EU ETS), particularly with regard to the restrictions imposed by the allocation of free allowances, which currently hinder investments in carbon capture technologies.

The paper is structured as follows. The next section provides the literature overview of the studied industrial CO2 sources, storage and utilization options together with the EU ETS System. In Section 3, the data collection method regarding the Southeast European industrial CO2 emitters, geological storage sites, and potential utilization sites is first explained. Thereafter, the mixed-integer linear programming model developed to determine cost-optimal CO2 source-sink pairs and transportation methods is presented. Section 4 provides the scenario analysis of the region and an assessment of the EU ETS system's effect.. Section 5 concludes the study.

## 2. Literature review

Academics have demonstrated a keen interest in contributing to the planning of carbon capture, utilization, and storage (CCUS) infrastructure development. Early endeavors commenced with the determination of minimum-cost, point-to-point pipelines that link CO2 emission sources with one or more sinks in specific geographic regions (Bock et al., [6]). As these approaches evolved, advanced Mixed-Integer Linear Programming (MILP) models began to address infrastructure sharing, scalability, and the temporal aspects of CCUS supply chain networks. SimCCS, developed by Middleton and Bielicki (SimCCS, [7]), incorporated a Geographical Information System (GIS) to estimate the cost implications of topographic conditions in the source-to-sink routes and shared CCS supply chains within the United States. Van den Broek et al. [8] created a toolbox based on ArcGIS and MARKAL (an energy bottom-up model) that introduced the time dimension into the design of CO2 infrastructure in the Netherlands. The InfraCCS initiative ([9]) took scalability to a new level by striving to design the optimal Pan-European CO2 pipeline infrastructure.

Uncertainties concerning carbon capture and transportation costs, financial incentives, and storage availability have been increasingly addressed, primarily through stochastic models. Lee ([10]) delved into the economic implications of emission inventories, operational costs, and product prices in Korea. Knoope, Ramirez, and Faaij ([11]) developed a model to examine the impact of changes in CO2 tariffs on the Dutch CCS infrastructure. Meanwhile, D'Amore et al. ([12]) introduced a framework for managing uncertainties related to European geological storage capacities. Recent efforts have enriched the literature by formulating multi-objective optimization problems. These efforts have simultaneously aimed at minimizing costs while addressing other crucial aspects, such as a) reducing environmental impact (Zhang et al., [13]), b) maximizing social acceptance (d'Amore et al., [14]), or c) maximizing mitigated emission levels (Leonzio et al., [15]).

However, it is noteworthy that despite these valuable contributions, an important regional gap exists in the Southeast European context. This gap holds particular significance due to the unique socio-economic and environmental challenges prevalent in the Southeast European region. These challenges—ranging from economic disparities and energy dependence to political instability and environmental vulnerability—make it a complex but crucial region for the development of sustainable CCUS infrastructure. Successfully implementing CCUS in this region could address both environmental responsibility and economic growth, but it requires tailored strategies that take into account the distinctive regional circumstances and challenges. The development of sustainable CCUS infrastructure in this region holds the potential not only to significantly reduce carbon emissions but also to promote economic growth, energy security, and technological advancement in a region that may have more limited resources at its disposal. Additionally, Southeast Europe has exhibited a growing interest in exploring and implementing CCUS technologies, recognizing their potential to play a crucial role in achieving climate goals. Consequently, comprehending the intricacies of CCUS supply chain optimization in this context becomes of paramount importance for the successful development of environmentally responsible industries. Moreover, as Southeast Europe becomes increasingly integrated into the broader European framework, its role in the transition towards a low-carbon economy gains additional significance. Our work aims to address this regional void by providing a tailored approach to the distinctive challenges and opportunities within this geographic region. In doing so, we aspire to contribute not only to the academic discourse but also to regional and global efforts in achieving sustainability, environmental responsibility, and economic prosperity in Southeast Europe.

In this section, we provide background and conduct an analysis of the CCUS supply chain framework to acquire insights into the feasibility of various approaches and to provide a clearer rationale for our model. Our examination involves pinpointing the primary sources of industrial CO2 emissions and assessing the portion of these emissions that can realistically be captured. Additionally, we survey potential storage possibilities and evaluate the emission reduction potential associated with specific CO2 utilization strategies.

### *2.1. $CO_2$ Emission Sources*

The industrial sector contributes approximately 20% of the European Union's total greenhouse gas emissions [16]. Within this sector, significant contributors to emissions include the iron and steel industry at 22%, the refining sector at 19%, the cement industry at 18%, and the fertilizer industry at 5% [16]. This study examines industries where CO capture technologies hold significant potential, as their production processes inherently generate emissions, making CCUS an essential tool for decarbonization.

The iron and steel industry stands out as a major source of CO2 emissions, often releasing millions of tons of CO2 annually. These emissions primarily stem from the combustion of fossil fuels in the steel production process. Notably, a significant portion of these emissions, estimated at 73%, can potentially be captured at the three primary emission points: coke oven gas (COG), blast furnace gas (BFS), and coke oven power plant stack (COG PPS) [17].

In contrast, oil and gas refining complexes are substantial CO2 emitters, with annual emissions reaching the millions. However, the challenge lies in the dispersed nature of emission points within these facilities, making carbon capture an expensive endeavor. Emission points within refineries can be categorized into three main groups: hydrogen production units (comprising 5%-20% of total emissions) with concentrated CO2 streams, large flue gas sources like furnaces and gas turbines (constituting 30%-50% of emissions), and small, low-concentration sources (making up the remaining 50%) scattered throughout the premises [18].

Cement plants also make a significant contribution to emissions, with individual facilities emitting several thousand tons of CO2 annually. Although more than half of a modern cement plant's emissions result from the calcination process itself, retrofitting fuel-burning kilns with post-combustion carbon capture units could potentially reduce a facility's total emissions by up to 40% [19].

In the ammonia production process, typically involving natural gas reforming to produce H2, CO, and CO2, two main carbon dioxide point sources emerge: the flue gas from the primary reformer burners and the CO2 stripper vent, responsible for separating CO2 from the ammonia syngas. Notably, the high-purity CO2 streams available at the stripper vents can be economically captured, leading to active participation by fertilizer plants in CO2 markets, supplying the food and beverage, as well as storage and transportation industries. Herron, Zoelle, and Summers [20] report that an estimated 57% of the high-concentration CO2 emissions from a fertilizer plant can be captured on average.

Within the four industrial sectors under consideration, steel manufacturing and oil refining face the most significant pressure to reduce CO2 emissions per ton of production output. In industries where a substantial portion of emissions results from process-related factors, benchmark reduction rates are relatively less demanding, as is the case with cement and ammonia production figures.

### *2.2. Storage Options*

Carbon dioxide can be securely injected and permanently sequestered within onshore or offshore geological formations, such as depleted oil and gas fields (DOGF) and saline aquifers (SA). To ensure safe containment, these reservoirs must possess sufficient depth, typically exceeding one kilometer, to maintain the injected CO2 in a dense phase due to natural pressure. Moreover, a reliable geological seal must be present above the reservoir, effectively preventing CO2 from escaping into the atmosphere.

Notably, DOGFs currently represent the primary preference for Carbon Capture and Storage (CCS) initiatives, as corroborated by the National Petroleum Council [21]. These fields are well-established and have demonstrated their capacity to store substantial gas volumes without adverse environmental impacts. While capacity estimates vary, the Intergovernmental Panel on Climate Change (IPCC) has approximated that hydrocarbon fields worldwide could potentially offer a storage capacity of 675-900 gigatons of CO2 [22].

On the other hand, saline aquifers, though less recognized, also serve as proven geological storage alternatives, potentially accounting for the majority of global CO2 storage capacity, estimated at 1000-10,000 gigatons [22]. However, as noted by a multinational oil and gas company, onshore saline aquifers often face more stringent environmental impact assessments, designed to mitigate the risks of water contamination and land pollution. Consequently, their utilization can be challenging in practice [22].

### *2.3. Utilization Options*

In Carbon Dioxide (CO2) utilization, the CO2 that has been captured finds application in the production of marketable goods. While a handful of CO2 utilization methods are currently operating profitably, the majority are in the demonstration phase. The potential utilization forms within the scope of this study are elucidated as follows:

Enhanced Oil Recovery (EOR): EOR represents a well-established and regulated mode of industrial CO2 utilization, with over 40 years of practical use. It entails injecting CO2 into the rock reservoirs of oil fields to enhance the recovery of oil and natural gas. The injected CO2 displaces the oil within the rock, getting trapped in the pore spaces due to capillary pressure. For EOR, high purity CO2 (typically at least 95%) is required, primarily to mitigate pipeline corrosion. While most EOR projects presently rely on natural CO2 sourced from underground deposits, it is technically feasible to substitute this with industrial capture sources [23].

Methane Synthesis: Power-to-gas (PtG) technology, utilizing electrolyzed H2 generated from renewable energy, is employed in the synthesis of methane by reacting it with CO2. PtG shows promise in alleviating supply fluctuations inherent in intermittent renewable energy sources. Although the diffusion of PtG is primarily hindered by hydrogen production costs, it holds significant potential as an industrial CO2 utilization method [24]. This technology requires CO2 streams of high purity, and for every ton of CO2, 0.18 tons of H2 are used to produce 0.36 tons of methane [25].

Greenhouse Crop Yield Enhancement: Enriching agricultural greenhouses with CO2 has proven effective in improving crop yields. Crops respond positively to increased CO2 concentrations (up to 500-1200 ppm) by exhibiting higher photosensitization rates and reduced evapotranspiration and stomata conductance, resulting in enhanced crop development while consuming less water. CO2 used in greenhouses is typically sourced from industrial sources or produced on-site by burners within the greenhouse [26]. This application necessitates very high purity CO2, and on average, around 265 tons of CO2 are required per hectare of covered greenhouse space.

Urea Yield Enhancement: Urea, a prominent nitrogen fertilizer, is produced by combining ammonia and CO2 under high pressure and temperature conditions. This process consumes a substantial amount of CO2 (0.75 tons per ton of urea produced), which is often supplied by the CO2 naturally emitted during ammonia production, typically resulting from natural gas refining. However, when natural gas is the feedstock, there is frequently a surplus of ammonia (5-10%), which could be utilized in conjunction with externally sourced CO2 [27]. This offers a potential solution for fertilizer plants specializing in urea production that may face CO2 shortages, which can be mitigated by utilizing CO2 emissions from other facilities.

Sugar Production: In industrial sugar production, impurities from raw sugar juice are removed via a carbonation process. This process necessitates the use of lime milk and pure CO2 (up to 0.36 ton per ton of sugar produced). Currently, most sugar factories produce lime milk on-site using fuel-burning kilns, with some of the CO2 emissions captured and utilized during the carbonation process. However, if lime milk is externally sourced, potentially with lower emission rates, sugar production facilities can become end users of industrial CO2 [28].

## 3. Methodology

In this section we first explain our data collection methodology encompassing the supply chain framework explained in the previous section. Namely, these are for the emission sources, storage sites and the utilization sites. Thereafter we provide our analysis for cost elements regarding carbon capture, transportation and storage costs. We conclude the section by explaining the optimization model used for forming the CO2 clusters.

### *3.1. Data Collection*

#### *3.1.1. Emission Sources*

Data pertaining to industrial CO2 emitters in Southeast Europe have been sourced from the European Pollutant Release and Transfer Database (E-PRTR), as of the March 2021 release. This registry offers comprehensive environmental information gleaned from approximately 30,000 industrial facilities distributed across the European Union Member States, Iceland, Liechtenstein, and Norway. It encompasses essential details such as emitter locations, principal business activities designated by NACE codes, and annual CO2 emission levels. As previously introduced in Section 2, we focus on four emitter categories where capturing technology use is foreseen. Namely, oil and gas refineries, fertilizer plants, iron and steel producers, and cement manufacturers. To facilitate our database search, we have applied the initial selection criteria outlined in Table 2. The implemented search strategy identifies

Table 1: Initial selection criteria for Industrial emitters

| | | |
|---|---|---|
| Country: | Romania, Bulgaria, Greece, Croatia | |
| Activity code (NACE Rev. 2): | 19.20 - Manufacture of refined petroleum products | |
| | 20.15 - Manufacture of fertilisers and nitrogen compounds | |
| | 24.10 - Manufacture of basic iron and steel and of ferro-alloys | |
| | 23.51 - Manufacture of cement | |
| Report year: | later than 2017 | |
| Pollutant name: | Carbon dioxide | |

Table 2: Initial selection criteria for industrial emitters

| **Criterion** | **Value(s)** |
|---|---|
| Country | Romania, Bulgaria, Greece, Croatia |
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| | 23.51 – Manufacture of cement |
| Report year | Later than 2017 |
| Pollutant name | Carbon dioxide |

36 major industrial facilities across the region, collectively emitting over 32 million tons of CO2 annually. These facilities are depicted in Figure 1, with circle sizes corresponding to emission volumes. Cement plants dominate the landscape, with 21 facilities producing a combined total of 14.5 million tons of CO2 per year. Refineries are the second largest contributors, comprising 10 facilities that collectively emit 10.1 million tons annually. Although fewer in number, the four fertilizer plants contribute significantly, with emissions amounting to 2.67 million tons per year. Notably, the region's only steel plant, Liberty Galati in Romania, stands out as the largest single emitter, with annual CO2 emissions reaching 4.1 million tons.

Industrial emitters in Romania and Croatia are relatively evenly distributed. In Romania, clusters still exist, although they are not as concentrated as those in Greece. In contrast, Greece shows a pronounced concentration of industrial facilities, particularly in the Central and Attica regions. Additionally, it's noteworthy that a higher density of emitters is evident in eastern Romania and Bulgaria, particularly in proximity to the Black Sea coastline. For a comprehensive list of these emitters, please refer to the appendix.

#### *3.1.2. Geological Storage Sites*

We identified potential geological storage sites through two primary sources. Initially, we drew upon the database released by Strategy CCUS [29]. This database, a culmination of a three-year EU-funded project that concluded in April 2022, recently cataloged potential CO2 storage sites, primarily small-capacity depleted oil and gas fields, across eight countries, including Romania, Croatia, and Greece. Subsequently, to further enrich the CCUS storage site repository, we incorporated saline aquifers extracted from the reservoir database as part of the ConsenCUS project [5]. Additionally, within the scope of the GeoCapacity project [30], we unearthed a prospective Bulgarian storage site known as "Galata."

Figure 2 displays the geographic distribution of all identified geological storage sites across the four countries. The region features a substantial presence of deep saline aquifers, characterized by both numerous locations and considerable storage capacities.

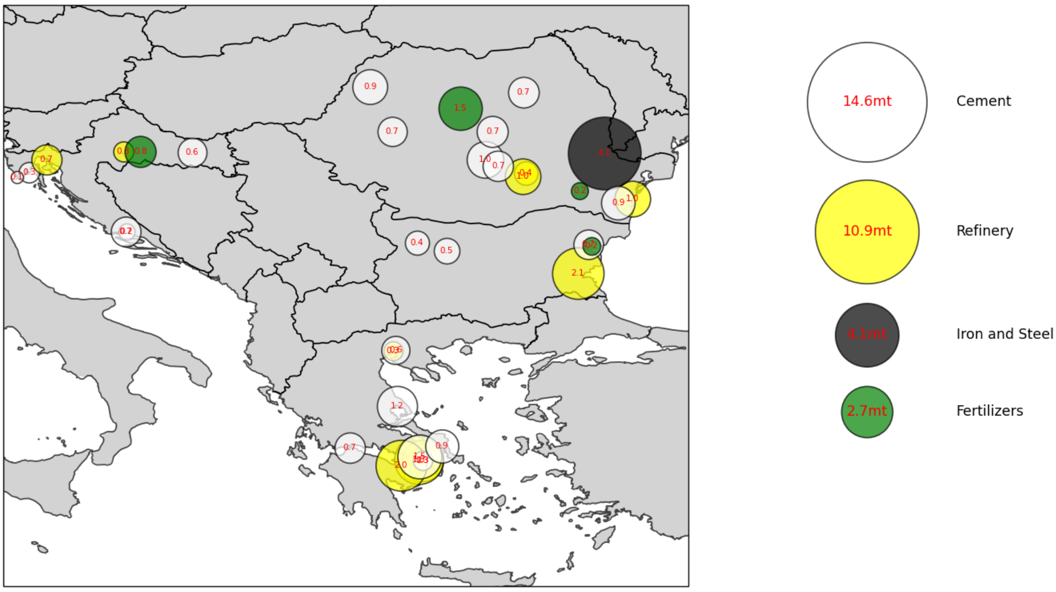



Figure 1: Industrial emitters (left), and their corresponding emission magnitudes (left). Aggregated emission for each sector (right) in million tons.

Depleted oil and gas fields, on the other hand, are predominantly concentrated in Croatia (125 million tons), with additional sites in Romania (45 million tons), Bulgaria (6 million tons), and Greece (2 million tons). It is important to note that these figures reflect storage sites cataloged in EU-wide databases. Storage capacity estimations for CCUS are inherently uncertain, as they depend on a range of assumptions about geological formations, reservoir integrity, and injectivity. As such, different sources may report varying outcomes based on the scope, resolution, and methodology of their assessments. For a comprehensive breakdown of the identified storage sites, please refer to the appendix.

### *3.1.3. Utilization Sites*

Given the fledgling state of the CO2 market, the identification of CO2 utilization sites necessitates a meticulous, case-by-case approach. For those utilization methods that have already achieved commercial viability, valuable insights can be gleaned from corporate registries like the ORBIS database. When evaluating prospective avenues for CO2 utilization, we turn to planned projects and the expertise of industry professionals.

In our endeavor to conduct a methodical database search for businesses capable of harnessing industrial CO2 emissions, we have harnessed the resources of the ORBIS database (version 218, as of January 2022), applying the specific search criteria delineated in Table 3.

Table 3: Selection criteria: CO2 utilization sites

| | |
|---|---|
| Country: | Romania, Bulgaria, Greece, Croatia |
| Activity code (NACE Rev. 2): | 01.13 - Growing of fruit, nuts, beverage and spice crops<br>20.15 - Manufacture of fertilisers and nitrogen compounds<br>10.81 - Manufacture of sugar<br>06.10 - Extraction of crude petroleum |
| Annual revenue: | minimum €1 million |
| Activity description in English: | available |
| Website: | available |

The search strategy yielded a total of 93 potential utilization sites. Upon closer examination of these sites, it became apparent that 73 of them were fertilizer plants, coinciding with those already accounted for among the emitters. As these plants are likely to have an internal CO2 supply, they were excluded from the distribution network. After this adjustment, the analysis identified 8 companies as potential CO2 delivery destinations as shown in Figure 3. Among these, 5 are greenhouses, and the remaining 3 are sugar factories. These selected entities were then integrated into the simulations and subjected to more comprehensive scrutiny. To determine their CO2 utilization capacities, we estimated their capabilities based on production metrics.

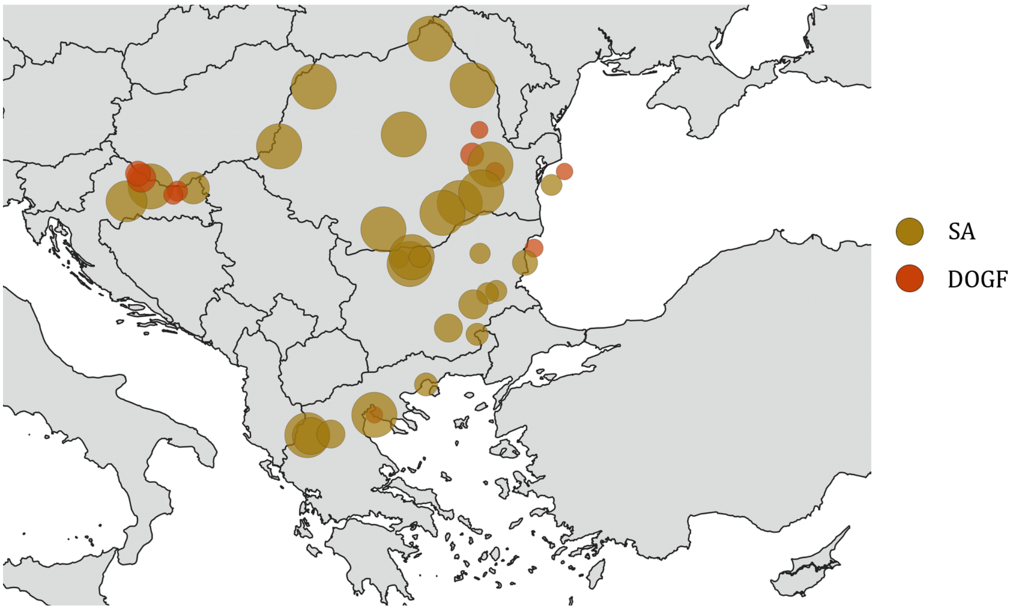



Figure 2: Geological storage locations

In addition to the aforementioned sites, our analysis also incorporates two forthcoming green hydrogen projects: the Danube electrolyser in Romania and the 'White Dragon' project in Greece. We assume that 50% of the hydrogen (H2) produced by these projects can be employed for methane synthesis, thereby allowing us to estimate the electrolysers' potential CO2 uptake. A comprehensive list of the identified utilization sites is available in the appendix.

### *3.2. Cost Analysis*

#### *3.2.1. Capture Costs*

The capture costs at the identified emission point sources have been established through reference to the findings of a report from the US National Energy Technology Laboratory [20]. Insights into the cost implications of carbon capture in various industrial contexts, encompassing cement kilns, steel furnaces, refinery H2 production units, and ammonia production plants, have been analyzed in this report. This analysis incorporates the use of methyldiethanolamine (MDEA) solvent-based post-combustion systems, as indicated in Table 4.

Table 4: Capture cost estimation, retrieved from [20], and [31]

| Point source | Cement Kiln-off gas | Iron and steel COG, BFS, PPS | Refinery H2 production | Fertilizer CO2 stripper vent |
|---|---|---|---|---|
| CO2 purity | 22.40% | 26.40% | 44.50% | 97.10% |
| Capture rate | 50% | 60% | 80% | 98% |
| Reference quantity Co2 captured (t/year) | 1,140,697 | 2,754,966 | 232,781 | 458,400 |
| Capital charges ($/ton) | 32.89 | 33.66 | 43.43 | 10.44 |
| Fixed O&M ($/ton) | 9.99 | 10.23 | 13.2 | 3.69 |
| Total fixed costs ($/ton) | 43 | 44 | 56.6 | 14 |
| Total fixed costs (€/ton) | 37 | 38 | 49.2 | 12 |
| Variable O&M ($/ton) | 14.99 | 15.34 | 19.81 | 5.54 |
| Consumables ($/ton) | 2.54 | 2.67 | 2.84 | 0.2 |
| Energy used ($/ton) | 16.58 | 17.89 | 20.72 | 11.19 |
| Purchased natural gas ($/ton) | 33.88 | 35.81 | 36 | 0 |
| Total variable costs ($/ton) | 67.99 | 71.71 | 79.06 | 16.93 |
| Total variable costs (€/ton) | 59.12 | 62.36 | 68.75 | 14.72 |
| Total ($/ton) | 110.87 | 115.60 | 135.69 | 31.06 |
| Total (€/ton) | 96 | 101 | 118 | 27 |

Certain adjustments have been made to the authors' cost estimations concerning energy-related factors taking into account the regional specifics. Specifically, we have set that power can be procured at a rate of €90 per megawatt-hour (MWh), and the cost

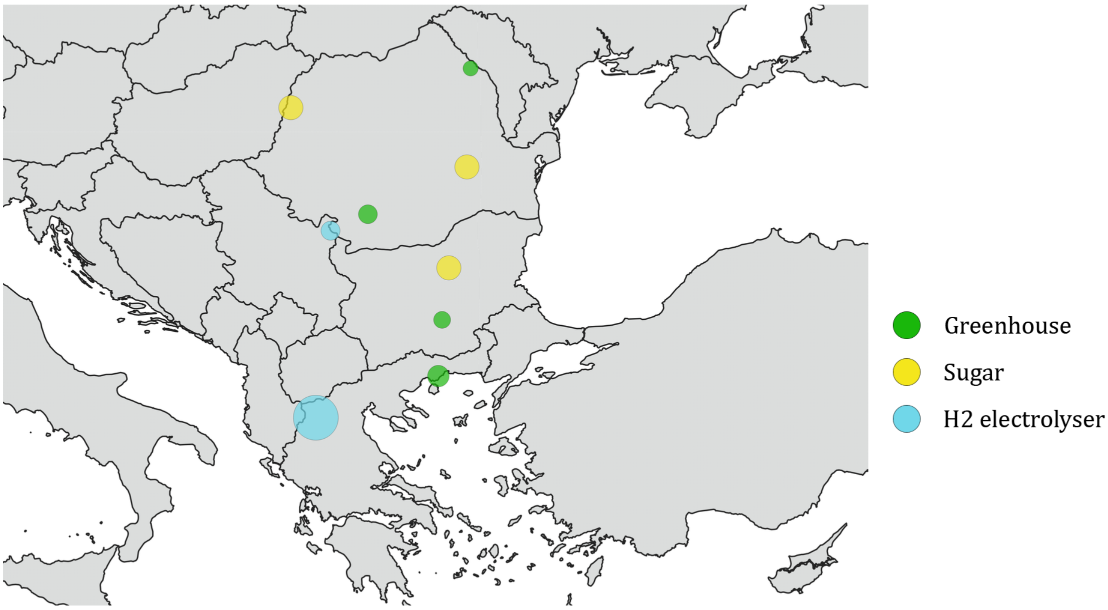



Figure 3: Utilization sites

of natural gas employed in the solvent regeneration process is approximated at €7 per million British thermal units (MMBtu). It is important to note that the cost breakdown vividly underscores the considerable impact of energy prices on the economics of carbon capture. At the specified price levels, expenses related to power and natural gas collectively contribute to up to 46% of the overall capture costs. This is noteworthy, particularly given that MDEA-based systems are estimated to require 35% less energy for solvent regeneration compared to the more prevalent monoethanolamine (MEA) counterpart [32].

As we move into the 2020s, the economic feasibility of Carbon Capture, Utilization, and Storage (CCUS) in Europe is poised to be contingent on the prevailing conditions of both the energy and, of paramount importance, the natural gas markets. At mid-2022 energy prices, the variable costs associated with carbon capture witness a notable surge, escalating by 150-200%, essentially doubling the total cost per ton captured when contrasted with the figures presented in Table 5. On the positive side, advances in capture technologies have the potential to offset some of the impacts of the energy price increase. However, it's worth noting that the energy efficiency potential of existing MDEA-based systems has not been extensively explored. Nonetheless, refined MEA-based carbon separation methods may yield lower operating costs. Various combinations of MEA solvents, along with the introduction of acid catalysts, have been proposed to achieve reductions in heat duty ranging from 50% to 66% when compared to baseline 5M MEA systems [13], [33]. Further energy savings can be attained through strategies such as flue gas splitting (7.4% reduction as determined by [34]) and enhanced waste heat recovery (with potential savings of up to 21.7% according to Tu et al. [35]).

### *3.2.2. Transportation Costs*

We consider two modes of transportation: pipeline and tanker. Regarding pipeline transport, the construction costs have been sourced from the research conducted by Mallon et al. [36] and Serpa et al. [37]. The capacity estimates draw from the findings presented by Poiencot and Brown [38]. As for operational expenses (OPEX) and the estimation of pumping station costs, we have referred to the cost analysis conducted by Knoope [11].

Table 5: Transport cost estimates

| | Pipeline | | | Pumping station | | | |
|---|---|---|---|---|---|---|---|
| | CAPEX | O&M | Capacity | CAPEX | Fixed O&M | Variable O&M | Energy |
| Inch | €/km/year | €/km/year | Mt/year | €/year | €/year | €/ton | €/ton |
| 4 | 18667 | 653 | 0.29 | 57065 | 14266 | 0.073 | 0.09 |
| 6 | 19400 | 679 | 0.66 | 128397 | 32099 | 0.073 | 0.09 |
| 8 | 22667 | 793 | 1.39 | 271059 | 67765 | 0.073 | 0.09 |
| 10 | 24333 | 852 | 2.10 | 410156 | 102539 | 0.073 | 0.09 |
| 12 | 26400 | 924 | 2.37 | 463654 | 115914 | 0.073 | 0.09 |
| 16 | 30933 | 1083 | 4.93 | 962974 | 240744 | 0.073 | 0.09 |
| 20 | 34667 | 1213 | 7.30 | 1426629 | 356657 | 0.073 | 0.09 |

We have derived our cost estimates for truck tanker transportation from the insights presented by [39]. We set that each truck has a tanker capacity of 18 tons, and the cost of transporting a tanker of CO2 is €2 per kilometer in marginal costs, equating to a fixed rate of €0.11 per kilometer per ton. This 11-cent figure aligns with the findings of [40]. Using the EU regulations [41] for truck drivers hours, and averaging the 1,2, and 3 shifts for trucks, we derive that the average working hours of one truck is 5,000 hours a year. Denote with $d(i, j)$ the distance between the nodes $i$ and $j$, and let $s(i, j)$ denote the average speed of the truck from $i$ to $j$. With the current pumping capacity of 20 tons per hour, the loading times for each truck will be around 1.25 hours, and hence the number of trucks used from point $i$ to $j$ will be derived by:

$$\left\lceil \frac{f(i,j)\left(\frac{d(i,j)}{s(i,j)} + 1.25\right)}{25 \times 5000} \right\rceil, \tag{1}$$

where $f(i, j)$ is the amount of CO2 transported from node $i$ to $j$.

The truck fixed, and variable cost for a year is considered using the annual salaries for truck drivers, shifts it covers, fuel costs, and the maintenance costs. We present the formulas in the table below, and in addition, we computed the costs based on the EU working regulations, and salaries are averaged for the countries. Where $DP$ is the depreciation per km(we assumed a lifetime of $1,000000km$ for the truck, and a resale value of around $15 - 20\%$ of the original price. This gives a value of around € 0.11. the values of depreciation and maintance are fixed for all the countries, but the wages do vary– for Greece the number is 0.17, whereas for the rest of the countries we averaged on 0.12. The maintenance is €0.18 per km. In addition to this, we will denote $N_{ij}$ the number of trucks needed to go from $i$ to $j$, and the fixed cost to "building" a truck fleet that transfers from the two arcs, will be $0.28N_{ij}$.

Truck transport is widely regarded as a viable option for transporting smaller quantities. However, it's crucial to acknowledge that at the scale of Carbon Capture and Storage (CCS), challenges such as CO2 leakage and complications related to high-pressure injection can lead to increased overall costs, as emphasized in expert discussions.

#### *3.2.3. Storage Costs*

Storage cost estimation is another challenge, as geological storage sites have their own location specific characteristics. The figures used – presented in Table 6 – are based on ZEP [42].

Table 6: Storage cost estimates

| | onshore-DOGF | | | offshore-DOGF | | | onshore-SA | | | offshore-SA | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Injection rate: | 1 Mta | 3 Mta | 5 Mta | 1 Mta | 3 Mta | 5 Mta | 1 Mta | 3 Mta | 5 Mta | 1 Mta | 3 Mta | 5 Mta |
| CAPEX: | 4 € | 3 € | 2 € | 8 € | 6 € | 4 € | 7 € | 5 € | 4 € | 14 € | 10 € | 6 € |
| OPEX: | 2 € | 2 € | 2 € | 3 € | 3 € | 3 € | 4 € | 4 € | 4 € | 5 € | 5 € | 5 € |
| Total costs: | 6 € | 5 € | 4 € | 11 € | 9 € | 7 € | 11 € | 9 € | 8 € | 19 € | 15 € | 11 € |

Broadly, it is commonly observed that onshore storage sites tend to be more cost-effective than their offshore counterparts, and within the onshore category, depleted oil and gas fields are typically regarded as a more economical choice compared to saline aquifers. In fact, expert discussions have affirmed that the expense associated with storing CO2 in saline aquifers is approximately twice that of depleted hydrocarbon fields. Nevertheless, it is essential to recognize that the expenses related to preparing depleted oil and gas fields may fluctuate, contingent upon the number of legacy wells requiring reinforcement to withstand the pressure exerted by CO2 injection. In contrast, saline aquifer storage sites, although entailing significant initial investment and typically lacking existing infrastructure, possess the advantage of avoiding decommissioning costs and offer potential economies of scale.

### *3.3. Optimization Model*

In this subsection, we develop a mixed-integer linear programming model to determine the least-cost way of capturing and storing away/utilising a predefined amount of CO2 emissions. Specifically, we address the key decisions such as how much CO2 should be captured at each node, which storage or utilization site to target. Our optimization model supports multiple transit modes, allowing for seamless transitions. For instance, if sea transport is required, the truck mode can be switched to ferry mode. Like trucks, ships also use cryogenic tanks to transport CO2, but on a much larger scale. These ships are specifically designed to carry large volumes of liquefied CO2, equipped with temperature and pressure control systems to ensure it remains in liquid form. In our model, transport costs are used to account for the impact of different modes.

The transportation network considered is denoted with $D = (N, A)$. A node $n \in N$ represents possible locations for CO2 sources, utilization sites, geological storage sites and fictional nodes for the different transportation methods. An arc $(i, j) \in A$ indicates the potential connection between locations $i$ and $j$. For the convenience of model formulation, we introduce a dummy source $u$ and sink $v$. The notation of the model is summarized in the tables 7,8,9 as follows

Table 7: List of Sets

| **List of Sets:** | |
|---|---|
| $N$ | Set of nodes |
| $N_s$ | Set of storage nodes |
| $N_u$ | Set of utilization nodes |

Table 8: List of Parameters

| **List of parameters:** | |
|---|---|
| $M_{ij}^k$ | maximum capacity of arc $(i, j)$ under mode $k$ |
| $F_{ij}^k$ | environmental cost for constructing arc $(i, j)$ under mode $k$ |
| $E_{ij}^k$ | environmental cost for constructing arc $(i, j)$ under mode $k$ |
| $E_j^s$ | environmental cost for storing at location $k$ interpreted as a tax credit for CO2 stored |
| $c_{ij}^k$ | transportation of one ton of CO2 flowing through arc $(i, j)$ under mode $k$ |
| $S_k$ | storage cost at location $k$ |
| $s_i^v$ | variable cost for capture at node $i$ |
| $s_i^f$ | fixed cost for capturing at node $i$ |
| $U_k$ | utilization cost at location $k$ |
| $Q$ | CO2 reduction target |
| $C_k^s$ | storage capacity at location $k$ |
| $D_k^s$ | demanded utilization at location $k$ |
| $TE_i$ | Total emissions at the source node $i$ |
| $cp_i$ | Capture rate at the source node $i$ |

Table 9: List of decision variables

| **List of decision variables:** | |
|---|---|
| $x_{ij}^p$ | the amount of CO2 flowing through arc $(i,j)$ of the mode of pipeline |
| $y_{ij}^p$ | indication of whether an arc $(i,j)$ of pipeline is constructed ($y_{ij}$=1) or not ($y_{ij}$=0) |
| $x_{ij}^t$ | the amount of CO2 flowing through arc $(i,j)$ of the mode of truck |
| $y_{ij}^t$ | indication of whether an arc $(i,j)$ of truck transportation is constructed ($y_{ij}$=1) or not ($y_{ij}$=0) |
| $x_{ij}^f$ | the amount of CO2 flowing through arc $(i,j)$ of the mode of ferry |
| $y_{ij}^f$ | indication of whether an arc $(i,j)$ of ferry is constructed ($y_{ij}$=1) or not ($y_{ij}$=0) |
| $y_i^c$ | the opening or closing of the CO2 capture at the source node $i$ |
| $x_i^c$ | the amount of CO2 captured at source node $i$ |

To simplify the presentation of the flow conservation nodes, we will denote with $b_i$ the following:

$$b_i = \begin{cases} -x_i^c, & \text{for } i \in N_e \\ C_k^s, & \text{for } i \in N_s \\ D_k^u, & \text{for } i \in N_u \\ 0, & \text{else} \end{cases} \quad (2)$$

Then our model can be written as following:

$$
\begin{aligned}
\min \quad & \sum_{(i,j)\in A}\left[(F^p_{ij}+E^p_{ij})y^p_{ij}+c^p_{ij}x^p_{ij}\right]+\sum_{(i,j)\in A}\left[(F^t_{ij}+E^t_{ij})y^t_{ij}+c^t_{ij}x^t_{ij}\right]+\\
& \sum_{(i,j)\in A}\left[(F^f_{ij}+E^f_{ij})y^f_{ij}+c^f_{ij}x^f_{ij}\right]+\sum_{i\in N}\left[s^f_i y^c_i+s^v_i x^c_i\right]\\
& \sum_{j\in N_s}(S_j-E^s_j)\sum_{(i,j)\in A, i\neq j}(x^p_{ij}+x^t_{ij}+x^f_{ij})-\\
& \sum_{j\in N_u}U_j\sum_{(i,j)\in A, i\neq j}(x^p_{ij}+x^t_{ij}+x^f_{ij}) \qquad (3)\\
s.t. \quad & \\
& \sum_{j:(i,j)\in A}\left(x^p_{ij}+x^t_{ij}+x^f_{ij}\right)-\sum_{j:(j,i)\in A}\left(x^p_{ij}+x^t_{ij}+x^f_{ij}\right)=b_i \qquad (4)\\
& \sum_{(i,j)\in A, i\neq j}(x^p_{ij}+x^t_{ij}+x^f_{ij})\le C^s_j, \quad \forall j\in N_s \qquad (5)\\
& \sum_{(i,j)\in A, i\neq j}(x^p_{ij}+x^t_{ij}+x^f_{ij})=D^u_j, \quad \forall j\in N_u \qquad (6)\\
& x^p_{ij}+x^t_{ij}+x^f_{ij}\le M^p_{ij}\times y^p_{ij}+M^t_{ij}\times y^t_{ij}+M^f_{ij}\times y^f_{ij} \quad \forall (i,j)\in A \qquad (7)\\
& 0\le x^c_i\le cp_iTE_iy^c_i \qquad (8)\\
& \sum_{j\in N_s}\sum_{(i,k)\in A, i\neq j}(x^p_{ij}+x^t_{ij}+x^f_{ij})+\sum_{j\in N_u}\sum_{(i,j)\in A, i\neq j}(x^p_{ij}+x^t_{ij}+x^f_{ij})\ge Q \qquad (9)\\
& y^p_{ij}+y^t_{ij}+y^f_{ij}\le 1 \quad \forall (i,j)\in A \qquad (10)\\
& y^p_{ij},y^t_{ij},y^f_{ij},y^c_i\in\{0,1\} \quad \forall (i,j)\in A \qquad (11)\\
& x^p_{ij},x^t_{ij},x^f_{ij}\ge 0 \quad \forall (i,j)\in A. \qquad (12)
\end{aligned}
$$

The objective function (3) minimizes the total fixed and variable costs of CO2 capture, transport and storage. In particular, the fixed cost consists of the infrastructure and environmental costs and the variable costs consists of transportation, storage, and utilization costs. Constraint (4) ensures the conservation of flow, i.e., the sum of the incoming flows equals to the sum of outgoing flows at each node except for the dummy nodes. Equations (5)-(6) correspond to the flow being sent to the sink nodes (storage and utilizer). Constraint (7) makes sure that arcs are built before used and that the flow on each arc does not exceed its maximum capacity. Constraint (8) forces the capture limit at the each source node. Constraint (9) enforces that the total flow quantity within the network should be no less than the predefined CO2 emission reduction target. The constraint (10) ensures that we pick only one transportation mode. Constraint (11) defines $y_{ij}$ as a binary variable, and finally, constraint (12) ensures the non-negativity for $x_{ij}$. In addition to the constraints above, we also add the constraints for the different pipeline diameters we use. We denote with $y^{p_i}_{ij}$ the binary decision corresponding to whether to build the pipeline with diameter $p_i$ for $i\in\{1,2,..,L\}$. To make sure we make the optimal decision on which pipeline to built, and of what diameter, we add the constraints

$$\sum_{k\in\{1,2,..,L\}} y^{p_k}_{ij}\le 1, \quad \forall (i,j)\in A. \qquad (13)$$

## 4. Scenario Development and Results

To gain thorough insights into the Carbon Capture, Utilization, and Storage (CCUS) potential in the region and to assess the incentivizing impact of the EU Emissions Trading Scheme (ETS), we conducted simulations with two main settings: a restricted scenario and an ample scenario.

In the restricted scenario, we consider currently available or soon-to-be-realizable CCUS opportunities. This involves the utilization of depleted oil and gas fields for CO2 storage, with annual injection rates capped at 1 million tons per annum (Mta), consistent with the scale of ongoing project developments [4]. Greenhouses are already incorporated as end-users of CO2, and power-to-methane facilities at electrolysers operate at limited capacities.

The ample scenarios explore the regional CCUS potential under more favorable conditions for deployments. We assume that depleted oil and gas field storage sites are supplemented with saline aquifer CO2 repositories with capacities of up to 5 Mta.

Utilization options are expanded to include hydrogen (H2) electrolysers operating at their design capacity, along with sugar factories that have adjusted their manufacturing processes to source CO2 externally.

For each of the selected countries, we determine the optimal CCUS supply chains and their corresponding cost levels based on the following assumptions: (I) The amount of CO2 available for capture at each industrial facility can be estimated as outlined in Section 1; (II) Capture facilities are designed to capture all capturable CO2 emissions; (III) Available transportation methods include 4-, 6-, 8-, and 16-inch diameter pipelines and tanker transport; (IV) Annual storage capacities are calculated with a 30-year operating life for the storage sites and are capped according to the timeframe. In each scenario, the model identifies cost-optimal source-sink pairs and provides annualized cost estimates for implementing the system over a 30-year period. In cases where total emissions surpass available sink capacities, the model aims to maximize reservoir utilization. When a country's storage and utilization capacities can accommodate all industrial emissions, the model determines the total CO2 mitigation. We use a dummy storage node to add excess $CO2$ that a country has no capacity to store, and it has to either pay a carbon tax, or buy allowances.

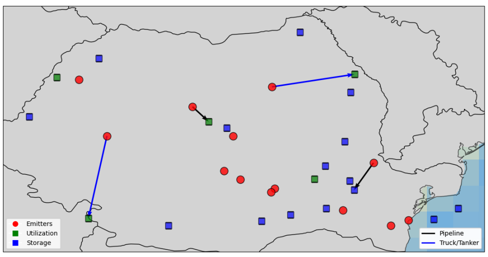
The assessment of the EU ETS scheme's incentivizing effect is conducted as follows. First, for each emitter, capturable emission levels are compared to the allocated free ETS allowances. In the restricted scenario, the current (Phase IV: 2021-2025) free ETS allowances, as published by the European Commission [43], are employed. In the ample scenario, the 2050 level of free ETS allowances is estimated, assuming that sectoral benchmarks will continue to decrease as specified by the European Commission. Second, the CCUS supply chains are optimized under the assumption that only emissions exceeding the free ETS allowances are considered for carbon capture. This is based on the premise that emitters may not engage in carbon capture development unless compelled to do so. Finally, the extent to which free allowances may distort carbon capture investments is assessed by comparing the standard cost-optimal results with ETS-driven average cost levels. A summary of the results is presented in the subsequent sections for each country.

All computations were performed on a desktop with an Intel Core i7-8650U CPU (8 cores, 1.9 GHz), 64 GB RAM, and a 256GB SSD, running Windows 11. The model was implemented in Python 3.11 using Gurobi 12.0.1 as the solver.

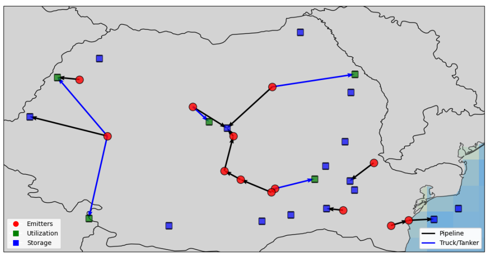
### *4.1. Romania*

In this subsection we explain the Optimal CCUS supply chain for Romania. As of 2019, Romania's annual industrial CO2 emissions were estimated at 25 million tons [44]. Out of this total, over 50%, approximately 13.9 million tons, was attributed to the thirteen large-scale emitters considered in this analysis. Among these emitters, cement factories are the most numerous, and the integrated steel plant, Liberty Galati, stands out as the country's largest emitter, contributing 4 million tons annually. These selected emission points have the potential to capture up to 6.5 million tons of CO2, resulting in a 26% reduction in the overall industrial emissions. The optimal CCUS network for the both scenarios is illustrated in Figure 4.

Initially, Romania has the capacity to prepare depleted oil and gas fields with a total capacity of 1.5 million tons per annum (Mta) for CO2 storage. However, this storage capacity significantly falls short of the country's capturable industrial CO2 emissions, which amount to 6.5 Mta. Consequently, we predict that all available sinks can be filled by the emissions of two fertilizer plants (RO3 and RO13) and two cement plants (RO6 and RO10) at an estimated annualized total cost of €112 million, equivalent to €73 per ton of CO2 avoided. Unfortunately, two major emitters, the largest fertilizer plant in the supply chain, Azomures' RO13, and CRH's cement plant, RO10, are separated from the depleted oil and gas field storage sites by the Carpathians, which, in practice, could significantly increase the costs of building pipelines between these source-sink pairs. while storage costs amount to €9.3 million per year. As depicted in figure below, there are only two short pipeline decisions to be build. One From Liberty Galati to the RO-S-4, and the other is from the fertilizer plan Azomures to the greenhouse RU-U-2. These pipelines are of diameter 6, and 4 respectively. The remaining of $CO2$ can be transported using trucks. The total cost is accounted at €409.536 million, which then for the time period of 30 years, becomes €13.5 million, while the storage costs amount to €1.74 million. Additionally, two




(a) Romania-restricted scenario




(b) Romania-ample scenario

Figure 4: Comparison of Romania scenarios: restricted and ample.

potential utilization-candidate greenhouses (RO-U-1 and RO-U-2) are identified in the ORBIS database, with a combined potential $CO_2$ demand of twenty thousand tons per year. Of particular interest is Sere Isalnita's 150-hectare cucumber greenhouse complex near Craiova (RO-U-2), which holds promise as a utilization site candidate due to the known positive response of crops to $CO_2$ enrichment (Kläring et al., 2007). Furthermore, Hidroelectrica's first electrolyser (RO-U-5) is expected to commence operation by 2026. Located on the island of Ostrovu Mare, this facility is anticipated to produce 7,500 tons of $H_2$ using the Danube's water, potentially creating demand for an additional twenty thousand tons of industrial $CO_2$, assuming that 50% of this will be utilized for methane synthesis (Ernst, 2021). While none of the utilization sites are in close proximity to the selected emission points, the two sites situated in southeast Romania could potentially source $CO_2$ from the biorefineries at Craiova and Calafat, as identified in the DataM biorefinery database [45].

When accounting for free ETS allowances, the landscape of CCUS deployment in Romania undergoes significant changes. For instance, Chemgas' fertilizer plant (RO3) appears capable of maintaining its $CO_2$ emissions below its Phase IV free ETS allowance levels. Due to the low allowance reduction rate in ammonia production, it is unlikely to face an allowance shortage by 2030. We note that by the time of the reporting the fertilizer plant has stopped its operations. On the other hand, the remaining emitters are expected to require substantial emission reduction measures (ranging from 17% to 53% of current emission levels) to stay within their 2030 allowances. Nevertheless, these reductions may not be significant enough to stimulate large-scale carbon capture developments. If only emissions above the free allowances are subject to carbon capture, Romania's 1.5 Mta storage capacity can be utilized at an annual total cost of €164 million, equivalent to €106 per ton. This cost is higher than that of the cost-optimal scenario, primarily because 58% of the emissions in the cost-optimal supply chains (0.89 Mta) can still be covered by free quota allocations.

By 2050, Romania will have a yearly storage capacity far exceeding its industrial emissions due to its vast deep saline aquifers, totaling 14,000 million tons (Mt). From a practical perspective, it is unlikely that opening four saline aquifer (SA) storage sites in southeast Romania—RO-S-15, RO-S-8, RO-S-14, and RO-S-13—is worthwhile. However, a single large $CO_2$ repository on the Wallachian Plain, such as RO-S-13 with a capacity of up to 5 Mta, can effectively serve the Liberty Galati steel plant (RO2) and all neighboring industrial facilities. If terrain conditions allow, the centrally located RO-S-10 could accommodate the country's remaining $CO_2$ emissions, eliminating the need for extensive pipelines between the Transylvanian basin and the Sud-Est.

The two sugar factories (RO-U-3 and RO-U-4) can also become recipients of industrial $CO_2$ if their lime production is outsourced. Both Agrana Romania and Zahărul Oradea produce approximately 250 thousand tons of sugar annually, requiring an estimated 180 thousand tons of $CO_2$ for carbonization. It is worth noting that both the $H_2$ electrolyzer at the Iron Gate (RO-U-5), assumed to utilize at least 80 thousand tons of $CO_2$ by 2050, and greenhouse RO-U-2 are now disconnected from the system. This indicates the need for alternative $CO_2$ sources for these smaller utilization sites.

The pipeline decisions for Romania are mainly of diameter 4, and 6. However, from Liberty Galati (RO2) to the Pontian - Moesian Platform (RO-S-14), and from the fertilizers SC AZOMURES SA (RO13) to the storage sites in Middle Jurassic - Moesian Platform (RO-S-16) the model favours the construction of pipelines of diameter 16. The remaining of the emissions can be transported using trucks, and the maximum number of trucks operating at the assumptions we have explained before, is 100.

As for the presented CCUS supply chain, it is estimated that the annualized total cost of avoiding Romania's total 6.5 Mta capturable industrial $CO_2$ emissions at ample scenario capture cost levels is €591 million. This translates into costs of €90 per ton of $CO_2$ avoided.

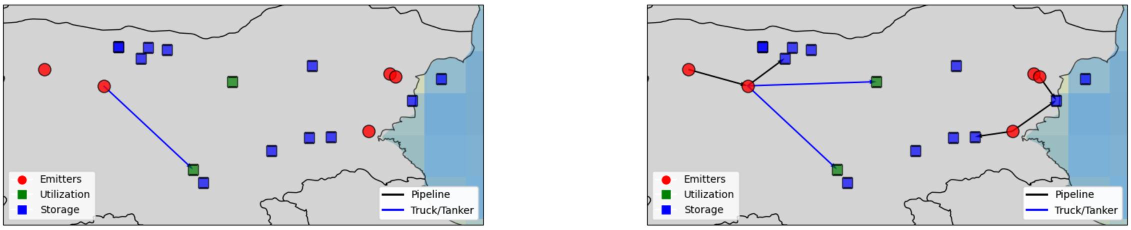
Due to the reduction of free ETS allowances, by 2050 all considered Romanian emitters could run at allowance deficits of up to 74%. These deficits can be significantly reduced through CCUS projects, although only a 5.6 Mta reduction in emissions is predicted to be incentivized at the current allowance reduction rates. Fertilizer plants, Liberty Galati, and the CRH and Holcim cement plants can meet their predicted emission reduction targets with carbon capture alone. The region's less efficient cement plants can also reduce their ETS quota purchases by up to 90%. Refineries, on the other hand, will need to find other means of emission mitigation, as their allowance deficits of 51-69% could only be reduced by 15 percentage points through CCUS. The total emission reduction of 5.6 Mta is estimated to cost an annualized €534 million, equivalent to €96 per ton of $CO_2$ avoided. The deviation from the cost-optimal average break-even ETS price decreases as the weight of uncaptured emissions within the fertilizer industry becomes less significant.

### *4.2. Bulgaria*

Bulgarian industrial facilities contributed to global $CO_2$ emissions by 7.78 Mt in 2019, led by Lukoil's refinery complex at Burgas that emitted over 2 million tons of $CO_2$ [44]. The five selected large-scale emitters (one fertilizer plant, one refinery and three cement plants) together accounted for roughly 3.9 Mta, more than a quarter of which may be avoidable applying CCUS. We illustrate the optimal CCUS network in Figure 5.

Short-term storage opportunities in Bulgaria, such as the use of depleted hydrocarbon fields, are limited. The only emitter to be able to cost efficiently is the Cement Company BG5 that uses trucks as mode of transportation at the cost €2360. Furthermore, the country's oil exploration activities are constrained, and only two depleted gas fields with suitable depths for $CO_2$ storage have been identified. The Chiren gas field, situated in Northwest Bulgaria, was converted into a natural gas storage site in 1974 and is currently being planned to continue serving its function with extended capacity [European Commission, 2022]. In contrast, the Galata offshore gas field (BG-S-1-off), which once supplied 16% of Bulgaria's gas needs, could potentially be utilized for CO2 storage by 2030, creating a capacity of 0.2 million tons per annum (Mta) for the country. Additionally, a small greenhouse (BG-U-1) in central Bulgaria could add 6,000 tons of annual sink capacity. Agropolychim's fertilizer plant (BG3) and Denvnya cement (BG2) were selected as the least-cost CO2 sources for the system, which could achieve a mitigation of 0.21 Mta of CO2 at an annualized total cost of €21 million, equivalent to €102 per ton. Transportation costs amount to €3 million, and storage is predicted to cost €2.2 million per year. Despite the seemingly modest scale of emission reduction, the establishment of a Carbon Capture and Storage (CCS) cluster in East Bulgaria with the Galata depleted oil and gas field could be a realistic first step for the country. Utilizing CCUS in parallel with other emission reduction measures, Galata's storage capacity of up to 6 million tons can potentially accommodate all capturable emissions of the two emitters. While CO2 mitigation costs are relatively high at €95 per ton, it could potentially be reduced by excluding the utilization site BG-U-1 (thereby avoiding long-distance truck transport) and by developing shared pipelines.

Free ETS allowances, however, are projected to exempt Agropolychim's fertilizer plant and Denvnya cement from the need to implement carbon capture in the mid-term. By 2030, these industrial facilities are expected to emit below their free emission allowances. This illustrates how energy-efficient manufacturing processes and modernized equipment can significantly contribute to CO2 emission reduction. For instance, Denvnya cement utilizes non-reusable waste as low-carbon fuel in its cement kilns, which, combined with other energy-saving measures, leads to substantially lower CO2 emissions compared to its competitors. On the other hand, without the two cost-optimal CO2 sources, Bulgaria's 0.21 Mta CO2 storage capacity can only be utilized to a limited extent.




(a) Bulgaria-restricted scenario

(b) Bulgaria-ample scenario

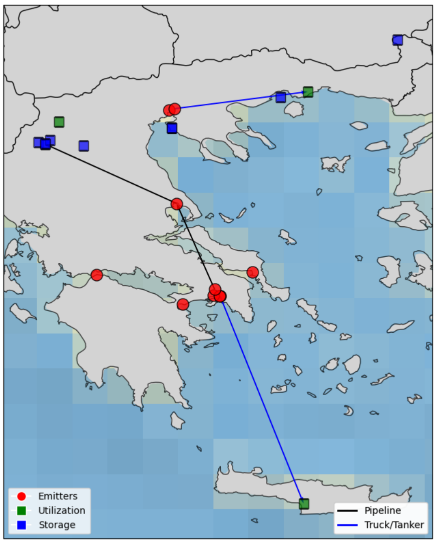
Figure 5: Comparison of Bulgaria scenarios: restricted and ample.

By 2050, Bulgaria is expected to have a combined CO2 storage and utilization capacity exceeding 19 million tons annually. With this substantial capacity, which greatly surpasses the country's total capturable industrial emissions, the opening of just two to three saline aquifer storage sites at a smaller scale will be sufficient to accommodate the country's entire 1.1 million tons of captured emissions. In addition to the Galata gas field, the Dolna Kamchia basin (BG-S-7) can function as the central repository for the Eastern cluster. Should the establishment of small-scale saline aquifer storage sites present disproportionately high costs or environmental concerns, Lukoil's refinery unit (BG1) can also be integrated into the potentially high-capacity BG-S-7 with minimal additional cost. In Northwest Bulgaria, both HOLCIN cement (BG4) and TITAN cement (BG5) can be optimally linked to a saline aquifer storage site near Pleven (BG-S-2), forming a second Carbon Capture and Storage (CCS) cluster. However, utilization sites once again become disconnected from the optimal CCUS supply chain due to their central locations, which are far from the studied CO2 sources. With three saline aquifer storage sites in operation, total emission mitigation can be achieved at an annualized total cost of €103 million, equivalent to €94.6 per ton of CO2 avoided. Transportation costs are estimated at an annualized €6.7 million, while storage costs account for €10 million per year. Maintaining an average sub-€100 break-even Emission Trading System (ETS) price is possible with the assumed 30% reduction in carbon capture fixed costs.

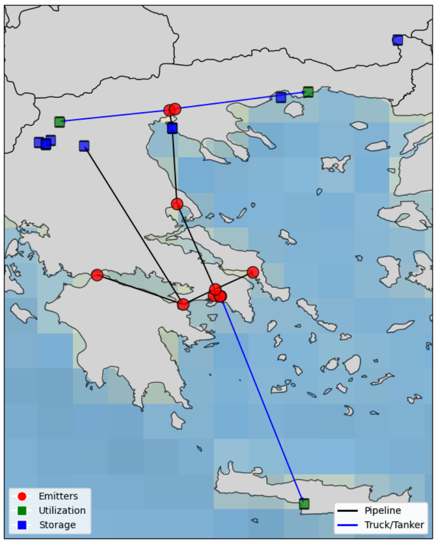
As free ETS allowances diminish by mid-century, most Bulgarian emitters will require carbon capture to meet their emission reduction targets. The only exception is Agropolychim's fertilizer plant (BG3), as its total emissions are expected to remain covered by free allowances. Denvnya cement's (BG2) ETS deficit could reach 36%, while the remaining emitters will need to purchase allowances for 37-83% of their CO2 emissions. In total, the ETS scheme incentivizes a nearly complete reduction in CO2 emission (0.92 million tons) CO2 emission reduction at an estimated total cost of €99 million, equivalent to €107 per ton of CO2 avoided. The average break-even ETS price converges with, but remains above, the cost-optimal levels due to the majority of economically capturable fertilizer emissions still being covered by free allowances.

### *4.3. Greece*

Greece's industrial CO2 emissions are estimated around 10.5 Mta in 2019, all of which could be attributed to the ten large scale emitters identified in the E-PRTR database [44]. Six cement factories are responsible for roughly half of the country's total industrial CO2 emissions, while four oil refineries – three of which are located in close proximity in the Attica region – together emit 5.45 Mt carbon dioxide a year. Approximately 2.9 Mta CO2 can be captured from the studied emission points which yields a 28% reduction in industrial emissions. We illustrate the optimal CCUS network in Figure 6.




(a) Greece-restricted scenario




(b) Greece-ample scenario

Figure 6: Comparison of Greece scenarios: restricted and ample.

Currently, the CCUS network of Greece focusses on using the Greenhouse utilization points GR-U-1, and GR-U-2 to sent the CO2 from emitters. The only storage available currently is the Pentafos(GR-S-2) with a capacity 170mt, and injection rates of 1mt. Our result indicate that it is optimal to build a pipeline that connects the two cement factories TITAN CEMENT S.A. - KAMARI PLANT (GR7) and HERACLES G.C.Co, VOLOS PLANT(GR10) which then builds a pipeline to the storage site Pentafos. These pipelines are of diameter 6 and 8 inches respectively. The cost for the transportation amounts to €1.6 million. By 2030, Greece is considering the establishment of its first small-scale CO2 storage site with a capacity of 70,000 tons per year, totaling 2 million tons, at the Epanomi gas field (GR-S-8) near the industrially active area of Thessaloniki. In addition to the Epanomi storage site, three utilization opportunities can be explored in this timeframe. Thrace Greenhouses (GR-U-1) in the Northeast region specializes in the cultivation of tomatoes and cucumbers in modern, geothermally heated greenhouses. If CO2 enhancement is implemented, the greenhouse complex can effectively utilize nearly 50,000 tons of industrial CO2 annually. Another greenhouse, Biamane (GR-U-2), is identified in Crete, with a more modest CO2 utilization potential of 265 tons per year. Furthermore, the White Dragon green hydrogen plant in West Macedonia is scheduled to complete the FID and EET phases by 2029. At its design capacity, White Dragon is expected to produce 250,000 tons of H2 for energetic use.

In this scenario, the White Dragon operates at one-tenth of its design capacity, increasing regional CO2 demand by 69,000 tons per year. Achieving optimal utilization of the country's total 0.19 million tons of sink capacity can be accomplished through carbon capture at Titan Cement's Thessaloniki plant (GR9) at an estimated yearly total cost of €23 million, equivalent to €125 per ton of CO2 avoided. Transportation costs are projected at an annualized €2.6 million, while storage costs amount to €0.4 million per year. Similar costs are assumed for offshore shipping of tankers. The greenhouse in Crete has marginal CO2 uptake, which does not significantly impact average emission mitigation cost levels. In practice, Crete's greenhouse is unlikely to be best supplied by GR9, while Thrace Greenhouses can be served by the biorefineries at Xanthi and Komotiní.

The Epanomi DOGF can then be utilized at higher annual injection rates to match the emission rates of Titan Cement's Thessaloniki plant. The Thessaloniki cement plant, however, is the most efficient installation of its kind in Greece. Due to its modernized equipment, industrial waste co-processing capabilities, and low-carbon cement mixtures, the plant is predicted to remain below its free Emission Trading System (ETS) allowance until 2030, even without any further reduction in CO2 emissions. Consequently, if only emissions exceeding free ETS allowances are considered, sourcing 0.19 million tons of CO2 from other industrial facilities is estimated to cost an annual €25.5 million, equivalent to €137 per ton of CO2 avoided. The relatively minor increase in the average

ETS break-even price can be attributed to the fact that only expensive-to-capture CO2 sources (i.e., cement plants and refineries) were identified in Greece, resulting in the cost increase being driven primarily by transportation costs.

By 2050, Greece's total storage and utilization capacity could expand to up to 20 million tons annually, primarily due to the extensive saline aquifers within the country. The White Dragon green hydrogen plant is anticipated to operate at full scale, consuming nearly 0.7 million tons of carbon dioxide per year. An analysis of the cost-optimal supply chain reveals that Greece's industrial emissions are concentrated centrally, primarily in the Attica region, while the majority of storage and utilization capacities are clustered in two hotspots: West Macedonia and Thessaloniki. In theory, both of these repositories have sufficient capacity to accommodate the entirety of the country's industrial CO2 emissions, should the need arise.

The refinery MOTOR OIL (HELLAS) could collaborate with the cement factory TITAN CEMENT S.A. - DREPANO PLANT(GR6) into building a pipeline of diameter 4 and 8 inches respectively. Then these both companies could use the storage site Vourinos - Western Macedonia (GR-S-7) to store their captured emissions. Furthermore, our model result indicate that more emitters need to collaborate into a unified pipeline network. In particular, MOTOR OIL (HELLAS) (GR4), TITAN CEMENT S.A (GR7), HERACLES G.C.Co, VOLOS PLANT (GR10), and TITAN CEMENT S.A. - DREPANO PLANT (GR6) could use a shared pipeline newtork to use the GR-S-9 for storing their emissions.

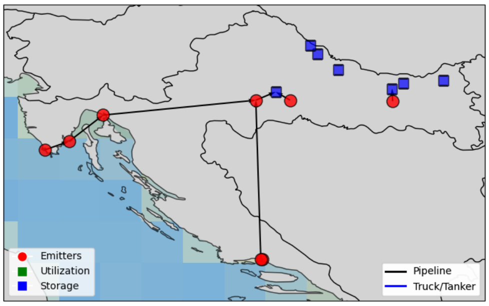
Hellenic Petroleum's industrial complex (GR3) could potentially collaborate with Titan Cement (GR9) at Thessaloniki, making use of the nearby repositories (GR-S-8, GR-S-9), thereby establishing the second CCS project in Greece. Given that the Epanomi gas field (GR-S-9) is also owned by Hellenic Petroleum, joint CCS development in Thessaloniki is a realistic possibility. The knowledge and experience gained from projects in Thessaloniki could naturally extend to carbon capture solutions implemented at other Titan Cement plants (GR6, BG7) and additional Hellenic Petroleum refineries (GR1, GR2). Cost-effectively, most of the remaining industrial facilities can be directed to West Macedonia, where emissions can either be utilized in Power-to-Gas (PtG) processes or stored in onshore saline aquifers (GR-S-7).

The establishment of this CO2 storage and utilization hub near the White Dragon H2 plant could create valuable economic opportunities for the otherwise less-developed northern region. However, environmental concerns regarding onshore saline aquifers might make offshore storage capacities at Thessaloniki (GR-S-9) a more attractive option, despite the higher cost. Regardless of the choice, Greek emitters would benefit from shared pipeline infrastructure, the development of which could be facilitated by the two major industry groups - Hellenic Petroleum and Titan Cement - responsible for more than a third of the country's industrial emissions. In this configuration, the total annualized cost of full CO2 emission reduction would be €330 million (equivalent to €117 per ton), with €50 million allocated for transportation and €20 million for storage.
With the expected reduction in free Emission Trading System (ETS) allowances by 2050, every Greek emitter may consider carbon capture as a viable emission mitigation option. Nevertheless, 21% of the country's capturable industrial emissions are projected to still be covered by free allowances. Consequently, CCUS projects at a scale of only 2.3 million tons per annum are expected to be incentivized. While the region's cement plants can significantly reduce their emissions to levels close to or below the required thresholds, refineries, once again, will need to purchase allowances or explore other means to mitigate approximately 50% of their emissions. When only emissions exceeding a plant's free permits are captured, 2.3 million tons of CO2 emission reduction is estimated to cost €281 million annually, equivalent to €123 per ton of CO2 avoided. Despite Greece not having readily accessible low-cost emission points for capture, the average ETS break-even price remains above the cost-optimal level, primarily due to the loss of economies of scale in long-distance transportation.

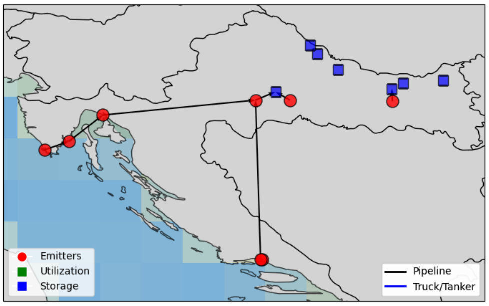
### *4.4. Croatia*

In 2019, Croatia's total industrial CO2 emissions amounted to 4.4 million tons, as reported by the European Environment Agency [44]. The country's eight primary emitters, comprising four cement plants, two refineries, and a fertilizer manufacturer, collectively accounted for 3.75 million tons of annual carbon dioxide emissions. Although no potential CO2 utilization sites have been identified within the country, the implementation of Carbon Capture and Storage (CCS) at full scale results in a substantial 36% reduction in emissions, equivalent to 1.34 million tons of CO2 annually. The optimal CCUS network for Croatia is presented in Figure 7. Croatia stands out due to its existing CO2 utilization projects, specifically in the form of enhanced oil recovery (EOR) initiatives. In both of the scenarios, the CCUS map for croatia very similar. These projects are already in operation at the Ivanić and Žutica oil fields. Furthermore, additional EOR projects are scheduled to become operational by 2025. Among them, the "iCORD project" plans to capture CO2 from undisclosed fertilizer and cement plants for injection into the Moslavina and Pannonia basin oil fields. Additionally, the "Bio-Refinery Project" aims to collect CO2 from selected biorefineries, further contributing to the country's efforts in reducing carbon emissions.

In the near term, Croatia's CO2 storage capacities may already surpass its capturable emission levels, reaching 3.4 million tons annually. Notably, the DOGF reservoirs at Kalinovac (HR-S-6) and Boksic (HR-S-5) alone offer sufficient storage capacity to accommodate the country's 1.34 million tons of capturable industrial CO2 emissions. Although specific details of the planned iCORD project are not yet publicly available, it is highly likely that the emissions from the fertilizer production plant at Kutina (HR5) and the cement manufacturer Nexe Grandja (HR7) will be the ones stored at the northern hydrocarbon fields.




(a) Croatia-restricted scenario




(b) Croatia-ample scenario

Figure 7: Comparison of Croatia scenarios: restricted and ample.

INA's refinery at Sisak (HR1) is strategically situated in close proximity to the DOGF storage sites. Consequently, the three small-scale emission points in northeastern Croatia (HR2, HR6, HR8), totaling 0.25 million tons of emissions, can significantly benefit from shared pipelines. The same holds for the two cement plants in the south (HR3, HR4), where transportation of CO2 is hampered by the presence of Bosnia and Herzegovina in between the source-sink pairs. Assuming these potential logistical challenges are overcome, the model projects annualized total costs of €137 million (€101 per ton) for a complete 1.34 million tons of emission reduction. This cost breakdown allocates €24 million to transportation and €8 million to CO2 storage. The majority of the emissions can be transported using only pipeline of diameter 4.

Croatia's largest emitter, Petrokemija's fertilizer plant (HR5), is not expected to be incentivized to invest in carbon capture due to its free ETS allowances available in the short term. Nonetheless, the remaining emitters are projected to need to reduce their emissions by 15-76% to avoid exceeding their 2030 free emission permits. Consequently, the EU ETS scheme is anticipated to incentivize carbon capture projects equivalent to 50% of Croatia's capturable industrial emissions, translating to 0.65 million tons. This provides significant support to the country's cement plants in fully meeting their emission reduction targets. At refineries, however, carbon capture serves as a partial solution. Given that free allowances are expected to cover the most economically capturable emissions in ammonia production and partially in cement emissions, achieving a 0.65 million tons emission reduction is estimated to cost €83.5 million annually, equivalent to €128 per ton of CO2 avoided.

By the mid-century, Croatia's storage capacities may see a significant increase, potentially reaching up to 17 million tons annually with the addition of saline aquifers. From a cost-optimization perspective, the saline aquifer at Popovaca (HR-S-3) stands out as a promising candidate to become the country's central CO2 storage site. This choice could alleviate the logistical challenges of transporting CO2 for emitters located along the coastline of the Adriatic Sea. If local demand for CO2 storage remains around 1.34 million tons, the surplus capacity at Kalinovac and the other Moslavina and Pannonia DOGF storage sites could be offered to neighboring countries. At 2050 capture costs, the total cost of the CCS supply chain under consideration is estimated at an annualized €120 million (equivalent to €90 per ton), with transportation costs reduced to €18 million and onshore saline aquifer storage amounting to €10 million.

Due to the slow reduction rate in ammonia production emission benchmarks, it's plausible that Petrokemija's fertilizer plant (HR5) might remain hesitant to invest in carbon capture, even in the long run. Conversely, the remaining emitters could be incentivized to capture 0.82 million tons at an estimated annual cost of €93.6 million, or €114 per ton of CO2 avoided. The more efficient cement plants, especially the CEMEX facilities (HR3, HR4) that utilize alternative fuels, are expected to continue meeting their CO2 reduction targets with CCS. However, refineries are likely to experience substantial (50-70%) ETS allowance deficits. In this scenario, the average breakeven ETS price again remains significantly above the cost-optimal levels, primarily due to the fact that the emissions from the most economically viable fertilizer facilities can still be fully covered by free allowances.

### *4.5. CCUS network for the combined countries*

When considering all countries combined, the restricted scenario offers only three available storage sites, limiting the potential benefits of resource sharing among the countries. Therefore, we focus on the network design for the ample scenario, which provides sufficient storage sites to facilitate resource sharing among all four countries. The optimal design of the CCUS network for this scenario is illustrated in Figure 8. Notably, the Sarmatian - Moldavian Platform in Romania (RO-S-6), with a capacity of 1234.9 Mt, shares its storage capacity with seven emitters from three different countries. Additionally, due to geographic advantages, CO2 captured at the Cement company Zlatna Panega Ciment (BG-5) is transported to utilization sites in all the four countries. Furthermore, when the annual injection rate reaches 5 Mt, 81.7% of the total captured CO2 is transported via pipelines of diameter

16. This indicates that, at higher injection rates, pipeline transportation becomes a more cost-efficient option. Interestingly, only four storage sites have enough capacity to store the emissions for the whole countries. That is the deep saline Silurian - Moldavian Platform (RO-S-6) , the Pentalofos (GR-S-2), the Hydrocarbon field Kalinovac (HR-S-6), and Popovaca (HR-S-3). The pipeline constructed that connects different emitters from different countries, suggests that a cross-country collaboration would lead to a much more efficient network design.

We proceed by conducting a sensitivity analysis concerning cost factors associated with technological maturity, including CO2 capture costs, storage costs, transportation costs, and utilization costs. The results indicate that CO2 capture cost exerts the most substantial influence on cost efficiency. For instance, a 20% reduction in CO2 capture costs yields a cost saving of 14.15%. Additionally, we examine the impact of environmental costs, which reflect the challenges associated with environmental regulations. Our findings reveal that a 10% increase in environmental costs leads to an 8.26% rise in the total cost of the CCUS network. This result underscores the urgency of implementing CO2 capture strategies as ETS allowances continue to diminish in the near future."

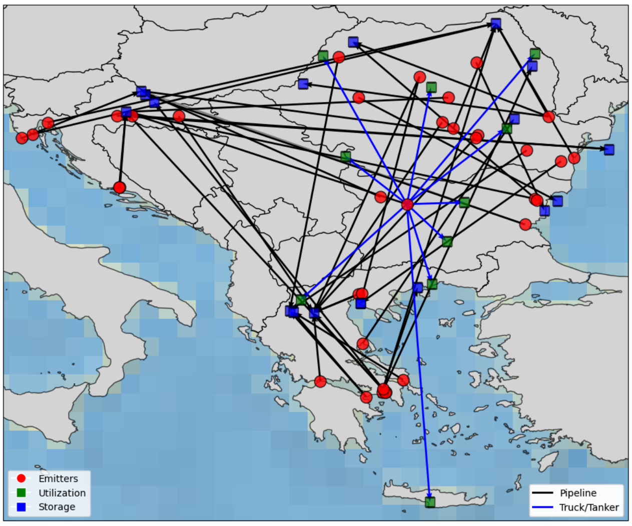



Figure 8: Combination of four countries scenarios

## 5. Conclusion and Policy Implications

This study examines the potential for carbon capture, utilization, and storage (CCUS) in four Southeast-European countries: Romania, Bulgaria, Greece, and Croatia. The industrial sectors analyzed, including fertilizer, oil refining, iron and steel, and cement industries, present an opportunity to capture an estimated 11.8 million tons of CO2 emissions. Implementing CCUS in these sectors would result in a 25% reduction in the combined industrial emissions of these countries, based on 2019 levels.

Depleted oil and gas fields offer substantial storage capacities, amounting to 178 million tons (5.9 million tons with a 30-year useful life). However, it's noteworthy that most of these storage sites are concentrated in Croatia (125 million tons) and Romania (45 million tons), while Bulgaria and Greece have limited short-term storage options. Saline aquifers, once proven safe for onshore applications, could provide ample storage capacities across the region.

Onshore storage of CO2 is subject to strict regulations and varies significantly by country. In the European Union (EU), the Directive on the Geological Storage of Carbon Dioxide provides the legal framework for carbon capture and storage (CCS), including onshore CO2 storage. The directive allows for the storage of CO2 in geological formations, both onshore and offshore, but member states have the authority to decide whether to allow or restrict it in their territories. Some EU countries, like Germany, have taken a more cautious approach, with stringent restrictions or outright opposition to onshore CO2 storage due to concerns over safety, potential risks to groundwater, and public resistance. While there is no widespread opposition to onshore CO2 storage in Southeast Europe, most countries in the region are still in the exploratory or early stages of considering CCS projects. For example, Bulgaria hosts the ANRAV-CCUS project with a capacity of 800 kt/year; Croatia has launched the KOdeCO Net Zero project with 377 kt/year; and Greece is developing two projects, IFESTOS and OLYMPYS, with a combined capacity of 2.9 Mt/year [46]. . Although Romania is the only SEE member state that has not yet been awarded an Innovation Fund project on CCS, it has shown clear interest by developing a National CCUS Strategy and Roadmap [47, 48]. The overall pace of CCS development in Southeast Europe is slower compared to Western Europe.

The prospects for CO2 utilization are challenging to evaluate at this stage. Without large-scale carbon-neutral fuel projects in progress, the current reviewed utilization pathways are unlikely to play a significant role in industrial decarbonization.

Despite transportation accounting for no more than 15-20% of the total cost of large-scale CCUS projects, the long distances between industrial areas and potential storage locations may pose logistical challenges at the national level. Cooperative planning and collaboration among emitters will be essential for the development of CO2 pipelines traversing countries. Greek and Croatian emitters, in particular, stand to benefit from shared pipeline infrastructure, with the peripheral hydrocarbon fields in Croatia offering significant potential for selling storage capacities to foreign emitters. This can be facilitated by the presence of company groups in the region, such as HeidelbergCement, Holcim, and Titan Cement, which operate fifteen cement production facilities across the four countries.

Effective synchronization of the involvement of these capital-strong corporations is crucial for optimally funding carbon capture projects. The rising EU ETS (Emissions Trading System) price is expected to make CCUS a commercially viable option in the studied industries. However, the allocation of free allowances could hinder carbon capture investments. For example, while capturing fertilizer industry emissions would be economically viable at the current ETS price (around €80 as of 2022 Q2), free allowances allocated to these facilities may deter them from undertaking carbon capture projects. Oil refineries, which are estimated to have the highest carbon capture costs and receive the lowest public support, are identified as the sector most in need of new emission mitigation options.

Governmental programs that establish a framework for cross-sectoral cooperation can enable, for instance, oil companies to fund carbon capture at fertilizer plants, facilitating industrial CO2 emission reduction. By 2030, if the EU ETS price reaches the predicted €129 [49], the cement and iron and steel industries could also become financial contributors to CCUS efforts. This would involve financing carbon capture projects at other facilities, regardless of the financial status and ETS allowances of individual emitters. Co-financing carbon capture allows the industry to pool resources into the most cost-effective emitter, share risks, and decarbonize in alignment with the increasing ETS price.

While the evolution of energy prices will play a critical role in the future of post-combustion carbon capture in Europe, this study provides a comprehensive view of CCUS possibilities that can assist policymakers in recognizing opportunities essential for the technology to advance and contribute to climate action. It is important to emphasize that the transition to a low-carbon economy is a highly complex process with many dimensions and factors influenced by decisions made by numerous stakeholders, including companies, policymakers, and society at national and international levels. Future studies can explore various directions, considering scenarios that incorporate regional regulatory frameworks, incentives, social acceptance factors, and different emission reduction technologies. In concluding this research, it is imperative to acknowledge the ever-evolving and dynamic nature of the energy sector. Our study has sought to contribute insights and methodologies that remain valuable in the ever-changing landscape of energy technologies, regulations, and policies. We stress the importance of continuous, collaborative discussions and research to stay at the forefront of addressing the urgent challenges and opportunities in the energy sector.

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## 6. Appendix

Table 10: Selected Industrial Emitters

| ID | Name | Emissions (ton/year) | Industry |
|---|---|---|---|
| BG1 | Lukoil Neftohim Burgas AD | 2,057,729 | Oil and Gas |
| BG2 | Cement company Devnia cement | 680,346 | Cement |
| BG3 | Agropolihim AD | 242,828 | Fertiliser |
| BG4 | Cement company Holcim BG | 447,929 | Cement |
| BG5 | Cement company Zlatna Panega Ciment | 509,000 | Cement |
| GR1 | HELLENIC PETROLEUM S.A. - INDUSTRIAL DIVISION OF ASPROPYRGOS | 1,330,000 | Oil and Gas |
| GR2 | HELLENIC PETROLEUM S.A. – SOUTH REFINERIES COMPLEX – ELEFSIS INDUSTRIAL FACILITIES | 1,840,000 | Oil and Gas |
| GR3 | HELLENIC PETROLEUM S.A. - THESSALONIKI INDUSTRIAL COMPLEX | 281,000 | Oil and Gas |
| GR4 | MOTOR OIL (HELLAS) - CORINTHOS REFINERIES S.A. | 2,003,520 | Oil and Gas |
| GR5 | HALYPS BUILDING MATERIALS S.A. | 289,000 | Cement |
| GR6 | TITAN CEMENT S.A. - DREPANO PLANT | 717,000 | Cement |
| GR7 | TITAN CEMENT S.A. - KAMARI PLANT | 1,500,000 | Cement |
| GR8 | HERACLES G.C.Co, MILAKI PLANT | 852,000 | Cement |
| GR9 | TITAN CEMENT S.A. - THESSALONIKI PLANT | 616,000 | Cement |
| GR10 | HERACLES G.C.Co, VOLOS PLANT | 1,250,000 | Cement |
| HR1 | Rafinerija nafte Sisak | 312,000 | Oil and Gas |
| HR2 | Proizvodnja cementa Koromacno | 326,000 | Cement |
| HR3 | TVORNICA CEMENTA ”SVETI KAJO” | 204,000 | Cement |
| HR4 | TVORNICA CEMENTA ”SVETI JURAJ” | 687,000 | Cement |
| HR5 | Proizvodnja gnojiva | 750,000 | Fertiliser |
| HR6 | Rafinerija nafte Rijeka | 708,000 | Oil and Gas |
| HR7 | NEXE GRADNJA d.o.o. | 645,000 | Cement |
| HR8 | Proizvodnja aluminatnog cementa | 114,000 | Cement |
| RO1 | SC ROMPETROL RAFINARE SA - Navodari | 993,000 | Oil and Gas |
| RO2 | LIBERTY GALATI SA | 4,100,000 | Iron and Steel |
| RO3 | S.C. CHEMGAS HOLDING CORPORATION SRL - Slobozia | 223,000 | Fertiliser |
| RO4 | HEIDELBERGCEMENT ROMANIA SA | 731,000 | Cement |
| RO5 | SC HOLCIM ROMANIA SA | 1,040,000 | Cement |
| RO6 | CRH CIMENT (ROMANIA) S.A. - Medgidia | 876,000 | Cement |
| RO7 | SC PETROTEL LUKOIL SA | 432,000 | Oil and Gas |
| RO8 | HOLCIM (Romania) SA - Ciment Alesd | 940,000 | Cement |
| RO9 | OMV PETROM SA - Petrobrazi | 984,000 | Oil and Gas |
| RO10 | SC CRH CIMENT (ROMANIA) SA | 747,000 | Cement |
| RO11 | HEIDELBERGCEMENT ROMANIA SA - Fieni | 716,000 | Cement |
| RO12 | FABRICA DE CIMENT CHISCADAGA | 664,000 | Cement |
| RO13 | SC AZOMURES SA | 1,460,000 | Fertiliser |

Table 11: Storage Sites Identified

| ID | Name | Total Capacity (Mt) | Type |
|---|---|---:|---|
| HR-S-1 | Drava | 1939 | SA |
| HR-S-2 | Osijek | 110 | SA |
| HR-S-3 | Popovaca | 230 | SA |
| HR-S-4 | Benicanci | 14 | DOGF |
| HR-S-5 | Boksic | 9 | DOGF |
| HR-S-6 | Kalinovac | 75 | DOGF |
| HR-S-7 | Molve | 43 | DOGF |
| RO-S-1 | Lotus+ | 18 | SA |
| RO-S-2 | Lebada+ | 2 | DOGF |
| RO-S-3 | Rosioru+ | 31 | DOGF |
| RO-S-4 | Oprisenesti+ | 9 | DOGF |
| RO-S-5 | Matca+ | 3 | DOGF |
| RO-S-6 | Silurian - Moldavian Platform | 1234.9 | SA |
| RO-S-7 | Sarmatian - Moldavian Platform | 603.2 | SA |
| RO-S-8 | Sarmatian - North-Dobroudjan | 1239.6 | SA |
| RO-S-10 | Sarmatian - Transylvanian Depression | 2696.8 | SA |
| RO-S-11 | Miocene - Pannonian Depression | 2194.4 | SA |
| RO-S-12 | Pliocene - Pannonian Depression | 676.4 | SA |
| RO-S-13 | Pontian - Moesian Platform | 1355.7 | SA |
| RO-S-14 | Middle Devonian - Moesian Platform | 1674.8 | SA |
| RO-S-15 | Sarmatian - Moesian Platform | 912.4 | SA |
| RO-S-16 | Middle Jurassic - Moesian Platform | 1325 | SA |
| GR-S-1 | Eptachori | 1300 | SA |
| GR-S-2 | Pentalofos | 170 | SA |
| GR-S-3 | Prinos-Kavala basin | 30 | SA |
| GR-S-4 | Mesohellenic Trough Eptachori | 1277 | SA |
| GR-S-5 | Mesohellenic Trough Pentalofos | 166 | SA |
| GR-S-6 | Evros - Northern Greece (studied) | 24.5 | SA |
| GR-S-7 | Vourinos - Western Macedonia (studied) | 70 | SA |
| GR-S-8 | *E*panomi Gas Fields - Thessaloniki | 2 | DOGF |
| GR-S-9 | τhessaloniki basin | 640 | SA |
| BG-S-1 | Galata | 6 | DOGF |
| BG-S-2 | Pleven | 1500 | SA |
| BG-S-3 | Pleven zone | 1600 | SA |
| BG-S-4 | Totleben | 4 | SA |
| BG-S-5 | Pavlikeni zone | 400 | SA |
| BG-S-6 | Marash | 15 | SA |
| BG-S-7 | Dolna Kamchia | 45 | SA |
| BG-S-8 | Cherkovo | 19 | SA |
| BG-S-9 | Yambol-south | 22 | SA |
| BG-S-10 | Galabovo | 80 | SA |
| BG-S-11 | Maritsa | 70 | SA |
| BG-S-12 | Popovo zone | 18 | SA |

Table 12: Utilization Sites Used

| ID | Name | Capacity (t/year) | Type |
|---|---|---|---|
| BG-U-1 | GREENS OOD | 6360 | Greenhouse |
| BG-U-2 | ZAHARNI ZAVODI AD | 90000 | Sugar factory |
| GR-U-1 | THRACE GREENHOUSES S.A. | 49025 | Greenhouse |
| GR-U-2 | VIANAME S.A. | 265 | Greenhouse |
| GR-U-3 | White Dragon H2 | 694444 | H2 production |
| RO-U-1 | M & R SRL | 397.5 | Greenhouse |
| RO-U-2 | SUD OIL SRL | 19875 | Greenhouse |
| RO-U-3 | AGRANA. ROMANIA S.R.L | 90000 | Sugar factory |
| RO-U-4 | ZAHARUL ORADEA SA | 90000 | Sugar factory |
| RO-U-5 | Danube H2 | 20833 | H2 production |

# From $CO_2$ Emissions to Jet Fuel: Analysis of Potential Sustainable Aviation Fuel Supply Chains in Europe

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**Abstract**

Producing jet fuel from $CO_2$ offers a promising pathway to reduce aviation's carbon footprint, but designing effective supply chains remains a critical challenge. This study develops an optimisation model to identify economically optimal networks of $CO_2$ point sources, conversion facilities, and airports in Northwest and Southeast Europe for 2030. The results highlight the pivotal role of high-concentration $CO_2$ sources, which are abundant in Northwest Europe but scarce in the Southeast, driving jet fuel production costs between €1387 and €1434 per tonne. The analysis compares three supply chain structures — centralised and decentralised conversion of $CO_2$ from point sources as well as the use of direct air capture technologies — and reveals how regional differences influence cost and feasibility. Our findings provide insights into the economic and logistical strategies needed to scale sustainable aviation fuel production.

*Keywords:* Carbon capture and utilisation, Sustainable aviation fuel, Supply chain optimisation, Jet fuel

## 1. Introduction

Environmental concerns and international climate agreements exert considerable pressure on governments and organisations to mitigate carbon emissions. At the heart of these efforts lies the Paris Agreement, which seeks to limit the increase in global temperature to well below 2°C above pre-industrial levels by 2050. This ambitious objective necessitates substantial reductions in greenhouse gas emissions, particularly carbon dioxide ($CO_2$) [1]. Realising these targets calls for rapid and transformative actions [2]. In light of these global challenges, the aviation sector has faced heightened scrutiny, as it contributed 2% of global emissions by 2022 [3]. With the electrification of aviation – especially concerning medium- and long-haul flights – presenting a technologically complex challenge [4], so-called sustainable aviation fuels (SAF) have emerged as a promising alternative for reducing the industry's carbon footprint. Producible in existing industrial infrastructures with present-day technologies – albeit with varying degrees of maturity –, these SAF are used as drop-in fuels, i. e. they are blended with conventional aviation fuels, with the potential to decarbonise the aviation sector [5].

Given that outlook it is anything but surprising that governments worldwide are enacting policies designed to accelerate the adoption of SAF, often establishing minimum targets for its integration into the aviation fuel composition. For instance, the European Union mandates a minimum share of 6% of SAF by 2030, increasing to 70% by 2050 [6]. Japan is striving to establish a SAF supply chain, whilst the United States intend to introduce tax credits to promote the utilisation of SAF [7]. Nonetheless, the successful deployment of SAF hinges on the identification of production pathways that reconcile economic viability with environmental impact.

Whereas SAF derived from biomass have garnered significant attention in recent years, concerns surrounding their (sustainable) feedstock availability, scalability, and economic viability have prompted an intensified search for alternative solutions ([8], [9], [10]). Offering high energy density, easy storability, and transportability while leveraging existing infrastructure and relying on non-biogenic feedstocks, e-fuels – broadly speaking, fuels synthesised from hydrogen and $CO_2$ – are considered particularly promising ([5], [9], [11],[12]). Once sourced from water electrolysis and ambient air via Direct Air Capture (DAC) technologies or emissions from industrial plants' flue gas [11], respectively, hydrogen and $CO_2$ are synthesised at refineries to aviation fuel which, as drop-in fuel, is supplied to airports. As such, e-fuels not only pose a technological challenge regarding sourcing and production, but also a logistical one of efficiently designing infrastructures and managing commodity flows to ultimately match supply and demand.

However, research in that field is largely missing. While the technological side of e-fuel production has been investigated in the past (e. g. [13]) – also in combination with carbon capture and utilization (CCU) (e. g. [14]) –, supply chain considerations have yet remained limited to CCU on a national scale (e. g. [15], [16], [17]). In this study, we will not only address the integrated optimization of CCU and SAF production supply chains, but we will do so with a particular focus on cross-country supply chains. Specifically, we develop a broadly deployable (i. e. not limited to CCU-based SAF production, but also fit for $CO_2$-based process industries such as methanol and synthetic polymers) mathematical supply chain optimization model and apply it to two key clusters in the European market. Heterogeneous in their industrial infrastructure, said clusters – Northwest Europe (NW; including the United Kingdom, the Netherlands, and Denmark) and Southeast Europe (SE; comprising Romania, Bulgaria, and Greece) – reveal insights into both infrastructural determinants of optimal supply chain designs and drivers of economic viability of e-fuel production. We validate our framework and key findings through expert interviews with stakeholders from industry. In addition, we conduct extensive sensitivity analyses to assess the robustness of our findings under different cost and infrastructure scenarios. Based on this framework, we find that access to high-purity $CO_2$ emitters is a key determinant of economic viability in point source $CO_2$ capture. However, given the relatively minor role of transportation cost, cross-country supply chains are beneficial when said access is limited due to sparsity of the domestic industrial infrastructure. This is of particular interest as the alternative to overcoming dependency on high-purity emitters, DAC, is currently and for the foreseeable future constrained by substantial capture costs ([18]). Although being competitive with the sole commercially feasible SAF production method, both domestic and cross-country e-fuel production costs exceed the ones of fossil fuels by around 100%. Being largely driven by conversion efficiencies in the production process, this insight highlights the pivotal role of technological advancements for the future trajectory of sustainable, economically viable, and scalable SAF production.

We will detail both our methodological contribution and the extensive computational study that allowed to derive these insights in Section 3 and Section 4, respectively, before concluding our paper in Section 5. We will, however, start by positioning our work through a thorough review of the existing literature on the structure of CCU supply chains as well as SAF production pathways (Section 2).

## 2. Literature review

We categorise literature relevant to this study into four domains. In Section 2.1 we focus on the design and optimisation of CCU supply chains, specifically addressing the capture, transportation, and utilisation of $CO_2$, although not explicitly aimed at the production of SAF. Afterwards, in Section 2.2, we explore various pathways for SAF production, which generally does not consider the integration of $CO_2$ captured from other industries. Given our focus on a particular type of SAF – i. e. e-fuels –, we review pertinent literature in Section 2.3. As quantitative decision support constitutes a corner stone of our research, we discuss related approaches in Section 2.4. Finally, Section 2.5 identifies the literature gap and highlights our own contributions.

### *2.1. Carbon capture and transport*

The CCU supply chain commences with the capture of $CO_2$, a process that is significantly influenced by the characteristics of the sources – emissions with a high concentration of $CO_2$, e. g., necessitate significantly less energy for $CO_2$ capture than lower-concentration emissions ([15], [19]) – and the selected capture technology. Research has identified various methods for capturing $CO_2$, each presenting distinct energy requirements and compatibility with industrial processes. Capture technologies are generally categorised into the following main types [20]:

- *Post-combustion capture* is typically applied directly to flue gases, rendering it suitable for integration into existing industrial facilities [21]. Nonetheless, this method incurs considerable energy and operational costs, primarily attributable to the degradation of the amine-based solvents employed in the process [22].

- Conversely, *pre-combustion capture*, in which fuel is processed prior to combustion, operates at elevated pressures and concentrations of $CO_2$. It has gained traction due to its efficiency with specific types of fuel ([23], [24]).

- *Oxy-fuel combustion*, characterised by the combustion of fuel in pure oxygen, produces a $CO_2$-rich exhaust that is relatively straightforward to capture. Nevertheless, it remains underutilised owing to high operational costs and technological immaturity ([20], [25]).
- Lastly, *direct air capture* has experienced recent advancements. However, it continues to face challenges related to low efficiency and high costs, prompted by the low concentration of $CO_2$ in the atmosphere, which generally renders it more expensive than point-source capture ([18], [26]).

Once captured, $CO_2$ must be transported to conversion facilities. Researchers have investigated various transportation methods, including pipelines, ships, and railways [27]. The costs associated with pipeline transport are predominantly proportional to distance, whereas shipping costs tend to stabilise over longer distances [28]. For instance, the expenses incurred in transporting $CO_2$ via onshore pipelines are estimated to range from €1.5 to €5 per tonne per 100 km, while those for offshore pipelines range from €3.5 to €9.5 per tonne per 100 km. In contrast, shipping costs fluctuate between €11 and €15 per tonne per 100 km. Due to its technological maturity and cost-effectiveness, pipeline transportation often emerges as the preferred option in studies related to CCU ([15], [29], [30]). Additionally, research indicates that $CO_2$ can be transported either as a gas or as a liquid, with the latter proving to be more cost-efficient due to its higher density, thereby reducing the diameter of the pipeline and the associated costs [31]. For optimal transport, $CO_2$ is compressed above its critical pressure, which necessitates an energy-intensive compression stage that constitutes a significant proportion of operational expenses [32].

### *2.2. SAF production pathways*

The second stream of literature concentrates on alternative pathways for the production of SAF, each characterised by distinct feedstocks, technological prerequisites, and associated costs. For instance, the Fischer-Tropsch (FT) pathway utilises carbon monoxide as a feedstock, necessitating a reverse water-gas shift reaction (RWGS) to convert $CO_2$ into CO. Despite being technologically mature and certified, this route remains constrained by its low production volume ([13], [33]). The energy and maintenance demands render the production of FT SAF significantly more expensive than conventional fuels ([34], [35]), with minimum jet fuel selling price (MJSP) estimates ranging from €2250 to €3250 per tonne of SAF ([9], [36]) as compared to roughly €685 per tonne of fossil jet fuel [37].

The methanol pathway demonstrates a cost structure and carbon reduction performance comparable to the FT process [38]. Both the methanol and FT pathways show similar projections for the MJSP; each necessitates substantial hydrogen inputs, which can constitute up to 80% of production costs due to their energy-intensive nature. Although SAF derived from methanol has yet to attain qualification (e.g., under ASTM D4054) and remains in a state of commercial immaturity ([39], [40]), methanol offers the distinct advantage of being a versatile intermediate product applicable across various industries.

Finally, the Hydroprocessed Esters and Fatty Acids (HEFA) pathway is currently the sole method for SAF production that has attained commercial viability. This pathway presents advantages, including reduced capital requirements and a high fuel yield per unit of feedstock. HEFA yields between 1137 and 1214 litres of SAF per tonne of feedstock ([41], [42]) which is substantially higher than yields obtained from alternative pathways. However, with a feedstock-dependent MJSP ranging from €990 to €1420 per tonne ([42], [43]), the HEFA pathway still is roughly 50 to 100% more expensive than conventional jet fuel production.

Beyond economic feasibility, evaluating the environmental performance of SAF production pathways is critical to understanding their role in decarbonizing aviation. Life cycle assessment (LCA) studies consistently show that the greenhouse gas reduction potential of SAF varies significantly depending on the production pathway, feedstock type, and energy source. The FT pathway, which converts biomass or waste into syngas and then into liquid fuels, offers up to 90% greenhouse gas (GHG) reductions when renewable or waste-based feedstocks are used. It also holds strong potential for scaling with diverse input materials [9]. The methanol pathway is an emerging power-to-liquid pathway that can achieve near-zero emissions if renewable electricity and $CO_2$ from direct air capture are used [44]. While still at lower technology readiness levels, this pathway offers a promising route for deep decarbonisation of aviation. HEFA, the most commercially advanced pathway, typically achieves 60–85% GHG reductions compared to conventional jet fuel, particularly when using waste-based feedstocks like used cooking oil or tallow [45]. Together, these pathways highlight the importance of feedstock choice and energy source in determining the environmental benefits of SAF.

### *2.3. Advances in e-fuel production and sustainability*

Recent research has examined diverse aspects of e-fuel production and sustainability. [46] introduced a generalized methodology for optimizing biomass–green hydrogen-based e-fuel systems, evaluating various pathways including green ammonia and sustainable aviation fuels. Similarly, [47] reviewed process intensification strategies designed to improve the efficiency and sustainability of e-fuel production, focusing on innovative reactor designs and system configurations. The techno-economic viability of e-fuels derived from atmospheric $CO_2$ and green hydrogen was assessed by [48], who underscored the importance of supportive policy frameworks to enhance cost-competitiveness. Complementing these efforts, [49] conducted a systematic review of techno-economic and life cycle assessments, identifying critical research gaps and ongoing challenges in the field. In addition, [50] evaluated methanol and ammonia as promising green fuels, comparing thermochemical and electrochemical production pathways and highlighting the pivotal role of efficiency improvements in achieving economic feasibility. Collectively, these studies underscore the rapid progress in e-fuel technologies and their potential to contribute meaningfully to a sustainable energy future.

### *2.4. Machine learning and optimization in SAF-related decision-making*

Lately, the use of computational techniques – particularly machine learning and optimisation methods – to support decision-making in the SAF domain has seen a rise in popularity. These approaches offer valuable tools to improve process efficiency, optimise supply chain configurations, and manage uncertainty in SAF production and distribution.

Machine learning has been applied in predictive modeling to optimise SAF production processes, including estimating conversion efficiencies and identifying key operational parameters that influence yield and fuel quality [51]. Such data-driven methods enable more accurate and adaptive modeling of complex production systems, supporting both design and real-time operational decisions. Furthermore, deep learning methods have been explored for anomaly detection in SAF production systems, contributing to process stability and operational efficiency [52].

On the optimisation side, we highlight how mixed-integer linear programming (MILP) and stochastic optimisation approaches are utilised for SAF supply chain design. These techniques address critical challenges such as cost minimisation, feedstock logistics, and system resilience under sustainability consideration, uncertainties in availability and market conditions

[53]. By integrating these optimisation frameworks, researchers and industry stakeholders can enhance decision-making across SAF supply and distribution networks. Finally, [54] discusses optimizsation techniques for bioenergy supply chains, directly relevant to SAF supply chain modeling.

*2.5. Research gap*

While each SAF pathway presents unique technical and economic challenges, to the best of our knowledge, a comprehensive analysis of the SAF supply chain that integrates CCU remains largely overlooked in the existing literature. Most studies (e. g., [13], [38], [42]) focus primarily on evaluating SAF production without considering the role of CCU. Although some recent works (e. g., [14], [55]) have started to explore the potential of CCU technology to reduce the carbon footprint of aviation when combined with SAF, these studies tend to concentrate mainly on technological aspects. In contrast, this study aims to fill this gap by optimising the SAF supply chain in conjunction with CCU, while also assessing its economic competitiveness relative to alternative production routes. Furthermore, we provide a detailed economic feasibility assessment by systematically varying key parameters such as capture costs and supply chain structures across different clusters of European countries – i. e. explicitly accounting for cross-border collaboration rather than restricting our focus to domestic considerations only.

## 3. An optimisation-based approach to SAF supply chain analysis

Aiming for a concise analysis of the economic viability of different carbon capture technologies and supply chain structures for CCU-based SAF production in the two European clusters NW (United Kingdom, the Netherlands and Denmark) and SE (Romania, Bulgaria and Greece), this study is based on two key building blocks:

- a *data collection process* in which we analyse field data and conduct expert interviews to accurately capture the projected 2030 market environment of SAF production and demand in the NW and SE clusters. In total, seven interviews were conducted to guide the design of the experiments. These interviews comprised organisations involved in the ConsenCUS project [56], as well as external companies selected to provide diverse perspectives and enhance the realism of the study. The selection process aimed to encompass every stage of the supply chain, from $CO_2$ capture to SAF transportation, thereby ensuring a comprehensive analysis. Table 1 provides a summary of the interviews and the topics discussed. Five of the seven interviews were conducted with companies from the NW cluster, while the remaining two were from the SE cluster. This distribution reflects the concentration of industry expertise in the NW region, where firms tend to be more established and diverse in their specialization. Consequently, insights from the NW cluster may be more comprehensive. However, perspectives from the SE cluster were also incorporated to capture regional variations. While differences in expertise levels across clusters may influence the generalizability of our findings, the study accounts for these variations by analyzing common themes across both regions.

| ID | Organisation type | Topics discussed |
|---|---|---|
| A | Energy transition network organisation | Objectives of ConsenCUS and general technical settings |
| B | $CO_2$-processes researcher | $CO_2$ capture technologies |
| C | CCU-technology developer | Formic acids and SAF synthesis |
| D | Energy transition consultant | $CO_2$ policies and objectives |
| E | SAF producer | SAF refining and transportation |
| F | Sustainable biofuels company | SAF refining and transportation |
| G | Industrial company using $CO_2$ capture | $CO_2$ policies and objectives |

Table 1: Interviews conducted with industry experts.

- a *mathematical optimisation model* to ensure an optimal design of the (cross-border) SAF production supply chain.

Subsequently, we will detail the data collection process first (Section 3.1) and the optimisation model afterwards (Section 3.2).

### *3.1. Data collection*

This section outlines the methodology employed for data collection and its subsequent integration into the model. Specifically, Sections 3.1.1 and 3.1.2 provide a detailed examination of the identification of $CO_2$ point sources (emitters) and SAF production facilities (refineries). Section 3.1.3 introduces the airports included in the analysis, along with their projected demand for SAF in 2030. Then, Section 3.1.4 discusses the supply chain structures studied in accordance with both the echelons described in Sections 3.1.1 to 3.1.3 and different $CO_2$ capture and conversion technologies and points. Finally, we elaborate on the transport- and conversion-related costs as well as conversion yields assumed in our study (Section 3.1.5).

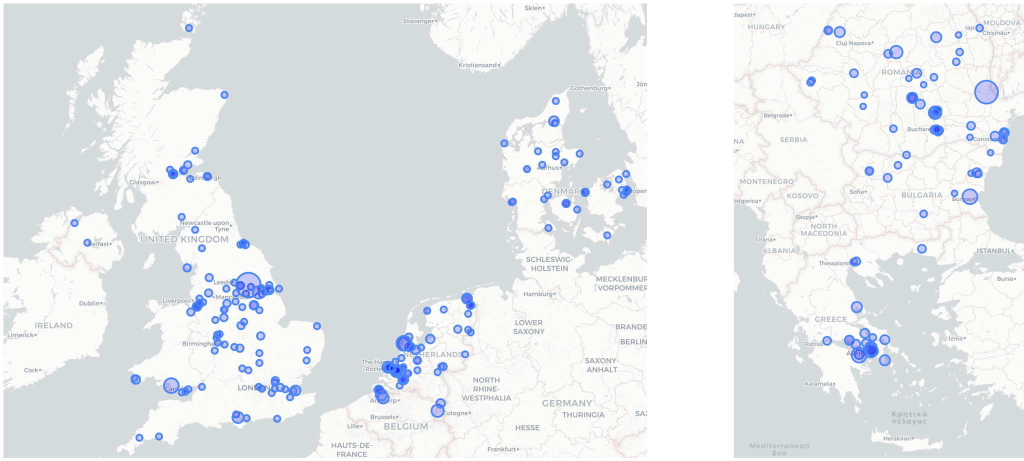
*3.1.1. $CO_2$ point sources*

The emitters analysed in this study were sourced from the ConsenCUS database [57], with the data collection guided by two primary selection criteria: industry type and the anticipated operational lifetime of the facilities. Emitters projected to cease operations before 2030, as well as coal-fired power plants, were excluded from consideration. Two major inter- and intra-cluster differences are observed in the emitters, respectively: within the NW cluster, both the number of emitters and the amount of $CO_2$ emissions is substantially larger than in the SE cluster, indicating a much higher concentration of industrial activity (cf. Table 2). At the same time, the spatial distribution

| **Country** | **Total emitters** | **Total emissions (Mt/year)** |
|---|---|---|
| United Kingdom | 104 | 70.72 |
| Netherlands | 72 | 78.33 |
| Denmark | 36 | 9.22 |
| Romania | 44 | 24.79 |
| Bulgaria | 11 | 4.82 |
| Greece | 20 | 16.25 |

Table 2: Summary of emitters per country.

of emitters varies significantly across different countries within the individual clusters (cf. Figure 1). In the Netherlands and Greece, for instance, emitters are concentrated around the Rotterdam and Athens area, respectively, which correspond to the principal industrial regions of these countries. Conversely, the United Kingdom and Romania display a more even distribution of emitters nationwide.




(a) Northwest Europe (b) Southeast Europe

Figure 1: Locations of emitters per cluster, with circle sizes indicating yearly emissions [57].

### *3.1.2. SAF production facilities*

In the transition towards the production of SAF, it is anticipated that refining companies will modify their existing facilities rather than construct new refineries. Interviewee F (cf. Table 1), e. g., named the complexity involved in site selection for new facilities, the strategic significance of proximity to feedstock sources, and the necessity for dependable energy supplies as key factors for the industry considering the utilisation of existing infrastructure a cost-effective and practical strategy to fulfill the requirements for SAF blending.

### *3.1.3. Airports*

The airports constitute the set of consumers of SAF. Insights gained from interviews with SAF producers and sellers suggest that refineries generally supply jet fuel directly to airports. Consequently, the geographical location and fuel consumption patterns of the airports are essential for the analysis.

This study focuses exclusively on airports that handle an annual traffic volume exceeding 200,000 traffic units (TUs; with a TU being defined as one passenger or 100 kilograms of mail or cargo). Airports that fall below this threshold exhibit negligible fuel demand and are consequently excluded from the analysis [29]. Figure 2 depicts the airports included in our study, along with an indication of their individual traffic volumes.


(a) Northwest Europe

(b) Southeast Europe

Figure 2: Locations of airports above 200,000 traffic units per cluster, with circle sizes indicating traffic quantity.

As opposed to traffic volumes, airport-specific fuel consumption data are not publicly available. To estimate SAF demand, we employ a three-step approach: first, we project each countries jet fuel demand in 2030 (i. e. the focal year of our analysis) and, from that, derive national SAF demand according to the political guidelines on SAF usage by 2030 ([58], [59]). Finally, we distribute SAF demand across each country's airports proportional to their share of national traffic volume. Subsequently, we detail the single steps.
To forecast each country's jet fuel demand for 2030, we apply an autoregressive–moving-average (ARMA) model with a trend component to historical jet fuel consumption data. For estimating parameters $p$ (order of the autoregressive model) and $q$ (order of the moving-average model), we rely on the *auto.arima* function in R. Various trend specifications are examined, including linear, quadratic, exponential, and broken linear models (i. e. a model facilitating capturing structural changes in the data / trend), with the latter yielding the most reliable forecasts.
A peculiarity of our data requiring special attention is the COVID-19 pandemic and the accompanying significant reduction in jet fuel demand in 2020 and 2021, followed by a recovery period in 2022 and 2023, after which demand is expected to revert to pre-pandemic trends [60]. To account for this anomaly, pandemic-related outliers within the data have been excluded, and forecasts are derived from adjusted data commencing from 2020. The

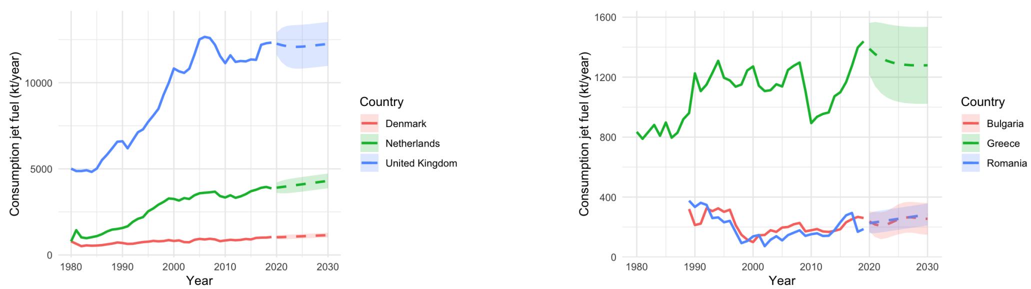



Figure 3: Projected jet fuel demand until 2030 for all countries in the NW (left) and SE (right) clusters, based on an ARMA$(p, q)$ model with a broken linear trend (95% confidence intervals marked in light color).

resultant forecasts, including the 95% confidence intervals, are depicted in Figure 3.

Table 3 provides a summary of the point forecasts for the year 2030, along with the model parameters used. To account for (near-)worst-case scenarios, we additionally present the upper limit of the 95% confidence interval.

| **Country** | **(p,q)** | **Break date** | **Point forecast 2030 (kt)** | **95% high forecast 2030 (kt)** |
|---|---|---|---|---|
| UK | (2,0) | 2006 | 12248 | 13522 |
| Netherlands | (1,0) | 2000 | 4301 | 4728 |
| Denmark | (0,1) | 1992 | 1151 | 1280 |
| Romania | (0,1) | 2000 | 284 | 357 |
| Bulgaria | (3,0) | 2000 | 255 | 361 |
| Greece | (1,0) | 1995 | 1279 | 1536 |

Table 3: ARMA model parameters, break dates, and 2030 jet fuel demand forecasts by country.

With the projection of total jet fuel consumption per country available, we are ready to estimate the SAF demand for 2030. Assuming that each country will exactly meet the political regulations on SAF usage, we derive the projected SAF demands by applying the EU's 6% SAF requirement [58] to each country's total jet fuel demand – barring the United Kingdom (not a member of the EU), which has instituted its own SAF mandate, stipulating a requirement of even 10% by 2030 [59].

Finally, for each country, we distribute the projected SAF demand across its airports proportional to their share of national jet fuel consumption. The latter, we derive from national jet fuel consumption figures in conjunction with traffic data from individual airports ([61], [62]). Table 4 exemplifies the approach for the Romanian airports included in our study.

| **Airport** | **Traffic Units** | **Share** | **Annual fuel consumption (in kilotonnes [kt])** |
|---|---|---|---|
| Henri Coanda Int. | 15,061,795 | 65.45% | 122.66 |
| Cluj Avram Int. | 2,958,570 | 12.86% | 24.09 |
| Traian Vuia Int. | 1,648,839 | 7.16% | 13.43 |
| Iasi Int. | 1,312,611 | 5.70% | 10.69 |
| Sibiu Int. | 731,588 | 3.18% | 5.96 |
| Craiova Int. | 514,110 | 2.23% | 4.19 |
| George Enescu Int. | 468,383 | 2.04% | 3.81 |
| Stefan cel Mere Int. | 317,875 | 1.38% | 2.59 |
| Total | 23,013,771 | 100% | 187.41 |

Table 4: Jet fuel consumption of Romanian airports in 2019, proportionalised to traffic volume ([61], [62]).

#### *3.1.4. Supply chain structures*

In accordance with our findings from Sections 2 and 3.1.1 to 3.1.3, we evaluate three distinct supply chain structures, differing in terms of the echelons involved (Sections 3.1.1 to 3.1.3) as well as the technologies and points of $CO_2$ capture and conversion. We detail these structures subsequently.

In *Structure I* (cf. Figure 4), $CO_2$ is directly captured from industrial emitters and, afterwards, transported via pipelines to refineries where it is transformed into formic acids (FA) which, in turn, are converted into fatty acid alkyl esters (FAA) and then, finally, into SAF. Lastly, the refineries directly supply the airports with SAF.

Whereas the conversion of $CO_2$ into FA is centralised at refineries in Structure I, *Structure II* introduces a decentralised approach as, e. g., suggested by interviewee A, an energy transition network organisation (cf. Table 1). Here, $CO_2$ is captured at the emitters' sites and immediately converted into FA using modular synthesis units, eliminating the necessity to transport $CO_2$. The synthesised FA is transported to refineries for conversion into SAF which are, again, directly supplied to airports (cf. Figure 5).

Confirmed by interviewees D and G, an energy transition consultant and an industrial company engaged in $CO_2$ capture (cf. Table 1), DAC is considered a promising alternative source of $CO_2$ ([18], [26]). *Structure III* investigates $CO_2$ capture exclusively from the atmosphere, permitting the production of SAF eliminating reliance on point-source emissions and resulting in a "green" $CO_2$ profile for the fuel. As can be seen in Figure 6, we assume $CO_2$ capture at the refinery sites with subsequent FA synthesis and SAF conversion (and, as usual, transport of the latter to the airports).

#### *3.1.5. Conversion yields, capture, conversion and transportation costs*

In this section, we briefly discuss our choice of all conversion- and transport-related parameter values. For an in-depth elaboration, the reader is referred to Appendix A.

The average $CO_2$ capture cost from point sources (i. e., emitters) is €24.70 per tonne. Since industries with lower $CO_2$ concentrations typically incur higher capture costs due to increased energy requirements for separation, we incorporate an industry-specific adjustment factor, $I_{t(i)}$, to this average cost. Here, $t(i)$ denotes the industry type of emitter $i$. Specifically, we include six types of industrial $CO_2$ emitters with their individual adjustment factors (cf. Table 5) as point sources in the optimisation model developed in Section 3.2. Clearly, economy-wide decarbonisation policies in the EU may lead to structural changes in some of these sectors, potentially reducing their emissions over time: power stations and refineries, e. g., may transition toward lower-carbon energy sources, affecting long-term $CO_2$ availability. However, our modeling approach accounts for this by providing flexibility in $CO_2$ sourcing and allowing for sensitivity analyses on $CO_2$ supply constraints.
Emerging technologies like DAC could supplement or replace such industrial point sources in the future, mitigating risks related to declining emissions from specific sectors. However, with a capture cost of €105 per tonne of

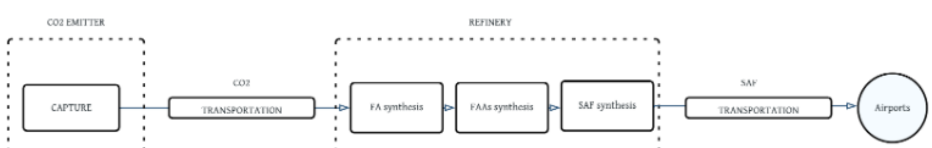



Figure 4: Supply Chain Structure I: Centralised conversion of industrial $CO_2$ into Formic Acid.


Figure 5: Supply Chain Structure II: Decentralised conversion of industrial $CO_2$ into Formic Acid with modular synthesis units.

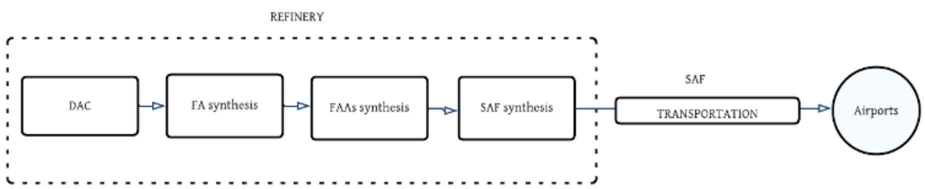



Figure 6: Supply Chain Structure III: SAF production using DAC at refineries.

$CO_2$ (assuming location-independent atmospheric $CO_2$ concentrations [63]), DAC is significantly more expensive than point source capture.

| **Industry** | **Cost variation** |
|---|---|
| Disposal | -65% |
| Fertilisers | -65% |
| Iron and steel | +38% |
| Cement | +18% |
| Refinery | +38% |
| Power station | +54% |

Table 5: Variation in capture cost between industries [64], [65].

Transforming $CO_2$ into FA is characterised by its conversion efficiency, referred to as *yield*, and conversion cost. For converting $CO_2$ into FA, we assume a yield of 0.80 tonnes of FA per tonne of $CO_2$ and a conversion cost of 264 €/t of $CO_2$ based on an estimated 25-year lifespan of the conversion unit (e.g., [29]). Analogously, the yield of transforming FA into SAF is assumed to be 0.375 tonnes of SAF per tonne of FA, incurring a conversion cost of 169.50 €/t of SAF.

Finally, transportation costs are – in-accordance with the scientific literature [66] – assumed to be linear in capacity and distance. Specifically, we consider both a distance-independent, but volume-dependent and a distance- and volume-dependent component. We refer to the former as fixed costs – primarily associated with material handling such as loading and unloading – and to the latter as variable costs which mostly relate to moving the commodity through the pipeline (e. g. fuel for pumps or compressors). For both $CO_2$ and SAF, we assume a fixed cost of 3.86 €/t and a variable cost of 0.07 €/(t · km), whereas FA is charged with a fixed cost of 3.86 €/t and a variable cost of 0.10 €/(t · km) to account for higher handling requirements. The distance between any pair of facilities $i$ and $j$ can be computed from location data.

Table 6 summarises the parameters, the notation we subsequently use to refer to them as well as their (default) values.

| **Parameter** | **Symbol** | **Value** | **Unit** |
|---|---|---|---|
| Capture cost $CO_2$ (DAC) | $C_{DAC}$ | 105.00 | €/t |
| Capture cost $CO_2$ (point source) | $C_{PS}$ | 24.70 | €/t |
| Capture cost modifier (point source) for the industry $t(i)$ of emitter $i$ | $I_{t(i)}$ | Table 5 | % |
| Conversion yield $CO_2$ → FA | $Y_{\mathrm{CO_2 \to FA}}$ | 0.80 | t FA/t $CO_2$ |
| Conversion yield FA → SAF | $Y_{\mathrm{FA \to SAF}}$ | 0.375 | t SAF/t FA |
| Conversion cost $CO_2$ → FA | $C_{\mathrm{CO_2 \to FA}}$ | 264.00 | €/t $CO_2$ |
| Conversion cost FA → SAF | $C_{\mathrm{FA \to SAF}}$ | 169.50 | €/t SAF |
| Distance between facilities $i$ and $j$ | $\delta_{i,j}$ | | km |
| Fixed transportation cost $CO_2$ | $FC_{\mathrm{CO_2}}$ | 3.86 | €/t |
| Fixed transportation cost FA | $FC_{\mathrm{FA}}$ | 3.86 | €/t |
| Fixed transportation cost SAF | $FC_{\mathrm{SAF}}$ | 3.86 | €/t |
| Variable transportation cost $CO_2$ | $VC_{\mathrm{CO_2}}$ | 0.07 | €/(t · km) |
| Variable transportation cost FA | $VC_{\mathrm{FA}}$ | 0.10 | €/(t · km) |
| Variable transportation cost SAF | $VC_{\mathrm{SAF}}$ | 0.07 | €/(t · km) |

Table 6: Cost and yield parameters and their values.

### *3.2. Mathematical optimisation model*

Besides the data collection and analysis, the other main building block of our study is the supply chain network optimisation. For that purpose, we rely on linear programming [67].

We start with a summary of the underlying assumptions:

1. The capture plants are co-located with $CO_2$ emission sources to eliminate flue gas transport.
2. Pipeline is the mode of transport for $CO_2$, FA and SAF due to their cost efficiency (cf. Section 2.1). We note that the optimisation framework allows for alternative transport modes and design variations by adjusting the arc weights. Therefore, in cases where infrastructure implementation plans are known, re-evaluating the model outcomes based on specific routing and construction scenarios is both possible and advisable.
3. Only existing refineries are used for SAF production in accordance with the anticipated industry trend (cf. Section 3.1.2).
4. The distances between emitters, refineries, and airports are calculated from geospatial coordinates.
5. Time-dependent values are averaged annually throughout the lifetime of the component.

Based on these assumptions, we now formalise the problem the linear program (LP) will represent. Note that we will describe the problem and define the model such that all three supply chain structures (cf. Section 3.1.4) are covered.

We define a directed graph $G = (V, K)$ where $V$ is the set of nodes and $K$ is the set of directed arcs. Specifically, $V = E \cup R \cup A$ where $E$ ($R$, $A$) is the set of nodes representing the industrial emitters (refineries, airports). With each node $e \in E$ we associate a weight $c_e$ representing its annual $CO_2$ emission capacity. Similarly, we associate a weight $d_a$ with each $a \in A$ defining the airport's annual SAF demand. Nodes are connected by the set of directed arcs $K = K' \cup K''$. Here, $K' = \{(e, r) : e \in E, r \in R\}$ represents the transport connections (pipelines) from emitters to refineries, and similarly, $K'' = \{(r, a) : r \in R, a \in A\}$ represents the transport connections (pipelines) from refineries to airports. With each arc $k \in K$, we associate a weight $w_k$ reflecting the cost per unit of flow on this arc. A flow $f_k$ on an arc $k = (i_k, j_k)$ assigns a non-negative number to said arc, representing the quantity transported from node $i_k$ to $j_k$.

A flow $f$ in graph $G$ is the entirety of flows on individual arcs. Flow $f$ is feasible if and only if

- for each emitter $e \in E$, the total outgoing flow does not exceed the capacity of $e$, $c_e$,
- for each airport $a \in A$, the total ingoing flow is at least as big as the demand of airport $a$, $d_a$, and
- for each refinery $r \in R$, the total outgoing flow from $r$ does not exceed its total ingoing flow, multiplied by a conversion factor $t$.

A flow $f$ is optimal if and only if it is feasible and there is no other feasible flow $f'$ with lower total cost $\sum_{k \in K} f'_k \cdot w_k < \sum_{k \in K} f_k \cdot w_k$.

Before modeling the problem defined above, we summarise the notation used in Table 7.

| **Sets** | |
|---|---|
| $A$ | set of nodes representing airports |
| $E$ | set of nodes representing $CO_2$ emitters |
| $K$ | set of all directed arcs representing transport connections |
| $K'$ | set of directed arcs representing transport connections from $CO_2$ emitters to refineries |
| $K''$ | set of directed arcs representing transport connections from refineries to airports |
| $R$ | set of nodes representing refineries |
| $V$ | set of all nodes representing $CO_2$ emitters, refineries and airports |
| **Parameters** | |
| $c_e$ | annual $CO_2$ emission capacity of emitter $e \in E$ |
| $d_a$ | annual SAF demand of airport $a \in A$ |
| $t$ | conversion factor |
| $w_k$ | cost per unit of flow on arc $k \in K$ |
| **Variables** | |
| $f_k$ | flow on arc $k \in K$ |

Table 7: Notation for the supply chain network optimisation LP.

With the problem and the notation defined, we are now ready to formulate the LP for the supply chain network optimisation:

$$\min \sum_{k \in K} w_k \cdot f_k \tag{1}$$

$$\sum_{k \in K': i_k = e} f_k \leq c_e \qquad \forall e \in E \tag{2}$$

$$\sum_{k \in K'': j_k = a} f_k \geq d_a \qquad \forall a \in A \tag{3}$$

$$\sum_{k \in K'': i_k = r} f_k \leq \sum_{k \in K': j_k = r} f_k \cdot t \qquad \forall r \in R \tag{4}$$

$$f_k \geq 0 \qquad \forall k \in K \tag{5}$$

Objective function (1) minimises the cost associated with flow $f$ while constraints (2) and (3) ensure that each emitter's capacity is respected and each airport's SAF demand is satisfied. Constraints (4) tie each refinery's inflow of intermediates to its SAF outflow. Finally, domain definitions (5) define non-negativity of flows on all arcs.

Subsequently, we shall argue that model (1) to (5) indeed captures all supply chain structures discussed in Section 3.1.4. In doing so, we link the LP's notation to the one defined in Table 6.

First of all, we notice that a positive flow $f_k$ on arc $k = (i_k, j_k)$ implies the emitters and refineries used.

Next, we define

$$t = Y_{\mathrm{CO_2 \to FA}} \cdot Y_{\mathrm{FA \to SAF}} \tag{6}$$

for all three structures to be evaluated.

Moreover, for Structure I, $f_k$ reflects the flow of $CO_2$ (FA) from an emitter (a refinery) to a refinery (an airport) for $k \in K'$ ($k \in K''$). Accordingly, we define

$$w_k = \begin{cases} C_{PS} \cdot (1 + I_{t(i_k)}) + C_{\mathrm{CO_2 \to FA}} + FC_{\mathrm{CO_2}} + \delta_{i_k, j_k} \cdot VC_{\mathrm{CO_2}}, & k \in K' \\ C_{\mathrm{FA \to SAF}} + FC_{\mathrm{SAF}} + \delta_{i_k, j_k} \cdot VC_{\mathrm{SAF}}, & k \in K'' \end{cases} \tag{7}$$

with, again, the notation from Table 6.

When $CO_2$ is converted into FA at the emitter sites (Structure II), $f_k$, $k \in K'$, is the $CO_2$ equivalent of the FA flow from emitter $i_k$ to refinery $j_k$. Therefore, for each $k \in K'$, we re-define in Equation (7)

$$w_k = C_{PS} \cdot (1 + I_{t(i_k)}) + C_{\mathrm{CO_2 \to FA}} + Y_{\mathrm{CO_2 \to FA}} \cdot (FC_{\mathrm{FA}} + \delta_{i_k, j_k} \cdot VC_{\mathrm{FA}}). \tag{8}$$

Finally, with DAC at refinery sites instead of point source capture (Structure III), we let each refinery $r \in R$ coincide with its own (artificial) emitter, i. e.

we define one artificial emitter $e(r)$ per refinery $r$ and $E = \{e(r) : r \in R\}$ as well as $K' = \{(e(r), r) : r \in R, e(r) \in E\}$. Moreover, for each $k \in K'$, we re-define in Equation (7)

$$w_k = C_{DAC} + C_{\mathrm{CO_2 \to FA}} \tag{9}$$

and, lastly, we set $c_e = \infty$ for each $e \in E$.

## 4. A comprehensive analysis of international SAF supply chains

In this section, we analyse the economic viability of the supply chain structures described in Section 3.1.4. In line with the scientific literature (e. g. [9], [36]), we base our analysis on the MJSP, i. e. the price at which all fuel production costs are accounted for (broadly speaking, the break-even point for SAF producers). For a given instance of our supply chain network optimisation problem, we calculate the MJSP as the optimal objective value divided by the total volume of SAF produced. In addition, we analyse the optimal solution's cost structure (i. e. the composition of the cost across the supply chain). We obtain an optimal solution via our LP from Section 3.2.

We organise our analysis according to the supply chain structures outlined in Section 3.1.4. Specifically, we start with investigating Structure I – the centralised conversion of $CO_2$ into FA in refineries – in Section 4.1. Subsequently, Section 4.2 assesses the decentralised conversion of $CO_2$ into FA at emitter sites using modular conversion units (Structure II), while Section 4.3 examines the implications of DAC at refineries (Structure III).

### *4.1. Structure I: centralised conversion of $CO_2$ into FA in refineries*

Structure I posits that $CO_2$ is captured at industrial emitters and subsequently transported to refineries for conversion into SAF. This section delineates the benefits of cross-border collaboration in SAF supply chains (Section 4.1.1) and delves into the impact of conversion yields, capture, conversion and transportation costs (Section 4.1.2).

#### *4.1.1. The impact of cross-border collaboration*

We start our analysis by evaluating whether – and if so, under which conditions – cross-border collaboration is beneficial in the design of SAF supply chains. In order to do so, we apply our LP to both the industry of each country individually and to the entire industry within the NW and SE cluster, respectively. For the capture, conversion and transport data from

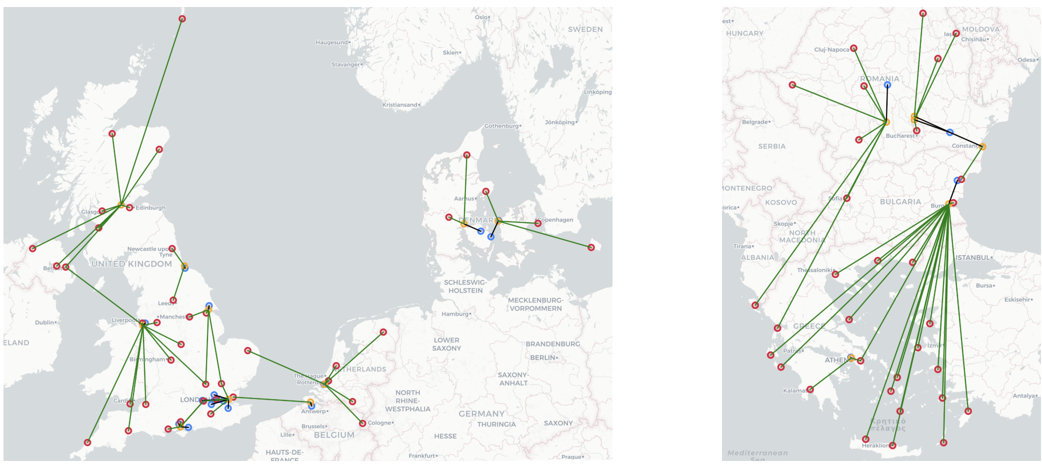
Table 6 and our 2030 SAF demand projections from Section 3.1.3, we obtain the results summarized in Table 8 (cf. Table 2 for the annual emissions in the countries included in this study).

| **Country** | **SAF demand 2030 (forecast in kt/y)** | **MJSP (€/t) domestic** | **MJSP (€/t) collaborative** |
|---|---|---|---|
| United Kingdom | 1352.20 | 1388 | |
| Netherlands | 283.58 | 1382 | 1387 |
| Denmark | 76.79 | 1390 | |
| Romania | 21.42 | 1412 | |
| Bulgaria | 21.66 | 1410 | 1434 |
| Greece | 92.18 | 1458 | |

Table 8: MJSPs for domestic and collaborative SAF supply chains in a 2030 high-demand scenario for Structure I (95% confidence interval).

We observe that, while collaboration in the SE cluster reduces the minimum jet selling price (MJSP) compared to the cluster's weighted average without collaboration (1443€/t), it has no noticeable impact in the NW cluster. A closer look at the collaborative supply chains' composition (Figure 7) explains this outcome: the supply chain design is primarily driven by the availability of emitters with high $CO_2$ purity – waste disposal sites and fertiliser manufacturers – which lower capture costs (see also Figure 1). In the NW cluster, the high emitter density and abundance of high-purity $CO_2$ sources across countries limit the benefit of collaboration, while in the SE cluster, where emitters are sparser and high-purity sources scarcer, cross-national supply chains become more advantageous (Figure 7b). Given that SAF transport is more cost-effective than $CO_2$ transport due to its lower volume, refineries near high-purity emitters are prioritised, even if this results in long-distance SAF distribution. For instance, a single refinery in Burgas, Bulgaria, supplies up to 18 Greek airports, sourcing all required $CO_2$ from a nearby fertiliser plant with 243 kt annual emissions – sufficient to meet these airports' SAF demand. Nonetheless, the SE cluster's MJSP remains 3.4% higher than the NW cluster's due to slightly higher capture costs and longer transport distances.

We acknowledge, however, that while these longer SAF transport distances may be favorable from a cost perspective, they can adversely affect the life cycle assessment of SAF. Increased transport distances – especially by road – may lead to higher emissions, potentially diminishing the environmental benefit of centralized supply chains. Recent studies highlight these trade-offs: [68] emphasize that feedstock transport can significantly influence SAF emissions, particularly in biomass-derived pathways; [69] show that maritime and rail transport have lower emissions than road.

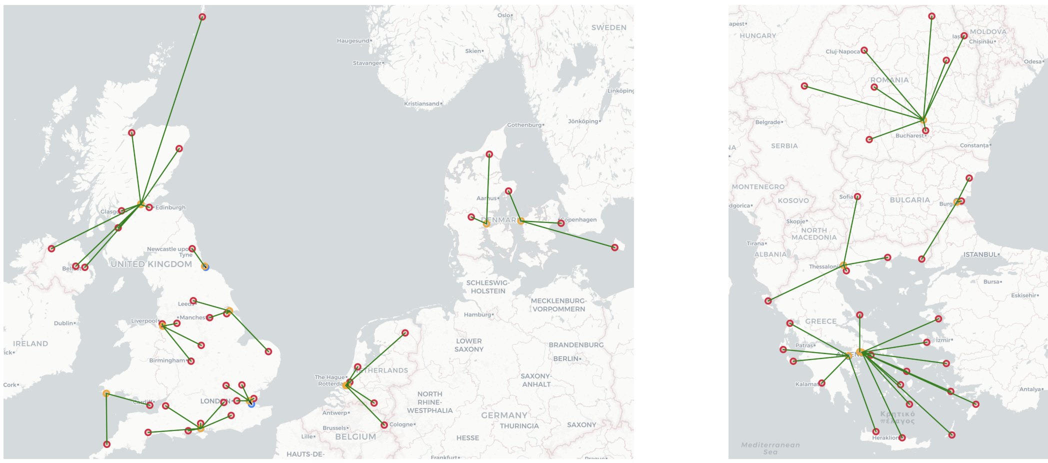



(a) Northwest Europe

(b) Southeast Europe

Figure 7: Optimal emitter (blue) and refinery (yellow) selection for airports (red) in Structure I with emitter **industry-dependent** capture cost.

Under decreasing capture cost due to technological advancement, the geographical distribution of emitters, refineries, and airports will become even more pronounced as the focus of supply chain optimisation shifts towards transport cost (and, therefore, distances). We emulate such a scenario by eliminating industry-specific capture cost entirely (i. e. we set $I_{t(i_k)} = 0$ for all $k \in K'$ in Equation (7)). The resulting supply chains in both clusters are depicted in Figure 8. Not surprisingly, proximity is now fundamental to minimising overall cost (via the impact of transportation cost) with $CO_2$ primarily sourced from the selected refineries' own emissions. In the NW cluster with its comparatively dense industrial infrastructure, this leads to supply chains turning completely domestic (Figure 8a), while cross-border supply chains remain in the SE cluster (Figure 8b). An increase of 3.6% in the NW cluster's MJSP contrasted with an only marginal increase of 0.6% for the SE cluster (as compared to a scenario with industry-specific capture cost) confirms the advantage of location coming with an abundance of high-purity $CO_2$ sources.




(a) Northwest Europe

(b) Southeast Europe

Figure 8: Optimal emitter (blue; mostly hidden behind refineries) and refinery (yellow) selection for airports (red) in Structure I with emitter **industry-independent** capture cost.

At roughly 1400 €/t, the MJSP across all scenarios so far proves to be competitive with what is currently the sole commercially viable method for SAF production, the HEFA pathway (cf. Section 2.2), with MJSPs reported in the literature ranging from 750 up to 1690 €/t ([43], [70], [71]) depending on the feedstock. This aligns with recent findings that stress the importance of regional resource synergies and infrastructure sharing in improving the economic competitiveness of SAF pathways [72]. As noted by interviewee E, a producer of SAF (cf. Table 1), however, HEFA's scalability is significantly restricted by the limited availability of suitable feedstocks, necessitating the exploration of alternative production methods. Production pathways based on an abundantly available feedstock like $CO_2$ provide such an alternative. Nevertheless, the price of fossil jet fuel, currently approximated at €685 per tonne [37], remains less than half of the calculated MJSP, making technological developments a prerequisite for economic viability of $CO_2$-based SAF.

It is important to note that the cost estimates presented in this study differ from the reference prices reported by the European Union Aviation Safety Agency (EASA), which range between €6,820 and €9,405 per tonne for synthetic aviation fuel derived from captured $CO_2$. This discrepancy is primarily attributable to key differences in system scope, design assumptions, and modeling approach: the EASA estimates are based on conservative techno-economic assumptions, reflecting current or near-term technology readiness levels, smaller-scale facilities, and less optimised supply chains. In contrast, our study evaluates an optimised supply network configuration that leverages economies of scale, minimises transport and capture costs through strategic siting, and selects cost-effective emitters with high $CO_2$ purity. Additionally, our model integrates cross-border collaboration and centralised refining where beneficial, further lowering the MJSP. As such, our results represent a techno-economic potential under idealised coordination and optimisation. We emphasise that this distinction is crucial when interpreting the comparability of our results with other reference values.

#### *4.1.2. The impact of conversion yields, capture, conversion and transport cost on the MJSP*

Knowing now that cross-border collaboration in SAF supply chains has a positive impact on the MJSP – especially in sparsely industrialised countries with scarcity of high-purity $CO_2$ point sources –, we go on to examine the sensitivity of the MJSP to variations in cost and yield parameters. We do so by varying each cost parameter's default value from Table 6 between $-50\%$ and $+50\%$, capturing both the usual cost uncertainties as well as cost reductions and increases due to maturing technologies and infrastructure investments, respectively.

The results for both the NW and the SE cluster are depicted in Figure 9. It is evident that the MJSP is largely driven by conversion cost, particularly the conversion from $CO_2$ to FA. Considering the order of magnitude of the conversion cost as compared to point source capture and transport (cf. Table 6), this is expected. While this is consistent for both clusters, we notice a subtle difference between the clusters upon a more detailed inspection: although marginal overall in either cluster, the variable cost of transport of both $CO_2$ and SAF has a much higher impact in the SE cluster (roughly five times as high as in the NW cluster). We can interpret this as the cost of a comparatively sparse industrial network: the fairly limited availability of $CO_2$ emitters – especially of high-purity emitters – and refineries drives transport distances and, hence, variable transport cost. Consequently, we expect a (partial) reduction of this effect when emitter dependencies are mitigated through, e. g., DAC technology. In Section 4.3, we will investigate whether this is indeed the case.

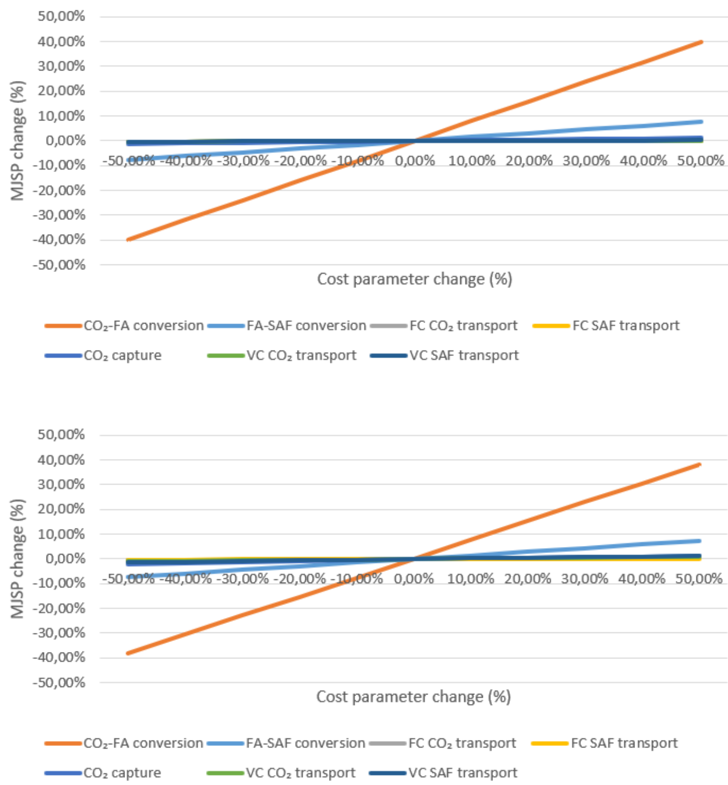



Figure 9: Sensitivity of MJSP with respect to cost parameters in the NW (top) and SE (bottom) cluster under Structure I.

With the previous findings indicating that the road to economic viability of CCU-based SAF leads through the reduction of conversion cost, it is worth noting that improvements could also result from leveraging the conversion yield. Altering our default total product yield $Y_{CO_2 \rightarrow FA} \cdot Y_{FA \rightarrow SAF} = 0.3$ – i. e. 1 kilogram of $CO_2$ generates 0.3 kilograms of SAF – within the range of 0.1 to 0.6 and plotting the resulting MJSP in Figure 10 confirms the key role of conversion processes in SAF production. However, our analyses also reveals that in fact substantial improvements are required for achieving the economic viability of CCU-based SAF production as compared to fossil jet fuel.

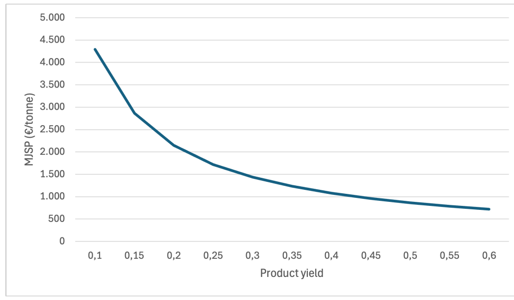



Figure 10: Sensitivity of MJSP with respect to total product yield.

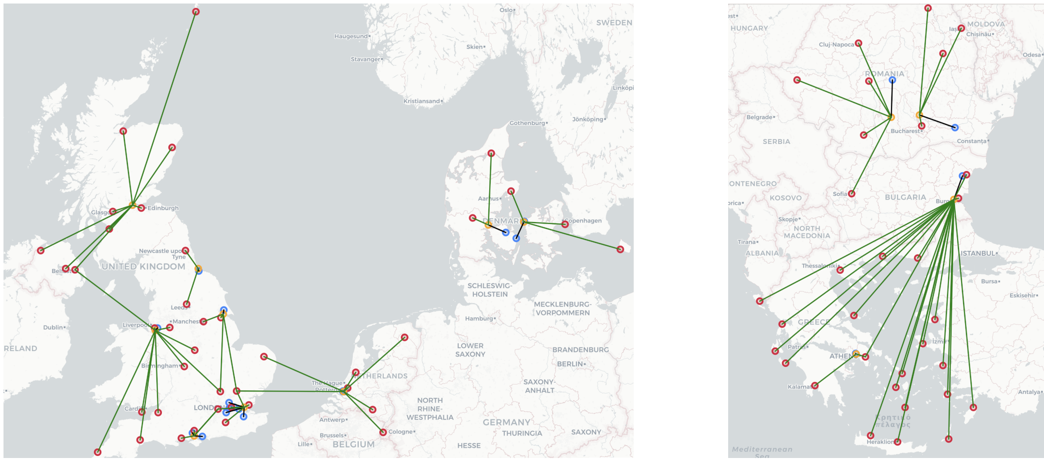
### *4.2. Structure II: decentralised conversion of $CO_2$ into FA at emitter sites*

Structure II, as illustrated in Figure 5, incorporates modular synthesis units designed to convert $CO_2$ into FA directly at an emitter's location. While this reduces the volume transported from emitters to refineries by a factor of $Y_{CO_2 \rightarrow FA} = 0.8$ as compared to Structure I, the variable transportation cost per tonne per kilometre increases ($VC_{\text{FA}} = 0.10 > VC_{\text{CO}_2} = 0.07$). Consequently, transportation costs decrease over short distances due to the reduced volume of FA, whereas they increase over longer distances because of the higher variable cost. The break-even distance $\delta$ can be determined by Equation (10)

$$FC_{\text{CO}_2} + \delta \cdot VC_{\text{CO}_2} = Y_{\text{CO}_2 \rightarrow \text{FA}} \cdot (FC_{\text{FA}} + \delta \cdot VC_{\text{FA}}) \tag{10}$$

indicating that for emitters located less than 77.2 km from refineries, the transportation of FA is more cost-effective than that of $CO_2$ in our study (cf. Table 6). The implications for the optimal supply chain design in cluster NW and SE are illustrated in Figure 11a and 11b, respectively. While, as compared to Structure I (Figure 7), the more cost-effective short-distance supply (of FA instead of $CO_2$) from emitters to refineries leads to a shift of supply chain designs to a reduced number of strategically positioned refineries, the MJSPs remain largely unaffected with €1385 per tonne in the NW cluster and €1434 per tonne in the SE cluster.

Given the overall marginal impact of transport costs as compared to conversion costs, this result is expected – just as the (almost) identical sensitivity pattern the MJSP exhibits when varying the default cost parameters from Table 6 (cf. Figure 12). A major impact of the modular conversion units may, however, come in the conversion process rather than with the transport: considering the reduced volumes managed by modular units, their




(a) Northwest Europe

(b) Southeast Europe

Figure 11: Optimised supply chains with modular conversion units (Structure II).

actual conversion cost may be higher in comparison to $CO_2$ conversion in refineries. The severity of the consequences for the economic viability of SAF production become evident in Figure 12.

### *4.3. Structure III: DAC at refineries*

Structure III, as illustrated in Figure 6, incorporates DAC technology, enabling the extraction of $CO_2$ directly from the atmosphere. Although DAC represents a promising and innovative approach, its current implementation encounters challenges owing to high and uncertain capture costs with estimates ranging from €90 to as much as €367 per tonne of $CO_2$ [73]. In accordance with substantial reductions anticipated as the technology continues to mature [63], we assume a capture cost of €105 per tonne in our analysis. The resulting optimal supply chain configurations for the default values from Table 6 are depicted in Figure 13.
DAC obviates the necessity for industrial emitters within the supply chain, as $CO_2$ is captured directly at the refinery sites. Consequently, we observe supply chains solely consisting of airports and refineries strategically located to minimise SAF transportation costs by prioritising proximity to airports.

A breakdown of the MJSP, combined with a sensitivity analysis analogous to Structures I and II, provides further insights into the economic details of DAC. The aforementioned strategic selection of refineries results in a 55% reduction in transport costs for SAF in comparison to Structure I in addi-

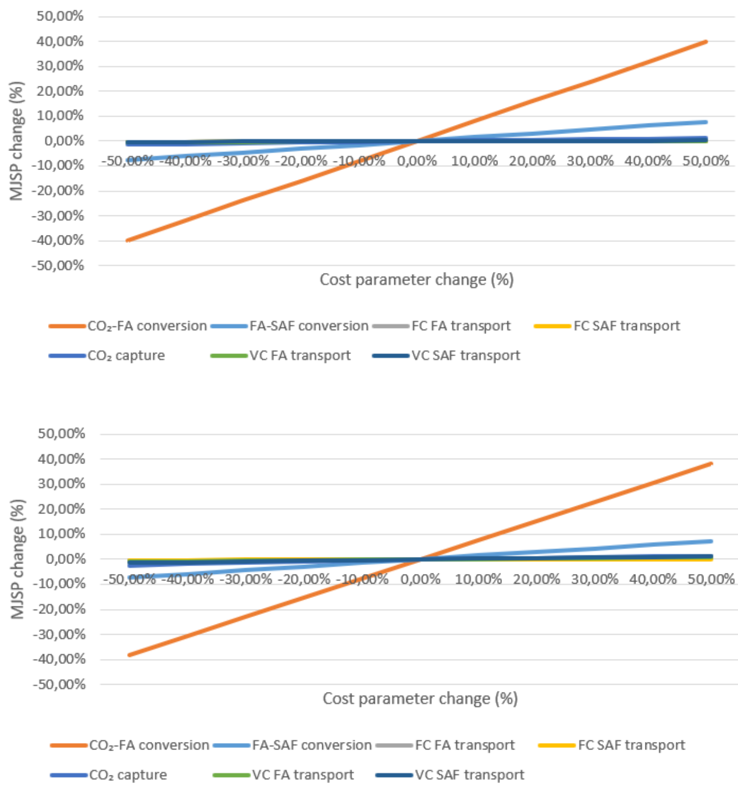
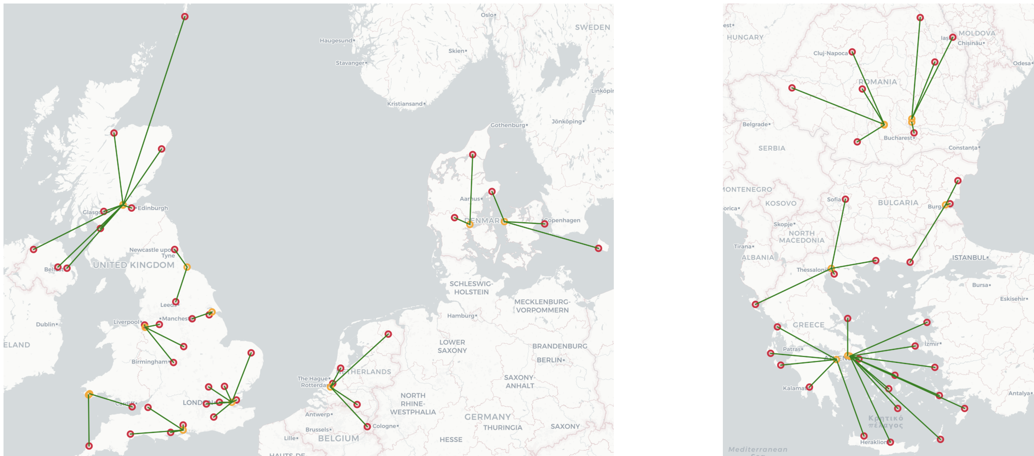



Figure 12: Sensitivity of MJSP with respect to cost parameters in the NW (top) and SE (bottom) cluster under Structure II.

tion to entirely omitting $CO_2$ transport. However, despite this reduction in transportation costs, the drastically increased capture costs associated with DAC drive the MJSP to €1691 (€1697) per tonne – a 22% (18%) increase in the NW (SE) cluster (Figure 14). Therefore, while we indeed see a mitigation yet not an elimination of the "price of infrastructure sparsity" as anticipated in Section 4.1.2 – the MJSP is still twice as sensitive to the variable transport costs of SAF in the SE cluster as in the NW cluster (Figure 15) –, the capture cost offsetting the savings in the overall marginal transport cost deems DAC economically infeasible. This is in line with studies such as [74], which underscore the economic infeasibility of DAC in the short term due to high energy demand and cost intensity of current DAC technologies. However, beyond that, our analysis also reveals that even substantial capture cost savings




(a) Northwest Europe (b) Southeast Europe

Figure 13: Optimised supply chains with DAC (Structure III).

(e. g., from technological progress) will still have an only moderate impact on DAC's economic viability (cf. Figure 15).

Despite the impact of the capture cost, it is evident in both Figure 14 and 15 that conversion costs are the key driver of the MJSP, emphasising the need for advancing conversion technologies to achieve economic viability of SAF.

## 5. Conclusion

In this study, we developed a generic mathematical optimisation model for the design of CCU and SAF supply chains. The research can guide decision-making for SAF production, specifically by integrating CCU into the SAF supply chain. Via the use of this framework we analysed the economic feasibility of CCU-based SAF production in two European country clusters with a particular focus on cross-border collaboration. This framework and our results are validated by industry experts in the field, underscoring its practical value as a decision-support tool.

A main takeaway is that cross-border SAF supply chains can offer substantial economic benefits, especially for regions with limited domestic $CO_2$ point sources. By accessing high-purity $CO_2$ from neighboring countries, these supply chains can overcome local $CO_2$ scarcity, where the savings in capture costs from foreign sources outweigh the added transport costs. This

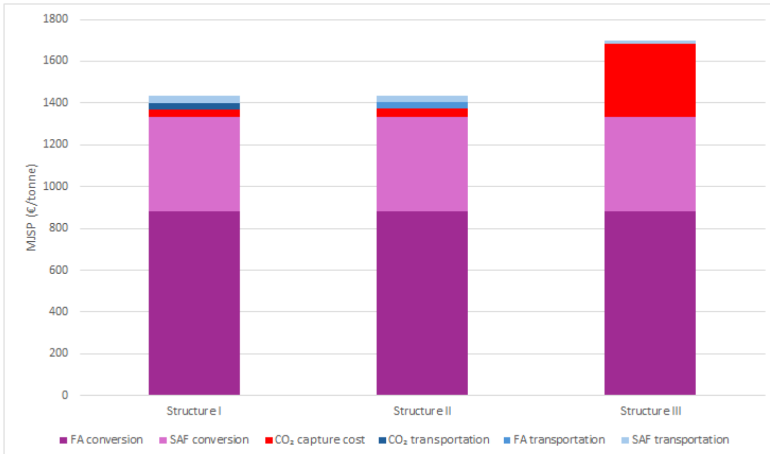



Figure 14: Breakdown of MJSP with centralised (Structure I) and decentralised (Structure II) conversion of $CO_2$ into Formic Acid and DAC (Structure III).

insight is valuable for the strategic planning of regional cooperation and infrastructure investments in Europe, where a diverse range of industrial capabilities exists across countries.

Although cross-border CCU-based SAF supply chains can rival the only commercially viable pathway – hydroprocessed esters and fatty acids – their MJSP remains roughly twice that of conventional jet fuel. Specifically, we find the $CO_2$-to-fuel conversion costs driving the MJSP, accounting for up to 92% of the MJSP in point-source-based CCU pathways – a finding that is consistent with conclusions from previous studies. For example, [44] and [48] both highlight the conversion step as the primary economic bottleneck in synthetic fuel production pathways. Moreover, our model indicates that while CCU-based SAF remains roughly twice as expensive as fossil jet fuel, it approaches the cost range of HEFA in scenarios with access to low-cost, high-purity $CO_2$ via cross-border collaboration. This aligns with recent findings that stress the importance of regional resource synergies and infrastructure sharing in improving the economic competitiveness of SAF pathways [75]. Further, our analysis of DAC's limited economic viability in the short term is consistent with studies such as [74], which underscore the high energy demand and cost intensity of current DAC technologies. We find that, while DAC

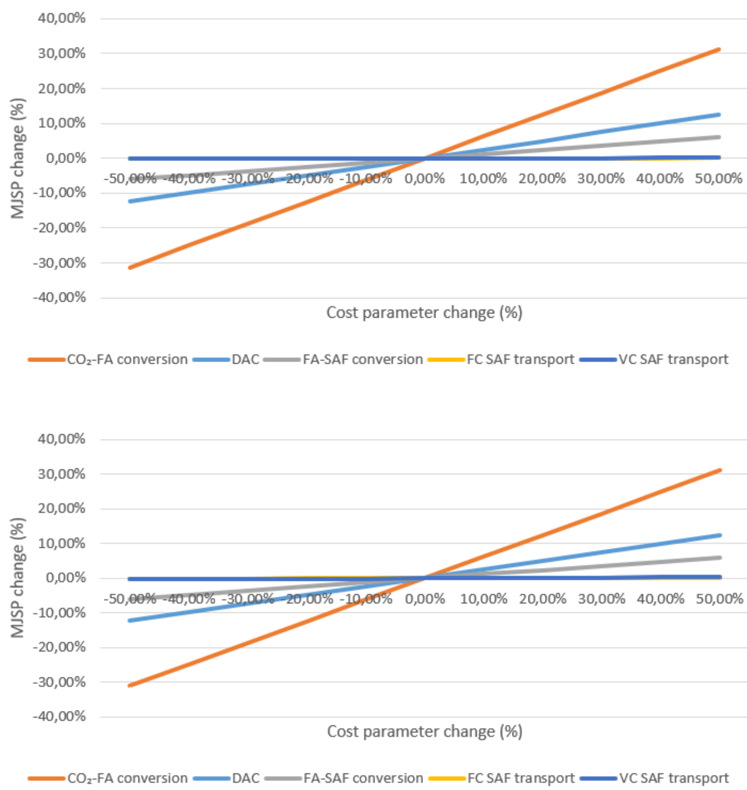



Figure 15: Sensitivity of MJSP with respect to cost parameters in the NW (top) and SE (bottom) cluster under Structure III.

mitigates dependence on emitter availability, it does not enhance economic viability. Quite the reverse: its substantially higher costs compared to point source capture render it economically infeasible for the foreseeable future.

In conclusion, all capture technologies and cross-border collaboration put aside, the future economic viability of SAF production is heavily dependent on technological advancements in conversion processes. However, a breakthrough in conversion cost reduction would emphasise the relative impact of supply chain logistics and transport costs, making investment decisions for cross-country infrastructure a particularly delicate matter that should carefully consider the expected development of capture technologies. In sparsely industrialised regions, reliance on $CO_2$ point sources justifies investments in cross-border networks. However, a future shift toward domestic sourcing via DAC would render such infrastructure redundant. Given the uncertain trajectory of DAC's technological progress and the relative insensitivity of MJSPs to transport costs, more flexible and slightly costlier transport options may be preferable to long-term infrastructure investments. Whatever developments the future may bring, the framework presented in this research provides policy makers, industry stakeholders, and researchers with a tool to assess the evolving trade-offs and opportunities in SAF supply chains, ensuring alignment between technology development, infrastructure planning, and decarbonisation goals.

While our findings align with previous research, certain limitations must be acknowledged. First, capture and conversion costs are based on current projections, which are expected to evolve as these relatively immature technologies advance. Similarly, cost calculations rely on specific assumptions from the literature, such as linear pipeline transport costs [66] and conversion costs based on a 25-year facility lifespan [56]. Although our sensitivity analysis covers a broad range of cost parameters, we emphasise the need for continuous integration of technological advancements to better guide decarbonisation efforts – our optimisation model offers the flexibility to accommodate such updates.
Adding to its current scope and functionality, our framework for supply chain optimisation should be extended beyond CCU and SAF production in the future. Expanding the analysis to incorporate storage processes as well as the production and logistics of (green) hydrogen, seems like a logical next step in achieving a comprehensive economic assessment of e-fuels.

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## Appendix A. Cost estimation

### *Appendix A.1. Capture cost*

In this analysis, we assume a $CO_2$ capture cost ($C_{PS}$) of €24.7 per tonne from point sources, excluding industry-specific adjustments. This estimate is based on studies conducted by the ConsenCUS project at three industrial sites: Aalborg Portland (a Danish cement plant), Petrobrazi (a Romanian refinery), and Grecian Magnesite (a Greek magnesite facility) [76]. These facilities report flue gas $CO_2$ concentrations ranging from 3% to 19%. Capture tests employing the alkali absorption technology developed by ConsenCUS yielded a cost estimate of €24.7 per tonne of $CO_2$.

### *Appendix A.2. Transportation cost*

Assuming pipeline transport for both feedstock and SAF, transportation costs are modeled based on the annualised capital expenditure (CAPEX) and operational expenditure (OPEX) of the pipelines. These costs are influenced by two primary parameters: capacity and distance. A linear model incorporating these parameters effectively represents transportation costs [66].

The total transportation cost ($TC$) is calculated using Equation (A.1):

$$TC = Q \cdot (FC + \delta \cdot VC)\,, \tag{A.1}$$

where $Q$ denotes the transported volume, $\delta$ is the distance between start and end point, and $FC$ and $VC$ represent the distance-independent (fixed) and distance-dependent (variable) cost, respectively.

For fuel transportation, $FC$ is estimated at approximately €3.86/t, while $VC$ ranges from €0.05 to €0.07/(t · km) [77]. These values also align with typical $CO_2$ transportation costs. By default, we set $VC$ to €0.07/(t · km) for both $CO_2$ and SAF. However, for FA transport, $VC$ is set at €0.10/(t · km) to account for additional handling requirements.

*Appendix A.3. Conversion costs and yields*

To estimate FA conversion costs, we assessed both CAPEX and OPEX (cf. [78]). An expert interview (Interviewee C, Table 1) validated the conversion yield ($Y_{CO_2 \rightarrow FA}$). Table A.1 summarises the cost parameters and the total cost of ownership (TCO) for FA conversion, assuming a 25-year operational lifespan of the conversion unit, consistent with assumptions made by ConsenCUS [56]. The conversion cost $C_{CO_2 \rightarrow FA}$ is then computed by multiplying the TCO by $Y_{CO_2 \rightarrow FA}$, resulting in a value of €264 per tonne of $CO_2$.

| | |
|---|---|
| CAPEX (M€/y) | 0.89 |
| OPEX (M€/y) | 1.75 |
| TCO (€/t FA) | 330 |
| $Y_{CO_2 \rightarrow FA}$ | 0.8 |

Table A.1: FA conversion-related yields and costs.

Just as we established the conversion cost from $CO_2$ to FA, we derive the conversion cost from FA to SAF, denoted as $C_{FA \rightarrow SAF}$, based on the associated TCO and conversion yield.

It is important to note that the conversion from FA to SAF is not a direct process. First, FA must be converted into FAA, which is then synthesised into SAF. The typical conversion yield from FA to FAA is 0.5. The subsequent conversion from FAA to SAF via the HEFA pathway generally achieves a yield of 0.75 to 0.85 per unit of feedstock, as reported in the literature [79]. However, Interviewee C (cf. Table 1) estimated a lower yield of approximately 0.5. As a compromise, we adopt an intermediate yield of 0.75. Consequently, the overall conversion yield from FA to SAF, $Y_{FA \rightarrow SAF}$, equals $0.5 \cdot 0.75 = 0.375$.

To estimate the TCO for the conversion of FA to SAF, we conducted a comprehensive analysis of multiple case studies focusing on the HEFA pathway for biofuels ([80], [81], [82]). These studies, based on various feedstocks and process configurations, report CAPEX estimates ranging from €13 million to €387 million, and OPEX variations between €22.7 million and €180 million per year, with refinery capacities spanning from 12 million to 230 million litres per year (ML/y).

Assuming a refinery lifespan of 25 years, as suggested by the literature (e. g., [29]), we compute the TCO for SAF to be €452 per tonne using an interest rate of 8% over the refinery's expected lifespan. Table A.2 summarises the results.

| | |
|---|---|
| CAPEX (M€/y) | 14.50 |
| OPEX (M€/y) | 107.37 |
| TCO (€/t SAF) | 452 |
| $Y_{\mathrm{FA}\rightarrow\mathrm{SAF}}$ | 0.375 |

Table A.2: SAF conversion-related yields and costs.

Finally, we compute the conversion cost from FA into SAF, $C_{\mathrm{FA}\rightarrow\mathrm{SAF}}$, from the TCO and the conversion yields as $\mathrm{TCO} \cdot Y_{\mathrm{FA}\rightarrow\mathrm{SAF}} = 169.5$ €/t.