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OPTIMAL CCUS SUPPLY CHAIN CONFIGURATIONS FOR PRODUCTION OF E-METHANOL, DECARBONIZED UREA AND SUSTAINABLE AVIATION FUEL IN THE NORTHWEST AND SOUTHEAST CONSENCUS CLUSTERS

<u>SCENARIO ANALYSES</u>

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ABSTRACT

This paper shows the optimal CCUS supply chains for the northwest (NW) and southeast (SE) ConsenCUS clusters in a 2030 setting, whereby decarbonized urea, e-methanol and sustainable aviation fuel (SAF) are produced and excess CO_2 captured is stored. It provides a valuable addition to the literature as there are no studies that optimize for this combination of end-uses and areas. By utilizing CO_2 and/or storing it in CO_2 storage sites, total emissions may be reduced. The three end-uses have growing demands, hence researching this end-use proves useful. During this research, various stakeholders of CCUS projects were interviewed in order to formulate scenarios. The scenarios analyzed include an international and national configuration as well as a single end-use setting. It was found that supply chains constructed in the international scenario (scenario 1) have the lowest total costs of 4,36 and 3,69 billion €/year for the NW and SE clusters respectively, whereas the national supply chain configurations (scenario 2) are most expensive, costing 5,29 and 4,48 billion €/year. In the international setting (scenario 1), 3,80% of total emissions may be captured, though the national supply chains (scenario 2) are able to capture more (4,78%). For these supply chains, conversion costs were the most significant cost factor of total costs. Given that (national) renewable levelized cost of electricity (LCOE) is the main determinant for conversion costs, total costs for international (scenario 1) configurations may be reduced by 29,36% for NW supply chains and 16,45% for SE supply chains, given that the best possible renewable LCOE scenario develops. For national (scenario 2) supply chains, total costs may reduce by 20,38% for the NW cluster and increase by 53,26% for the SE cluster due to differences in national renewable LCOE. The single-end use scenario (scenario 3) found that storages are optimal for supply chains with low end-use demands. For these, costs are minimized if all storages identified by ConsenCUS become available. If storages with low readiness levels become unavailable, costs may increase with 0,09% in the NW cluster. SE cluster cost would be largely affected if onshore storages become unavailable, as it will experience a 0,15% cost increase.

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1. INTRODUCTION

It is widely acknowledged that industrial activities have drastically increased CO_2 emissions, thereby promoting climate change. Negative effects of climate change include (among others) severe storms, increased drought, rising oceans, a loss of species, food shortages, health risks and poverty (United Nations, n.d.). To combat climate change and its negative impacts, the European Union set the goal to obtain a carbon-neutral industry by the year 2050 (IEA, 2017). This goal was established in the Paris Agreement of 2015. To achieve this goal, industries could make use of Carbon Capture Utilization and Storage (CCUS) technology. According to IEA (2017), CCUS systems could decrease greenhouse gas emissions by 7 Gt annually by 2050. This amounts to almost 15% of the total annual GHG emissions in 2019 (Richie & Roser, 2020).

CCUS technologies rely on industries capturing the CO_2 released by their production processes. After the capturing stage, the CO_2 is compressed and transported to storage sites or it is utilized as feedstock for new products. A graphical explanation of the structure of CCUS is offered in figure 1. The storage option (CCS, Carbon Capture and Storage) implies that captured CO_2 is injected into underground storage sites. Currently, there are two main options for CO_2 storage available, namely saline aquifers (SA) and depleted oil and gas fields (DOGF), which can be located on- or offshore. The CO_2 utilization option (CCU, Carbon Capture and Utilization) is different from the storage option as the captured CO_2 is not stored but re-used for the production of several commodities that are generally polluting upon use. Urea, methanol and aviation fuel are examples of such commodities. Urea contains carbon that dissipates into the air in the form of CO_2 once it has been applied to the soil (West and McBride, 2005). Such emissions can be countered by combining captured CO_2 with "green" ammonia (ammonia produced with renewable electricity) to form carbon neutral urea. Similarly, conventionally produced methanol uses natural gas, biomass or coal as feedstock (Basile & Dalena, 2017), whereby "new" CO_2 is released into the atmosphere upon combustion. Hence, carbon neutral production methods can be applied to form e-methanol from captured CO_2 and water using electrolysis. A final example is aviation fuel, which is generally produced from fossil fuels as well. To counter CO_2 emissions, sustainable aviation fuel (SAF) can be produced using carbon neutral methods. The aforementioned products (decarbonized urea, e-methanol and SAF) are the only CO_2 utilization commodities considered by this thesis.

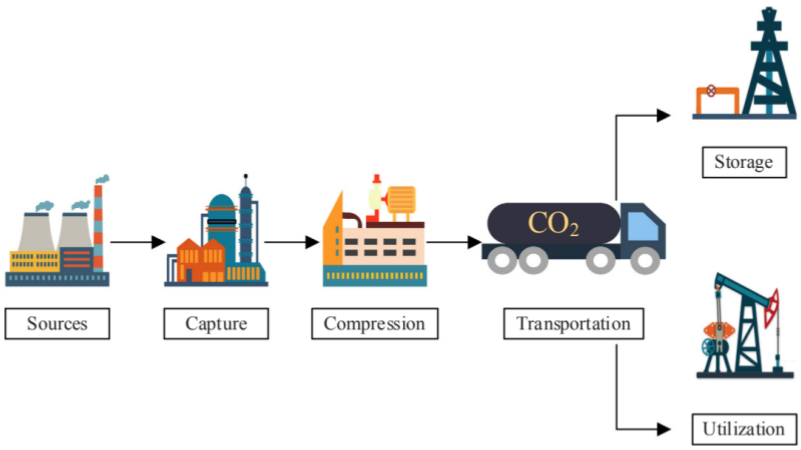


Figure 1 – CCUS structure (Zhang et al. 2020)

The ConsenCUS initiative intends to organize such CCU and CCS practices across Europe. Specifically, it aims to provide "an industrial roadmap to a net-zero carbon future" by forming "carbon neutral clusters" (ConsenCUS, n.d.). Currently, there are 19 partners from 7 countries collaborating in the ConsenCUS project, each creating carbon neutral clusters located across northwest and southeast Europe. The formation of an integrated cluster among carbon emitters, commodity producers and end-users benefits all parties as it allows for an efficient exchange of resources (CO_2 or end-products) between nodes.

Past research has been performed on the optimization of supply chain networks for CCUS (Hasan et al., 2015, d'Amore & Bezzo, 2017, Zhang et al, 2018, Zhang et al. 2020, Leonzio et al, 2020). These have explained the economic constraints of CCS as well as CCU networks and their associated feasibility. Case studies by Wasserman et al. (2022), Collodi, Azzaro, Ferrari & Santos (2017) and Pérez-Fortes et al. (2014) investigated the optimal supply chains for CO_2 utilization. However, these studies generally focus on one specific region or a set of countries not associated with the ConsenCUS project. The optimal supply chain found in these studies cannot be replicated across all countries as each country has varying amounts of CO_2 supply, utilization and end-use demand. In other words, it is important to realize country specific differences. The aforementioned studies also focus on a combination of end-uses and/or storage that is different from the combination studied in this thesis. Thus, this study addresses a combination of end-uses and storage that is new to the literature and therefore aims to add to the literature by preforming a CCUS optimization study for a novel combination of end-uses and storage that is specific to the ConsenCUS country clusters (NW and SE), thereby posing the following research question:

What are the optimal structures for CCUS supply chains in the NW and SE clusters in which decarbonized urea, e-methanol and SAF are produced and excess CO_2 is stored?

This research question will be addressed by solving various instances of a deterministic linear programming model. The model is constrained to find the minimal total costs of a CCUS supply chain, given the experiment settings of each respective instance. There are multiple instances: each instance represents a different scenario with different data points. Scenarios are computed based on various sources including (CCUS) literature, ConsenCUS and interviews conducted with parties involved.

This study is relevant as it could aid CO_2 emitters and end-users to reuse or store CO_2 in the most cost-efficient manner. To date, there is only little demand for CO_2 as a resource compared to the global anthropogenic CO_2 emissions reaching 37 Gton CO_2 per year (Zhang et al., 2020). However, if CO_2 is used as feedstock, all end-use synthesis processes have the potential to avoid approximately 2% of the EU's CO_2 emissions (about 3.54 Gt CO_2 per year, Götz, 2016). To reach the 2050 climate goals, it is expected that utilization of CO_2 for each of the three end-uses will increase. This claim is supported by the global demand growth for methanol as a fuel: according to the Transforming Energy Scenario (IRENA, 2021) demand will grow to 500 Mt by 2050. It implies the potential for e-methanol to directly replace fossil methanol. Furthermore, e-methanol has the potential to replace a significant quantity of petroleum-based hydrocarbons and petrochemicals, either directly or through methanol derivatives (IRENA, 2021). A similar demand growth is expected for SAF as the aviation industry is expected to experience a four to six-fold growth by 2050, thus increased attention has been paid to reduce its carbon footprint (Gonzalez-Garay, 2022). O'Malley et al. (2021) argue that SAF will take up 5,5% of the projected 2030 EU fuel demand, whereas it only accounted for 0,05% in 2019. Urea demand predictions show similar patterns due to the predicted population growth. As the global population is expected to grow to 9.1 billion in 2050, food production is expected to increase with 100-110% in 2050 compared to 2005 (Tilman et al, 2011). This implies a significant increase in fertilizer production, with estimates ranging between 50% and 100% in 2050 compared to 2005. Considering the fact that natural gas is currently the major raw material for ammonia manufacturing (and hence for urea) it can be said that decarbonized urea has the ability to replace fossil urea in the near future as the EU is working towards a net-zero carbon industry.

The structure of this thesis is as follows. A theoretical background summing up the existing CCUS literature and this study's literature contribution will be provided. Following this, the methodology applied to answer the research question will be explained. Next, the data used for the experiments is outlined, after which the scenarios are presented. Subsequently, he results of each experiment will be presented followed by a conclusion with managerial takeaways, limitations and suggestions for future research.

2. THEORETICAL BACKGROUND

This section will give a detailed overview of the literature on the various CCU supply chain elements. The utilization of CO_2 will be specified for the three end-uses decarbonized urea, e-methanol and SAF. In this paper, CO_2 storage will be considered as a fourth end-use that comes into play if CO_2 demand for the other three end-uses has already been satisfied.

2.1 Capture

Capturing CO_2 is the first stage of CCUS. There are three primary types of industrial CO_2 capture systems, namely post-combustion capture systems, pre-combustion capture systems, and oxyfuel combustion systems (Zhang et al., 2018; Leung et al., 2014). Each of these methods are used in different settings. There is not a single method that is best, this depends on CO_2 compositions and flow rates (Hasan et al., 2015). The concentration of CO_2 in the flue gases is also relevant. The majority of emitters release CO_2 at a concentration of 15% or less (Wilcox, 2012). Every source varies from others regarding the rate of CO_2 flow, the composition of CO_2 in the exhaust flue gas, and the moisture content of the flue gas. Furthermore, higher concentrations of CO_2 in flue gas generally result in lower costs (Hasan et al., 2015). CO_2 concentrations are usually consistent among emitters in a certain industry (Leung et al., 2014).

Various authors have argued against the economic feasibility of CO_2 capturing (Blomen, 2009, Leung et al., 2014, Hasan et al., 2015). For instance, Blomen (2009) states that CO_2 capture contributes around 70–80% to the overall cost of CCS system. Therefore, according to Hasan et al. (2015), it is crucial to prioritize the capturing stage in the CCUS network as it incurs the highest costs.

2.2 Transportation

After capture, CO_2 must be transported to a utilization or storage site. Research by Zhang et al., (2018) suggests that transportation can be facilitated by pipelines (onshore and offshore), ships, train tankers, and trucks. According to Leonzio, Foscolo & Zondervan (2020), pipelines are the most technologically advanced transportation method whilst also having the lowest costs. The literature agrees that this is the main transport option to be modeled (Leung et al., 2014, IEA, 2020; NPC, 2019). Only in scenarios where offshore CO_2 storage is the aim, shipping could be viable (depending on volume and distance, IEA, 2020). Rail and truck transport is rarely done and typically allows transportation of very small CO_2 volumes (Smith, 2021). However, current pipeline infrastructures are not in place but are attributed a large role in the future of CCUS (Stewart et al., 2014).

The three end-uses also require transportation. As urea often comes in prilled form, it requires transport by truck. E-methanol and SAF can be transported by pipeline (Nugroho et al., 2022), but as was the case with CO_2 pipelines, there are no e-methanol and or SAF pipelines in place. No predictions on pipeline construction for these end-uses were found.

2.3 Utilization

The possible end-uses for CO_2 investigated by this thesis are urea, e-methanol and SAF production, though there are many additional end-uses for CO_2. According to Dalena and Basile (2018), the most used applications of captured CO_2 are urea (180 Mt per year), inorganic carbonates (60 Mt per year), polyurethane (15 Mt per year), polycarbonates (5 Mt per year), and salicylic acid (0.17 Mt per year). Surprisingly, there is currently little amounts of captured CO_2 being utilized. In a SETIS report, Dobrée (2016) commented on the uses of CO_2. It was found that the industrial sector utilizes 130 million tons of CO_2 each year for various processes, including enhanced oil recovery (EOR, accounting for 60 million tons), urea/fertilizer production (accounting for 36 million tons), and other applications such as the food and beverage industry. It was predicted that this quantity could increase by a factor of five in 2030. Finally, utilization technologies are likely to be attractive to large CO_2 industrial emitters, especially in areas where it might not be possible to geologically store CO_2 (Chauvy, de Weireld, 2020). The following research is available for each end-use researched in this thesis.

Decarbonized urea

The first end-use considered is urea. Urea is a chemical consisting of about 46% nitrogen and it is one of the primary sources of nitrogen supply for plants among chemical fertilizers. It is available for purchase in the form of prilled or granules (Dobrée, 2016). Apart from its use as fertilizer, it has a variety of other applications, including the production of melamine, urea-formaldehyde resin, and ruminant dietary supplement (Koohestanian et al., 2018). Urea is synthesized by reacting liquid ammonia and CO_2 (Chehrazi, 2022). To make the process carbon neutral, it is necessary to synthesize ammonia by combining hydrogen and nitrogen and not via fossil fuel. The hydrogen required for this process must come from electrolysis, which means that renewable energy sources must be used to power the electrolyzer (Pérez-Fortes, 2016). Research finds that the operating costs for decarbonized (carbon neutral) urea are higher than its benefits, with electricity being the primary cost element. From analysis, Pérez-Fortes (2016) shows that the most influential variables are electricity, investment cost, and urea selling prices.

Demand for urea is consistent with population growth: The European urea market is projected to grow up to 2030, which would result in a CO_2 feedstock demand of 7 Mt/year (Pérez-Fortes, 2016). This implies a growth in carbon neutral urea demand in the coming years.

E-methanol

The second end-use of CO_2 studied in this thesis is methanol, specifically e-methanol. Methanol serves as a crucial chemical building block for the manufacture of formaldehyde, acetic acid, and methylamine and olefines (Dalena & Basile, 2017). These can in turn be used for various commodities like paints, furniture, windshields, car parts, carpets and plastic but also for fuels (Collodi et al., 2017). Methanol can be derived through three pathways according to Dalena & Basile (2017). The first two methods involve the production of synthesis gas (or: "syngas") from different types of fossil fuels. This syngas is then converted into crude methanol after which it is refined. The first method uses natural gas to form syngas, whereas the second method uses coal and biomass. Methanol from biomass ("bio-methanol") is carbon neutral but not considered in this thesis as it does not make use of captured CO_2 from industry. Approximately 90% of methanol is produced from natural gas (Blug et al., 2014). The third and final pathway is methanol from catalytic hydrogenation of CO_2, whereby syngas is generated and used to produce methanol. If this methanol is produced with green hydrogen, i.e., hydrogen produced with renewable electricity, then this methanol can be considered e-methanol (given that non-fossil CO_2 was used). Green hydrogen is obtained by water electrolysis employing renewable electricity (Sollai et al., 2023). Fuels made with green hydrogen are often referred to as Power-to-X. A negative aspect of Power-to-X is that CO_2 bonds require high energy to break and renewable electricity is expensive. Therefore, producing e-methanol is currently not competitive. Luckily, researchers find that it is expected to become more competitive in the mid-term future, due to new European policies being established. Given these high costs, there is currently less than 1 percent renewable methanol being produced compared to methanol from gas (65%) and coal (35%) according to IRENA (2021).

Demand for methanol as fuel has gained significant popularity due to the regulatory and policy changes in the transportation industry (Collodi et al., 2017): many countries are enforcing a fuel blending standard ranging from 5% to 100% methanol.

SAF

Sustainable Aviation Fuel (SAF) is the third end-use that will be considered by this paper. SAF is used as a substitute for conventional aviation fuels. It can be synthesized using through various pathways, including the Fischer-Tropsch (FT) process, Hydro-processing (HP, also called fatty acid pathway), and Alcohol to Jet (ATJ) processes. The FT process involves converting biomass-derived syngas into long-chain hydrocarbons, while HP converts vegetable oils or animal fats into hydrocarbons through hydrotreating and hydrocracking. ATJ involves converting alcohols into jet fuel through dehydration, oligomerization, and hydrogenation.

According to an article by Le Feuvre (2019), the IEA's New Policies Scenario, the demand for oil in the aviation industry is expected to increase by approximately 15% by 2030. This is similar to the expected growth in demand from passenger vehicles. Such an increase in demand will result in aviation accounting for approximately 3,5% of global energy-related CO_2 emissions by 2030, compared to just over 2,5% at present, even though there are ongoing efforts to improve aviation efficiency (Le Feuvre, 2019). Similar to methanol, SAF demand increases through the adoption of fuel blending standards. Different SAF variants (ATJ, HP) have different standards for fuel blends. SAF blending goals are set based on the proportion of SAF to be used in relation to the overall national fuel consumption. For instance, the European Union's target is to achieve 5% SAF utilization by 2030 and 63% by 2050, according to EASA's report (2022).

<u>Storage</u>

This paper considers storage to be a final end-use. Carbon storage (CCS) is an important end-use if all demand for captured CO_2 is already satisfied and there is no other way in which it can be utilized. Chauvy & de Weireld (2020) expect that it could be possible to utilize up to 10% of anthropogenic CO_2. The other 90% will have to be stored. There are various technicalities that come into play with CCS.

CO_2 can be stored in geological formations such as depleted oil or gas fields (DOGF), saline aquifers (SA), or it can be dissolved into seawater (Davidson, 2001). The expenses associated with CCS vary greatly depending on the storage characteristics (IEAGHG, 2011). Characteristics include location (onshore or offshore), field type (DOGF or SA), and capacity. Onshore DOGFs offer the most cost-effective solution. However, these reservoirs are not very common and therefore less accessible. Nonetheless, they are currently the main option for CCS projects as these fields are well established and have already shown their capability of storing gases without contaminating the environment. In contrast, offshore SAs come at a much higher cost (IEAGHG, 2011). The reason for this is the significant pre-FID (Final Investment Decision) costs incurred due to the need for exploration. This is particularly true for SAs as there is a higher risk of spending funds on exploring aquifers that may end up not be suitable for storage (Davidson, 2001).

2.4 Contribution

Table 3 below provides an overview of the existing literature on CCUS supply chain optimizations. As said, CCS is being considered a final end-use in this research. Note that the research subject column also contains the country (countries) that was (were) studied in the research. One difference between this thesis and the existing literature is the range of end-uses studied. Table 3 shows that the specific combination of end-uses and storage investigated by this thesis was not studied by any other research. That is, most of the existing literature aims to optimize CCS supply chains (this includes Zhang et al., 2018, Hasan et al., 2015, d'Amore, 2017) or CCUS supply chains whereby urea and methanol are the only studied end-uses (this includes Leonzio, Foscolo & Zondervan, 2020, Zhang et al., 2020 and Jarvis & Samsatli, 2018). No studies were found that consider SAF as end-use in combination with methanol and urea. If SAF is studied as end-use, it is considered a sole end-use (see Wasserman et al., 2022). A second difference between this study and the existing research is the country or set of countries that was investigated by each paper. Some studies have analyzed international interaction between countries (Leonzio, Foscolo & Zondervan, 2020 and d'Amore, 2017) but most of the literature considers merely one specific country. It was explained before that each country has differing amounts of CO_2 supply and end-use demand, making it important to study individual country differences. This research studies a set of countries that has not been studied in combination before. Namely, it looks at the SE European (Bulgaria, Romania and Greece) and NW European (Denmark, The Netherlands and the UK) ConsenCUS clusters and considers their individual CO_2 supply and end-use demand levels as well as their combined levels. This allows to find interactions between member countries, which, (as said) have not been widely found before.

Research subject	Author	CCU (methanol)	CCU (urea)	CCU (SAF)	CCS (storage)
Optimization of supply chain for utilization (non-specific end-use) and storage in **China** (case study).	Zhang et al., 2018				✓
Optimization SC network CCS and CCU (EOR) in the **US.**	Hasan et al., 2015				✓
Optimization of CCS supply chain in **Europe.**	d'Amore & Bezzo, 2017				✓
Optimization of CCUS supply chain in **Germany** (storage and methanol utilization).	Leonzio et al., 2020	✓			✓
Optimization op CCUS supply chain in **Germany, Italy** and **the UK.**	Leonzio, Foscolo & Zondervan, 2020	✓	✓		✓
Optimization of CCU supply chain for SAF in **Germany**	Wasserman et al., 2022			✓	
Optimization of CCUS supply chain in **China** (scenario analysis)	Zhang et al., 2020	✓	✓		✓
Optimization of CCUS supply chain for CO_2 storage and methane production in **Italy**	Leonzio & Zondervan, 2020				✓
Cost analysis of CO_2 conversion (utilization: urea/methanol) technologies in **the UK.**	Jarvis & Samsatli, 2018	✓	✓		✓
Cost analysis for methanol, urea and SAF from captured CO_2 in **SE** and **NW Europe.**	*This study*	✓	✓	✓	✓

Table 3 – Literature table

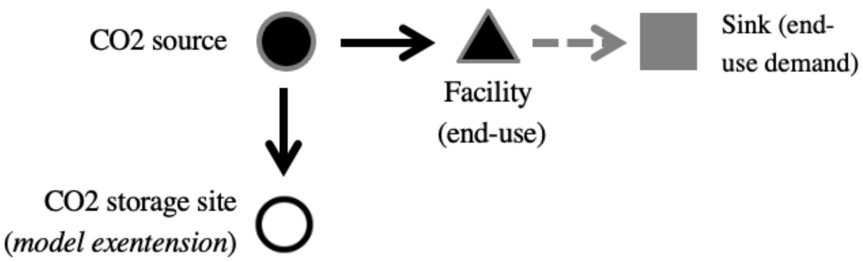
3. METHODOLOGY

A model developed by Wouda, Romeijnders, Ursavas will be used to optimize a CCU supply chain for the northwest and southeast clusters. The model is further explained in the upcoming section. Additionally, interviews have been conducted in order formulate various scenarios. After the scenario results had been constructed, interviews were held for validation purposes. In the following sections, the interviews conducted, scenario formulation and data descriptions will be provided.

3.1 Conceptual model

The conceptual model used for this thesis is an extension of the model developed by Wouda, Romeijnders and Ursavas (2023). Their model aims to provide a network of construction decisions, whereby decisions are selected if the sum of their costs is minimized. This sum is given by the objective function given below. It represents the minimal total costs of all elements of the supply chain. Various constraints are applied to the model which will be explained below. Instances of the objective function are solved using deterministic linear programming. Each scenario is analyzed by solving different deterministic instances of the model and for each instance the experiment settings (datapoints) have been altered to fit the circumstances of the given scenario. Figure 2 provides a simplified visualization of the model used across the scenarios. The sets of vertices and edges that are depicted by this figure are explained by the legend below. Following this, the assumptions, input parameters and decision variables are defined. Finally, the constraints applied to the model are provided.

Figure 2 –visualization of model by Wouda, Romeijnders and Ursavas (2023)



V, nodes

The set of vertices (nodes) V of the acyclic graph $G = (V, E)$ that represent construction decisions. The vertices V consist of three subsets, namely a set of source nodes (emitters) V^u, facility nodes (conversion) V^f and sink nodes (consumption/storage) V^v. This results in $V = V^u \cup V^f \cup V^v$. The model is extended to contain storage node, but this node is not dependent on any construction decision.

E, edges

The set of edges E included in $G = (V, E)$. These represent the construction decisions for the flow of resources within and between nodes.

<u>Assumptions</u>

(1) The costs, CO_2 supply and product yields are constant over time (only demand for end-uses has a time factor applied to it).
(2) Capacities of facilities are constant over time and it they are similar across all facility nodes in the dataset.
(3) Currently existing facilities selected for construction are able to convert to renewable electricity-based solutions in a 2030 setting.
(4) CO_2 storage capacity for leftover CO_2 emissions will only depend on injection rate (which is linear and stays constant) and not on total storage capacity.

(5) CO_2 storage injection rate is equal to the average injection rate across storage sites and is similar for each type of site (DOGF or SA).
(6) To determine e-methanol demand, container vessels must have a set number of days travelled per year and a constant average speed.
(7) CO_2 capture and transportation costs as well as conversion costs and transport costs of end-products are linear, meaning that greater quantities of CO_2 captured and transported will not result in lower costs per ton CO_2.
(8) Industry capture costs with similar flue gas characteristics have equal costs.
(9) CO_2 pipeline infrastructure is currently non-existent and has to be constructed. The lifetime of such a pipeline is 50 years.
(10) Transport to sinks is done via truck and is outsourced.
(11) Trucks are always fully loaded.
(12) Transport capacity from facilities to sinks is equal to the demand of the sink it is transported to.
(13) Conversion costs are dependent on the yield of the respective end-product.
(14) Conversion costs for urea are constant with ammonia conversion costs.
(15) Renewability of electricity at transport edges is not considered for total emission calculations.

<u>Parameters</u>

Node set	Edge set
(1) $\varphi_u, \varphi_f, \varphi_v, \varphi_s$ = Latitude for source, facility, sink and storage nodes respectively (coordinate, continuous)	(1) c_u = CO_2 capture costs at source node (€/ton R)
(2) $\lambda_u, \lambda_f, \lambda_v, \lambda_s$ = Longitude for source, facility, sink and storage nodes respectively (coordinate, continuous)	(2) c_{uf}, c_{us} = end-use to sink transport costs (€/ton R)
(3) *Rs* = resource supplied/released (categorical: 0 = CO_2, methanol = 1, urea = 2, SAF = 3)	(3) = CO_2 transport costs from source node to facility node (€/ton R)
(4) *Rr* = resource required/inputted (categorical: 0 = CO_2, methanol = 1, urea = 2, SAF = 3)	(4) c_f = CO_2 conversion costs at facility (€/ton R)
(5) $d_j(\omega^s)$= demand at the sink (indexed by s, ton R per year)	(5) c_{fv} = end-use to sink transport costs (€/ton R)
(6) $u_i(\omega^s)*$ = resource supply at the source (indexed by s, ton R per year)	(6) c_s = end-use to sink transport costs (€/ton R)
	(7) σ_u* = capacity CO_2 captured at source (ton CO_2/year)
	(8) σ_{uf}, σ_{us} = capacity of CO_2 transport to facility or storage (ton CO_2/year)
	(9) σ_s* = capacity CO_2 injection at storage (ton CO_2/year
	(10) σ_f = conversion capacity of facility (ton R/year)
	(11) σ_{fv}= capacity of end-use transport (ton R/year)

* Capacity at the source edge equals the supply at the relative source node but both are required as separate model parameters.

Decision variables

1. x_{ij} = Network decision for edges; binary for node edges (1 if constructed, 0 otherwise), continuous for edges between nodes.
2. c_{ij} = Individual edge cost for edges included in the network decisions expressed in €/year. Depending on edge types c_{ij} is the result of the multiplication between edge decision x_{ij} (binary or continuous) and the respective capture (c_u), conversion (c_f), or transport (c_{uf}, c_{us}, c_{fv}) cost.

Objective function

The above variables form the objective of the model, which aims to minimize the cost of constructing a network of decisions $x = (x)_{ij} \geq 0$ on the edges $(i,j) \in E$. This can be written as follows:

$$\min_{x,f,z} \sum_{(i,j)\in E} c_{ij} x_{ij}$$

In other words, the addition of all edge construction decisions x_{ij} (construction decision, binary for nodes and continuous for edges) multiplied with edge costs c_{ij} (depending on the edge type decision $c_{ij} = \{c_u, c_f, c_{uf}, c_{fv}, c_{us}\}$).

Constraints

The above objective function has the following constraints (explanations provided below):

(1) $\sum_{s\in S} p_s z_s \leq \alpha$
(2) $\sum_{j\in I(i)} f_{ji}^s = \sum_{j\in O(i)} f_{ij}^s$
(3) $f_{ij}^s \leq b_{ij}(x, \omega^s)$
(4) $\sum_{j\in V^v} f_{jv}^s \geq d(\omega^s)(1 - z_s)$
(5) $f_{ij}^s \geq 0$
(6) $x_{ij} \geq 0$
(7) $z_s \in \{0, 1\}$
(8) $\sum_{i\in V^v} f_{ij} \geq \sigma_u x_i$

(1) *Feasibility constraint:* the model's subproblem determines whether a scenario is feasible or not. The fraction of infeasible scenarios allowed is defined by α. Therefore, the probability (p) that an infeasible scenario ($z_s = 1$) occurs must be lower than α. If parameters are deterministic then the number of scenarios is 1 and α < 1 must be satisfied in order to obtain any decision.
(2) *Balance constraint:* The feasible edge flows (f_{ij}^s) of *R* between sources, sinks and facilities at each edge must be balanced with outflows of *R*. The balance constraint does not apply to storage nodes. Storage nodes are not subjected to balance constraints because the inflow of CO_2 from source nodes to sink (storage) nodes does not have to equal the inflow of CO_2 from the sink (storage) nodes to the artificial sink nodes.
(3) *Capacity constraint:* Feasible flow (f_{ij}^s) of resources *R* along edges may not exceed capacities b_{ij} for network decisions (*x*) or for scenario-specific demand rate of that resource (ω^s).
(4) *Demand constraint:* the feasible flow (f_{jv}^s) of *R* to sink nodes will always be equal or greater than the scenario-specific demand ($d(\omega^s)$) for the respective *R*, thereby satisfying end-use demand in any feasible scenario (as represented by z_s). For infeasible scenarios demand does not have to be satisfied.
(5) *Minimum flow constraint:* The feasible flow (f_{ij}^s) of *R* along the edges must be equal to or greater than 0.

(6) *Minimum network decision constraint:* The number of edge decisions (x_{ij}) must be equal or greater than 0.
(7) *Scenario feasibility factor constraint:* The factor determining the feasibility of a scenario (z_s) must be 0 (feasible) or 1 (infeasible).
(8) *Storage constraint:* The edge flow of CO_2 from all source nodes that does not flow into facilities must be stored at storage nodes. Without a constraint for storage, the excess CO_2 emitted by source nodes but not utilized by facility nodes will enter the atmosphere. This storage constraint determines that all source flows of CO_2 (f_{ij}) to sink (storage) nodes is greater or equal to the CO_2 capture capacity (σ_u) of the source node, given that this emitter is selected as a network decision (x_i). The original model created by Wouda et al. (2023) does not incorporate this constraint. Hence, this new constraint can be considered an addition to the model.

3.2 Interviews

Interviews will be used to construct plausible scenarios as well as verify their results. This research includes six newly conducted interviews with experts on the topic of CCU and CCS as well as seven previously conducted interviews. The table below displays the company, country, the interviewee (representative of the company) and the subjects covered during the interviews. The complete interview transcripts can be found in appendix 8.

Company	Country	Interviewee	Subject	Appendix number
Previously conducted interviews				
CO_2 Smart Use	The Netherlands	Petrus Postma	CO_2 utilization feasibility	10.1
MOL group	Hungary	Csaba Gal	Current state and future of CO_2 storage	10.2
INEOS	Denmark	Johan Byskov Svendsen	CCU (e-methanol) and CCS	10.3
GreenChem	Denmark	Juanita Davila	CCS offshore/onshore	10.4
Gasunie	The Netherlands	Gareth Noble	CCS/CCU/transportation methods	10.5
Neste	The Netherlands	-	SAF production	10.6
SkyNRG	The Netherlands	-	SAF production	10.7
New/personally conducted interviews				
ISPT (methanol project, networking for CCU)	The Netherlands	Antonie de Haas	E-methanol incentives in the Netherlands	10.8
European Energy (e-methanol)	Denmark	Alexander Reumert	Power-to-X (e-methanol), green hydrogen	10.9
GeoEcoMar (research on geological storage)	Romania	Alexandra Dudu	CO_2 storage in Europe	10.10
Stamicarbon (urea plant design)	The Netherlands	Joey Dobrée	Urea manufacturing and demand	10.11
ConsenCUS	Denmark	Kate Harboe	Model discussion and validation (scenario 1 and 2)	10.12
BGS	The UK	Karen Kirk	Model validation (scenario 3)	10.13

Table 4 – Overview of interviews conducted

3.3 Data collection

This section will discuss the fundamental data that will be used for each model parameter. It will be applied across all scenarios, though some parameters are changed for sequential scenarios (this will be indicated in experimental settings). The upcoming section outlines locations of CO_2 emitters, end-use facilities, end-use consumers and CO_2 storage sites. The locations of CO_2 emitters will be discussed first, followed by the locations of conversion facilities and storage sites. After this, the demand for each end-use will be determined. Cost parameters for each supply chain element will be discussed last. Capacity parameters will also be supplied in this section.

3.3.1 CO_2 emitters $(\varphi_u, \lambda_u, \sigma_u)$

Data on emitters and end-uses is provided by ConsenCUS (ConsenCUS.eu, 2022A). This database lists emitters and provides their coordinates and respective quantity of CO_2 emissions. The data has been selected based on industry and company-lifetime expectations. Companies were grouped based on industry in order to make distinctions between capturing costs. The selected emitters operate in the fertilizer, cement, power generation, oil and gas refinement, iron, steel and waste disposal industry. The factories that are expected to be closed due to bankruptcy have been excluded. Financial status of each plant has been verified by consulting the ORBIS database (ORBIS, 2022). Moreover, plants utilizing coal for operations are also excluded as European coal regulations imply that coal will not be utilized anymore in 2030 (European Commission, n.d.). In table 5, the total number of emissions per country is given.

Table 5 lists countries in both clusters from highest to lowest emissions. Note how the UK has the highest emissions and Bulgaria has the lowest. With the UK on top and the Netherlands closely following, the NW cluster emits more than twice as much as the SE cluster. Out of all countries, Bulgaria and Denmark have the least CO_2 emissions. Total NW emissions add up to 158,3 Mt. Romania and Greece dominate the SE cluster emissions. In this cluster the total emissions entail 45,9 Mt. Across clusters, it can be said that the electricity sector and fertilizer industry emit a large portion of total CO_2. The waste disposal sector is quite small and sites operating in this industry are only present in the NW cluster.

Figures 3 and 4 below are the maps of the participant countries of the NW and SE clusters. The diameters of the circles represent the quantity of emissions at that specific location. Industrial activities are clustered in most areas. Specifically, there is one large industrial cluster in the Centre of the UK and one along the West coast of the Netherlands. Note that the same scale is applied across all countries which allows for comparison between emitters of various industries, clusters and countries. Even though this thesis considers a 2030 setting, emissions data is from 2022. This is because emissions are assumed to stay constant (as described by the methodology section).

Cluster	Country	Total emissions (Mton/year)	Number of emitters
Northwest	Netherlands	78,3	72
	United Kingdom	70,7	104
	Denmark	9,3	36
Southeast	Romania	24,8	44
	Greece	16,2	20
	Bulgaria	4,8	11

Table 5 – CO_2 emissions for the selected countries

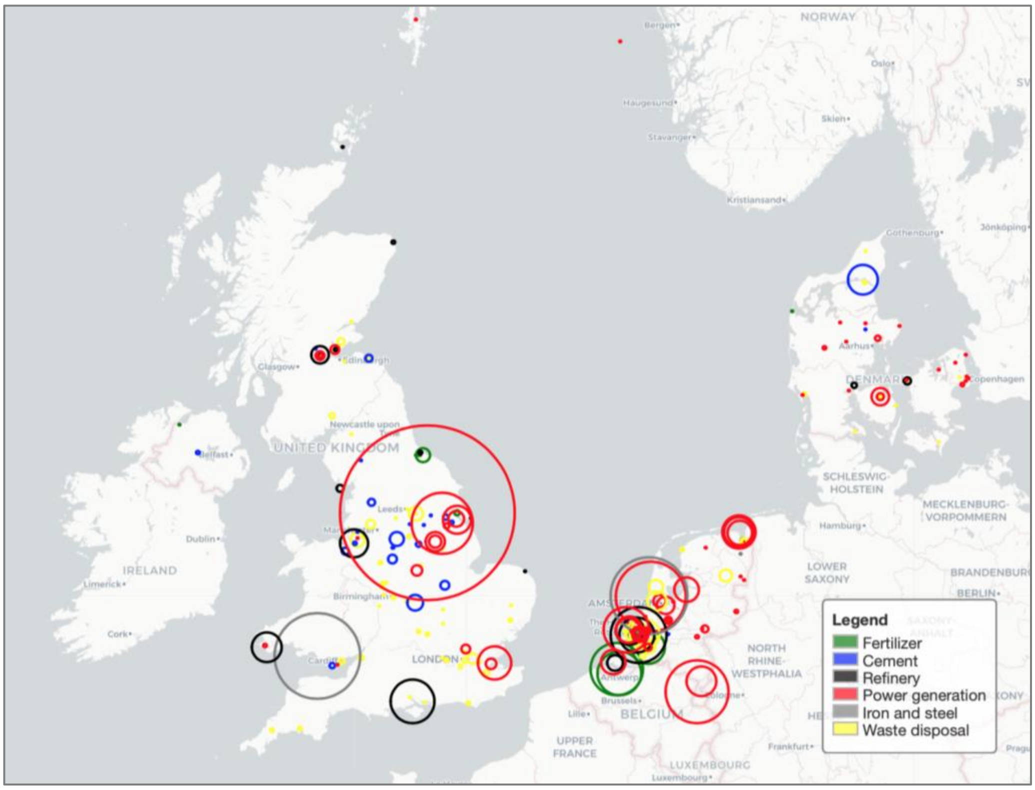


Figure 3 – CO_2 emissions for the NW cluster

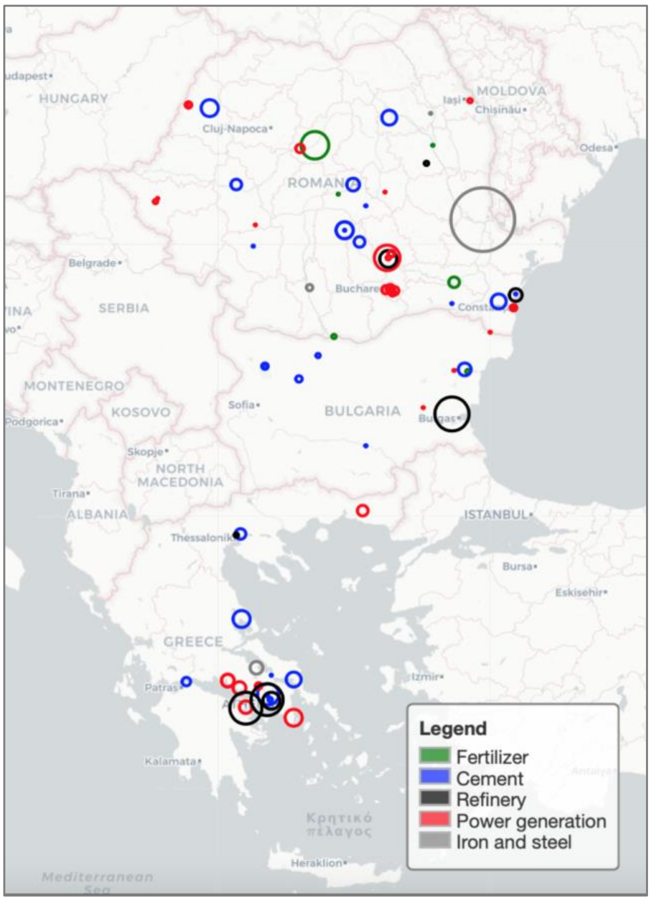


Figure 4 – CO_2 emissions for the NW cluster

3.3.2 Conversion sites e-methanol, urea and SAF ($\varphi_f, \lambda_f, \sigma_f$)

Facilities that convert CO_2 into the three end-uses are selected with a high level of uncertainty. Namely, production data for facilities (no matter the industry) is often classified or willingly excluded for public access for strategic reasons. Nonetheless, this thesis uses five separate databases to identify urea, methanol and SAF conversion facilities expected to be operational by 2030.

The first source used to find plants is the ORBIS database (2022). ORBIS provides worldwide data on companies and the industry they operate in. The data was filtered on reporting years (2018-2023), NACE code and trade description. NACE code 2014 and 2015 were used to find methanol and urea facilities. Upon further inspection of the online presence of companies, 193 companies were gathered. These companies represent current or previous years' operations and are expected to still operate in the respective industries by 2030. Secondly, GEO (2022) was used to locate potential SAF refineries. Currently operational refineries were selected, as the NESTE and SkyNRG interviews (see table 4) pointed out that access to existing feedstock supply chains is required. Two IEA databases were used as well, the first being the Clean Energy Demonstration Projects Database (IEA, 2022B). This database aims to map demonstration projects of clean energy technologies globally. Sites that are expected to be operational after 2030 were excluded which resulted in 17 projects. The second IEA database that has been consulted shows operational and future hydrogen projects across Europe (IEA, 2022C). This includes many power-to-X projects, among which are ammonia, SAF and methanol synthesis by means of hydrogen and captured CO_2. 10 companies that are expected to be operational were selected from the NW cluster. Unfortunately, no SE cluster projects were listed by either of the two IEA databases. The fifth and final source is ConsenCUS (2022B), which provides an additional three methanol and two SAF projects that are expected to be active by 2030. Table 6 lists the number of sites selected for each county and end-use.

Figures 5 and 6 below depict the various conversion facilities in each country. It stands out that the SE cluster has a relatively high amount of urea facilities and low amount of SAF and methanol facilities, which can be partially explained by the lack of planned sustainable energy projects. Moreover, the competitive landscape for urea manufacturing is quite fragmented (more small producers), whereas the SAF and e-methanol markets are relatively consolidated (large, more specialized refineries).

The capacities of facilities are calculated as follows. The IEA Clean Energy Demonstration Projects database provides the estimated conversion capacities for each future or current project. However, not every project has a predicted capacity associated with it. On top of that, the companies from the ORBIS database do not provide any capacity whatsoever. Looking at the available data from the IEA database, it has been found that urea, methanol and SAF plants have a capacity of 178.59 kt/year, 72.66 kt/year and 324.94 kt/year respectively. However, existing capacities selected from ORBIS have much larger capacities (Yara Sluiskil averages about 1.9Mton Mtpa). Hence, for the sake of simplicity, a capacity of 1 Mt/year is assumed for the base scenario. Finally, it is assumed that facilities using fossil fuels will be able to apply sustainable production methods by 2030 (see methodology assumptions). This was confirmed by previous interviews with NESTE and SkyNRG as well as newly conducted interviews with e-methanol and urea experts (European Energy and Stamicarbon, see table 4).

Country	Denmark	Netherlands	United Kingdom	Romania	Bulgaria	Greece	Total per end-use
End-use							
Methanol	10	11	5	4	10	4	44
Urea	7	17	18	38	32	26	138
SAF	3	8	18	5	1	4	39
Total	20	36	41	48	42	34	**220**

Table 6 - Conversion facilities from ORBIS (2022), IEA (2022B, 2022C), ConsenCUS (2022B)

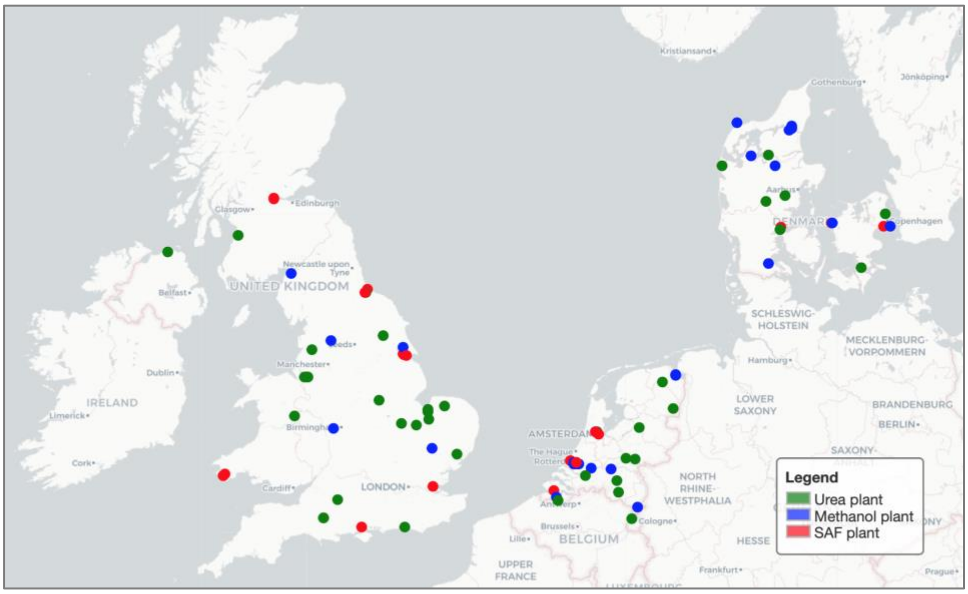


Figure 5 – Conversion plants per country, NW cluster

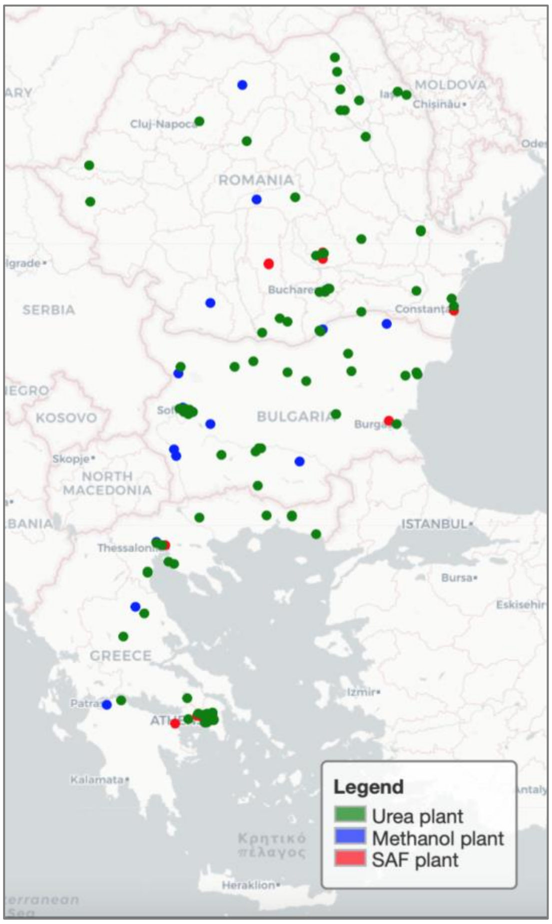


Figure 6 – Conversion plants per country, SE cluster

3.3.3 Storage sites (λ_s , φ_s, σ_s)

CO_2 storage sites have been identified as follows. In contrast to the NW cluster in which CO_2 utilization is prominent, CO_2 storage sites are relatively more abundant in the SE cluster. The number of storage sites per country can be found in table 9 below, data was provided by ConsenCUS end-user database (2022B). It must be said that these storage sites have varying levels of readiness. This is indicated by the Storage Readiness Level (SRL) as explained in the paper by Akhurst et al. (2021). Only when SRL 9 is obtained may the site be injected with CO_2. However, sites with these levels are currently non-existent, as was also confirmed during the GeoEcoMar interview (see table 4). Hence, all sites no matter their SRL have been selected, as sites may have an increased SRL in a 2030 setting. An overview of SRL methodology is provided in appendix 1.

It is assumed that injection rate of CO_2 storage determines the yearly storage capacity of sites, not total site capacity. This is because storage sites are currently rarely exploited and capacity is plenty (confirmed during the interview with GeoEcoMar, see table 4). Hence, CO_2 storage injection rate will be treated as the capacity for storage sites. The average of the minimum and maximum yearly injection rate capacity is taken as storage capacity. This amounts to a storage capacity of 3,52 Mt CO_2/year. This value corresponds with the literature; Carneiro et al. (2015) studied 163 storage sites in Mediterranean Europe and found a total injection capacity of 558 MtCO_2/y with an average injection rate of 3,4 MtCO_2/y. This rate is assumed to be the same across on- and offshore sites.

Table 7 shows the number of sites in each cluster along with their readiness levels and category (on- or offshore). Figure 7 depicts these as dots on a map. Storage sites in the SE are mostly SAs, although there are none in Greece. SAs and DOGFs are more even in the NW, though Denmark merely provides DOGFs. Finally, in the NW, most sites are offshore (due to political constraints on onshore locations) whereas the SE sites are mostly onshore (due to large land masses with low number of inhabitants, there is a lesser amount of public resistance).

Country	Planned CO_2 storage sites	Offshore	Onshore	Sites with SRL > 3
DK	19	6	13	0
NL	10	10	0	2
UK	126	126	0	26
RO	15	0	15	0
GR	7	2	5	0
BG	11	0	11	0

Table 7 – Storage sites (ConsenCUS, 2022B)

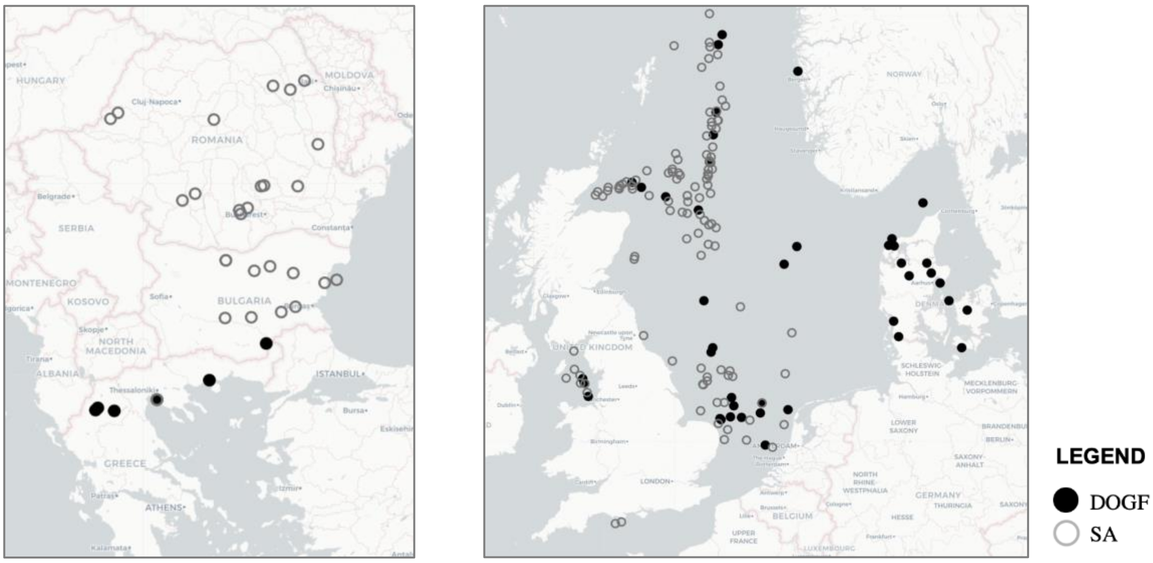


Figure 7 – Storage sites across clusters

3.3.4 End-use demand ($\varphi_v, \lambda_v, u_i$)

Locations where end-uses are consumed and the quantities in which they are consumed have been selected for each end-use. Urea demand originates from agri- and horticulture industry, methanol demand comes from the freight shipping industry and SAF is demanded by the aviation industry.

Decarbonized urea

Urea is demanded in large quantities by crop farmers. However, farms are dispersed across countries making individual demand and location is difficult to find. Hence, two other types of urea consumption sites will be considered. These being the manufacturers, who also perform retailing activities in many cases, and the smaller local wholesalers. The ORBIS database was used to find the smaller fertilizer wholesalers. Companies were filtered by NACE code 4675 and selected based on their activity, latest available year and total revenues. Only the companies with publicly available revenues from the year 2022 were considered. For the sake of simplicity, the companies making up the first 95% of revenues were selected. Details on second group, the large manufacturer retailers, were shared during the Stamicarbon interview (see table 4). These include OCI Global, Yara, Eurochem and ICL. Their locations and revenues were found using the ORBIS (2022) database. This resulted in a selection of 47 total companies, 33 being local wholesalers and 14 being larger manufacturing and/or retailing companies.

Demand was calculated by adding up revenues for each manufacturer to find the total market value of fertilizers across each country. This value was then used to find market share of each respective company. Next, the hectares of arable land for each country were multiplied with the amount of fertilizer used per hectare using data from the WorldBank (2020a, 2020b). Finally, this value was multiplied with the market share and the CAGR of 1.2% for 2030 (gathered from Stamicarbon interview, see table 4) to find the expected demand for each company in 2030. This is summarized by appendix 2.

E-methanol

Methanol is used as additive to many products, hence total product demand is virtually impossible to calculate. At present, e-methanol is predominantly used as fuel for container ships. Its demand is highly dependent on willingness to pay, as was confirmed by the interview with European Energy (see table 4). To elaborate, the observed trend is that companies with good customer relationships purchase e-methanol as it allows them to claim carbon neutrality towards their customers. There are various organizations promoting use of e-methanol such as the IMO (International Maritime Organization) and the IECCP (Institute for European Energy and Climate Policy) by releasing certifications for different ratings of methanol. Climate-responsible companies are pursuing certified green e-methanol, freight sipping companies being the main one. This observation was gathered from the interview with European Energy (see table 4).

Each major port within the clusters was identified using the ISL Port Database (ISL, n.d.). This database lists only relative cargo ports and excludes irrelevant leisure ports. Data on the respective cargo handled for each port during 2021 has been gathered from various sources, see table10. The total TEU per county has been sourced from UNCTAD (2021). Subsequently, the respective amount of TEUs for each port was found by multiplying the share of national cargo handled in each port with the national TEUs. This number was then multiplied by a country-specific CAGR factor that was calculated based on TEUs for the years 2010-2021 (also from UNCTAD, 2021), resulting in the TEU per port. Following this, the number of ships per port has been calculated by dividing TEU per port with average ship size in TEU (which is 5000 TEU). Fuel consumption per port was then calculated by multiplying the number of ships per port with average fuel consumption per ship. The latter was calculated by using the equation adopted from (Gudehus & Kotzap, 2012), which measures fuel consumption for vessels in kg/sm (sm being a nautical mile, 1 sm = 1,853 km) for given speeds in knots and a given average vessel size of 5000 TEU. It is assumed that vessels sail at an average speed of 23 knots (40km/h, Maritime Page, n.d); for this speed the fuel consumption as given by Gudehus and Kotzap becomes 121,42 kg/km. Dawson et al. (2018) found that ships sail approximately 200.000 km per year. Given the consumption per kilometre, average yearly consumption equals 24,28 Mton per ship per year. Finally, the total fuel consumption has been multiplied with the expected blending ratio. CE Delft (2022) estimates that the aforementioned measures by the IMO and IECCP will have limited effects until 2030. Therefore, they estimate that the share of renewable low carbon fuels will amount to just 1%. Hence, it is expected that 1% of 2030 fuel consumption at ports will come from e-methanol. This number is presented for each port in the last column of appendix 3.

<u>SAF</u>

There is merely one demand site for SAF, namely airports. It was confirmed by NESTE and SkyNRG (see table 4) that SAF is transported directly from production facilities to airports (facilities being the already exiting refineries). Similar to the selection of e-methanol consumption sites, airports were selected by the amount of traffic at each airport. However, airports make use of traffic units and not TEU. A traffic unit is a single 100 kg passenger or cargo equivalent. Airports were selected from various sources which are included in appendix 4. For the sake of simplicity, the airports making up 95% or more of traffic units were selected.

SAF consumption for each airport was found by finding the share of traffic units for each airport. This was then multiplied by the CAGR, which has been set at 13,7 % (SkyQuest, 2023). Finally, this value was multiplied with the projections for fuel blending, as the aforementioned calculations are for conventional fuel and not for SAF. Current aviation fuel is a blend of conventional fuel and SAF and will continue to be in 2030. Consequently, to determine the demand forecasted for the 2030 scenario, it is necessary to multiply it by the percentage that represents the proportion of SAF blended with conventional aviation fuel. According to the EU initiative ReFuel, (ESEA, 2022) this percentage is expected to be a minimum of 5% by 2030. An overview of SAF demand calculations is provided in appendix 4.

3.4 Cost parameters (c_u, c_{uf} , c_{us}, c_f, c_{fv})

This section discusses the cost parameters associated with the various parts of the CCUS supply chain, including capture costs, transportation costs (pipeline and truck) and conversion costs.

<u>Capture costs</u>

Capturing costs differ per industry as CO_2 concentrations in flue gasses vary. The ranges for levelized cost of CO_2 capturing (LCC) per industry is given by IEA (2019), see table 8. These values show that LCC can vary between 15 and 342 $ per ton CO_2 captured. LCC of capture provides a good indication of yearly costs per ton CO_2 captured (i.e., the annualized CAPEX and CAPEX).

Industry	Capturing costs in $/ton (IEA, 2019)
Power generation	50-100
Cement	60-120
Iron and steel	40-100
Ammonia (fertilizer)	25-35
Refining	15-25

Table 8 – Carbon capturing costs overview (IEE, 2019)

As said, industries considered in this thesis are the fertilizer, cement, iron and steel, power, refinery and waste disposal industry. Some of the values presented above were gathered from NETL (2014), who performed a case study for carbon capturing prices in the US for the year 2014. Their cost findings are supplied by table 9. They are in line with the values from IEA. In the NETL case, power and gas was purchased at 59$/MWh and 6.13$/MMBtu respectively.

To account for the expected price changes in 2030, values of energy costs have been adjusted. According to Statista, (n.d.) renewable electricity prices could drop 25-58% depending on the type (wind or solar). Moreover, Reuters (2015) expects a drop of 30-50% by 2030, putting renewable energy on a par with conventional electricity prices for EU markets. Conventional prices in EU were about 60 € in 2021 (Ember, 2023), whereas renewable source LCOE was 48 $/MWh for solar and 75 $/MWh for offshore wind (IRENA, 2022). The interview with European Energy (see table 4) confirmed that the levelized cost of energy (LCOE) is the most important measure to determine electricity prices. It was implied that companies should use a mix of wind and solar energy. Hence, the average of wind and solar LCOE in 2021 was calculated 61.5 $/MWh. Adding the expected LCOE drop of 30%, the LCOE in 2030 will be 43.05 $/MWh (indeed on par with present conventional electricity prices). This is a price drop of 37.1% compared to the 59 $ used by NETL. Hence, energy prices are lowered by this amount. Finally, gas prices are expected to rise to 6.35$/Mcf, or 6.58$/MMBtu (Capital, 2023). This represents a 7.34% increase to the 6.13 $/MMBtu price used by NETL, so gas price is adjusted for this.

Power and waste industry data was not analyzed by NETL and hence added. Natural gas-fired plants typically have emissions with 4% CO_2 (David et al., 2007) and waste incineration has 95,6% CO_2 (UNFCC, 2017). Respective costs for power generation industries were assumed based on percentage differences in prices from the IEA (2019) data. For instance, cement is 15-20% per ton more expensive than power generation, so power generation costs are 17,5% lower than cement industry costs. Waste incineration is assumed to be equal to fertilizer industry considering their similar flue gas CO_2 concentration.

	Cement	Iron and steel	Fertilizer	Refining	Power generation	Waste disposal
CO_2 purity	22.40%	26.40%	97.10%	99%	4%	96.5%
Total fixed costs (€/ton)	37	38	12	7.2	31	12
Other variable ($/ton)	17,53	18,01	7,74	3,38	14,46	7,74
Purchased electricity ($/ton)*	16.58 (12,10)*	17.89 (13,05)*	11.19 (8,16)*	9.98 (7,28)*	13.68 (9,98)*	11.19 (8,16)*
Purchased natural gas ($/ton)*	33,88 (36,37)*	35,81 (38,44)*	0 (0)*	0 (0)*	27,95 (30,00)*	0 (0)*
Total variable costs ($/ton)	66,00	69,50	15,90	10,66	54,44	15,90
Total ($/ton)	103,00	107,50	27,90	17,86	84,97	27,90
Total (€/ton, 1$=0.93 €2023)	95,79	99,97	25,95	16,61	79,02	25,95

Table 9 – Capture cost breakdown, altered from NETL (2014)

*Purchased energy and gas were altered from NETL, power and waste industry were added using calculations. Added data is represented by brackets.

<u>Transportation costs CO_2 (pipeline)</u>

Costs for pipeline transportation varies within the literature. According to Hasan et al. (2014), transportation costs depend on the location of the emitters, utilization and refineries. They state that most literature considers the transportation cost to be $6–8 per ton of CO_2 transported, although this may vary from $0.20 to $40 per ton CO_2. A study by McCoy and Rubin (2008) showed that pipeline capacity and length are the most critical cost drivers of CO_2 transport by pipeline. Smith (2021) finds that various modeling studies agree that the combined cost for CO_2 transport and storage is the same in all regions of the world and is commonly valued at $10/ton CO_2. From his particular study, it was found that pipeline transport and storage costs could vary from 4 to 45$/ton CO_2 (all lengths). Finally, IEA found that pipeline transportation is cheaper than shipping from 800 km onwards, costing 26$/t. In their model, a pipeline capacity of 2 Mt/year was assumed. Additionally, for a distance of 100km the transportation costs for pipeline and ship amount to 4$ and 21$ respectively.

From the interview with Stamicarbon and European Energy (see table 4) it became clear that there is currently no proper pipeline network in place in Europe (apart from one network, mentioned by Stamicarbon). In the US however, there is a CO_2 pipeline network for EOR practices. The interview with GeoEcoMar and Stamicarbon (see table 4) also confirmed that there is no pipeline structure in place and recommended to establish a pipeline network similar to the US. However, CO_2 transport by pipeline is considered most economically viable (Leonzio et al., 2020). Hence, it is assumed that these have to be constructed which brings along significant capital expenses.

Pipeline transport costs consist of capital expenses and operating expenses, the former being the largest cost factor. This factor can be expressed as the levelized cost of investment for a pipeline. This usually depends on pipeline diameter, length and flow rate. However, for this study the equation is based on flowrate. In order to obtain the capital expenses for a CO_2 pipeline system, the study by McCollum and Ogden (2006) will be used, which formulates the CAPEX for CO_2 pipeline transport as follows:

$$I = 24.7 \times m^{0.35} \times L^{1.13}$$

In this equation, *I* refers to the total investment costs onshore pipelines (€ per kg/s/length); *m* is the mass flow (kg/s) and L is the length (m). In this thesis, the flow rate *m* is dependent on capacity of the average storage CO_2 injection rate (3,52 Mton/y) and the maximum required CO_2 feedstock for facilities. The above equation will be used to calculate CAPEX for pipelines, but flowrate is adjusted to ton/year instead of kg/s. An expected lifetime of 40-50 years is assumed, according to IEA (2022D). Therefore, the capital expenses calculated with the above equation are annualized over the maximum lifetime of 50 years.

An overview of operating expenses has been reported by Knoope (2015) and can be found in table 16. The value of 2,00% of CAPEX found by Chandel et al. (2010) will be applied. There will be no time-factor applied to CO_2 transportation costs as they are assumed to stay constant over the coming years.

<u>Transportation costs end-uses (truck)</u>

As was explained before, it is assumed that end-uses are transported by truck. For trucking end-uses, there are no capital expenses since transport is set to be outsourced. Urea, e-methanol and SAF manufacturers pay the trucking companies on demand; they require a fixed amount of investment per kilometer driven and per quantity transported. Della (2023) data shows that current rates average 2.00€ for 20 t loads (average truck load, trucks are assumed to be fully loaded in order to obtain the lowest cost). Hence, a constant value of 0.10 €/km/ton will be used to calculate transport costs by truck. It is assumed that truck transport costs stay constant over the coming years and that 20 t trucks will drive as many times as is necessary in order to satisfy all demand (yearly capacity becomes capacity at the sink). There are no capital expenses involved, as transport is not in-house. Thus, it is also assumed that truck capacities and costs are linear (more demand implies more trucks bought, each having the same capacity). Costs are also expected to stay constant over time.

<u>Conversion costs</u>

Each end-use is subjected to different conversions cost. They also require varying levels of CO_2 as feedstock. For each end-use, the levelized costs were identified and divided by the respective amount of CO_2 feedstock required per ton end-product. Levelized costs are the minimum selling price needed to break even as a loss is otherwise incurred. Hence, levelized costs are an adequate determinant for a plant's yearly OPEX and (annualized) CAPEX originating from production.

To determine the levelized cost of decarbonized urea (LCOU) is difficult to determine exactly in a 2030 scenario, as prices fluctuate and the market is fragmented. Sources found were ambiguous (costs ranged from 300-1500 $/t). Hence, a different method was applied: in this thesis it is assumed that LCOU greatly depends on levelized cost of green ammonia (LCOGA). Namely, during the interview with Stamicarbon (see table 4) it was explained that 1 ton urea requires 0,73 ton of CO_2, and 0,57 t ammonia. Green ammonia is essential in order to produce decarbonized urea. Therefore, LCOGA are assumed to be guiding for the LCOU. Bose et al. (2022) find that grid-connected ammonia plants in the U.S. produce at a cost of 540-640 $/ton and natural-gas-based ammonia produces around 300–400 $/t. Depending on electricity mix of the grid, they may have higher or lower CO_2 emissions. They also found that using a combination of renewable sources at locations of existing ammonia facilities corresponds to a LCOGA of 570−850 $/ton ammonia. For the base case, LCOGA is assumed to be 710 $/t. This is 120 $/ton or 20% higher than conventionally produced ammonia. It is assumed that the 20% increase is reflected in LCOU. LCOU and LCOGA are also assumed to stay constant until 2030 (this assumption was made during the interview with Stamicarbon, table 4). Hence, LCOU is set 20% higher than current LCOA, which was estimated at 300$/ton for a scenario using commercial scale urea market price and technology that will be operational in 2030 (hence, changes in price over time is somewhat accounted for). Applying the 20% higher LCOU to the expected LCOU in 2030 gives a value of 360 $/t, or 336.06 €/t. Finally, this has to be divided by the product yield to obtain the costs per ton CO_2; a value of 458.47 €/tCO_2 will be used as conversion cost parameter, as it is assumed that the amount of required CO_2 feedstock per ton is relative to fraction of total costs.

An attempt has been made to source the levelized cost of e-methanol (LCOEM) from IRENA's (2021) innovation report, which summarizes LCOEM assessments that range from 570 $/ton to 1000$/t. The production processes in these analyses are using captured CO_2 from flue gases or the atmosphere. However, IRENA does not specify the electricity sources used. A more recent study by Hank et al. (2018) did provide electricity sources; the best possible scenario for e-methanol from wind park-generated electricity had a LCOEM of 1028 €/t. The interview with European energy gave a detailed overview of levelized costs and confirmed that the price was around 700€. It was also stated that a large portion of that is due to that electrolysis costs. To get the cost per ton CO_2, CO_2 yield must be accounted for. There is 1,37 ton of CO_2 required to produce 1 ton of e-methanol (Ravikumar et al., 2020). Dividing by this yield, the final conversion cost for e-methanol becomes 750.36 $/ton CO_2, or 700.63 €/ton CO_2. Again, it is assumed that CO_2 feedstock required per ton product are relative to total cost per ton.

The levelized cost of SAF fuel (LCOF) is based on the value found by Del Monte et al. (2022). They performed a technoeconomic assessment of the HEFA pathway for SAF production and found that overall expenses are primarily driven by the price feedstock and costs of hydrogen and electricity. The LCOF for a scenario in which light gasses are valorized (this is called ATR) turned out to be most economically viable, at a value of 570 €/t. A minimum of 3,00 tons CO_2 is required per ton SAF (ICF, 2021). Therefore, the final conversion costs can be found by dividing 570 by the yield, which amounts to 190.00 €/ton CO_2 as CO_2 feedstock for SAF is assumed to be relative to total production costs.

3.5 Scenarios

Scenarios are formulated based on the above literature and on previously and newly conducted interviews (see table 4). Optimizing the CCUS supply chain using the above model requires various uncertain input variables. Multiple scenarios must be analyzed as various modelling instances could turn out to be true. Interviews have established that data is uncertain and scales may vary widely. All scenarios constructed are set in 2030, as predictions become rather uncertain for scenarios set further into the future. Relatively accurate data for 2030 is available and many of the ConsenCUS datapoints are based in a 2030 setting. Table 10 below provides a summary of the scenarios considered.

<u>Scenario 1: international interactions, all end-uses</u>

The model is used to determine construction decisions that offer the lowest costs. Lower costs might be achieved if the data extends across multiple countries. This is because distances might be shorter and therefore transport costs are lower. Additionally, from interviews (ISPT, European Energy, Stamicarbon, see table 4) it became clear that renewable energy supply is the main factor that is looked at when determining the location of a CO_2 utilization plant. Renewable energy is expected to drop in a 2030 setting as costs tend to decrease over the years. Specifically, the period 2010 to 2021 is characterized by a drastic improvement in the competitiveness of renewables. This renewable energy cost component is not just important for utilization but also for storage. Namely, if the carbon footprint of CO_2 storage uses significant amounts of non-renewable energy, its purpose is defeated (from interview with GeoEcoMar, see table 4). Thus, a sensitivity analysis is performed to estimate the impacts of the renewable energy as a cost factor.

International interactions are important to consider as it is expected that total cluster demand will be satisfied at the lowest possible costs. In addition, renewable energy costs between CCUS supply chains should be analyzed as the impact of future renewable electricity costs reductions (which is a predictor for conversion costs) on total supply chain costs can be determined. These costs will likely reduce more drastically in an international context.

Scenario 2: national interactions, all end-uses

Another aspect to consider is that renewable electricity markets are localized, whereas end products can be transported globally (interview with European Energy, see table 4). This means that the production of commodities depends on the location of a production cluster with the highest supply of renewable energy. In contrast, end-users can be located anywhere (location is irrelevant and solely depends on demand levels). It is also the far largest factor to consider when localizing operations; other factors such as transport play a minor role in low scale facilities (European Energy, see table 4). This was also confirmed by the Stamicarbon and INEOS interview (see table 4). It was found that new green ammonia production facilities are solely based on the cost of electricity (Stamicarbon, see table 4). Therefore, a scenario that disregards international interactions and only considers national CCUS supply chains has been computed. ISPT, INEOS and Gasunie interviews (see table 4) also imply that some countries have advantages over others in terms of their renewable energy supply. A sensitivity analysis is done to determine differences in competitiveness of national green electricity markets and their resulting effects on the overall CCUS supply chain cost.

This scenario is important to consider as it allows for cost comparison between national and international settings (the former being this scenario, the latter being scenario 1). Additionally, it is valuable to analyze individual country electricity costs so that the impact of local electricity costs on total supply chain costs can be assessed. This could imply that some countries are better suitable for CCUS operations than others if cost minimization is the goal.

Scenario 3: storage-oriented (single end-use) scenario

From interviews it became clear that for storage especially, there is a lot of public resistance against CO_2 storage (GeoEcoMar, Gasunie, see table 4). This goes especially for offshore (GreenChem, see table 4) and is less apparent for end-use facilities because they can be moved to wherever the feedstock and electricity is least expensive. Therefore, there are a lot of CO_2 utilization initiatives. However, according to some, storage should be the main focus. For instance, the CO_2 Smart Use interview (see table 4) made clear that CO_2 storage is more suitable for industry CO_2 capture than utilization, due to the differences in CO_2 type (industry CO_2 is “gray” meaning that it has a higher carbon footprint). INEOS adds to this by arguing that CCU will not be used on a large scale and that CCS is more viable. In 2040 this could be 50/50. The MOL Group (see table 4) stated that CO_2 storage is temporary solution for the next 20-30 years, the focus should be on substituting fossil fuels. INEOS adds to this by believing that CCS will be needed until the end of the century and countries with a major industry will not be able to quit emissions before 2050. Hence, a scenario with lower end-use demand is formulated. Specifically, the three end-uses will be looked at in isolation. This lower demand will automatically result the model to shift towards storage rather than utilization (i.e., more storages will be selected). Furthermore, a sensitivity analysis is computed to demonstrate differences in storage possibilities, as storages might not be equally suitable (as implied by SRL) or accepted (as implied by offshore versus onshore).

This scenario will provide valuable insights as it will demonstrate a supply chain that will be realized if demand turns out to be low (namely, CCU might only apply one end-use). As a result, the optimal supply chain likely includes differing amounts of facilities and storages. A sensitivity analysis is important to perform as not all storages might be operational in the future and this will impact total costs.

Name	Settings	Standard data parameters changed
International scenario with renewable electricity sensitivity	Base data with sensitivity analysis for price of green electricity, all end-uses and storage.	Base data with altered prices for capture and conversion (c_u, c_f).
National scenario with (localized) renewable electricity sensitivity	Base data with no international interaction, so each instance only contains base data for individual countries, all end-uses and storage is applied.	Base data with altered prices for capture and conversion (c_u, c_f), adapted for local markets.
International scenario with single end-uses, storage-oriented with storage type sensitivity	Storage-oriented scenario with low demand (single end-uses) and sensitivity of storage selection for SRL and onshore/offshore locations.	For this setting, single end-use demand d_j and capacity (σ_f) is set, sensitivity for selected storages (φ_s and λ_s).

Table 10 – Scenario descriptions

4. RESULTS AND DISCUSSION

This section discusses the results of scenario analyses considering numerical examples applied to the conceptual model using the data described above. Each scenario will be presented as follows. An overview of the proposed supply chain will be provided followed by an analysis of the decisions. For every scenario, a breakdown of the optimal supply chain and its respective costs will be provided, as well as a sensitivity analysis. For each scenario, the main takeaways are presented last.

4.1 Scenario 1 (national and international interaction)

Results (optimal supply chains)

This scenario presents the optimal CCUS supply chain for the NW and SE clusters, whereby international interactions among cluster countries are in place. The supply chains for NW and SE are depicted in figures 8 and 9 respectively. Experiment settings are provided by appendix 5, the data and scenarios resulting from this data are deterministic. The following section will first outline the elements included in the NW and SE supply chains, followed by an economic analysis, general takeaways and validations.

Each NW country contains one industrial cluster. These are located at Ellesmere Port, Rotterdam and the surrounding area of the island of Funen in Denmark. CO_2 is supplied by 9 sources which are not necessarily built within clusters. The supply is facilitated by 1 cement producer, 1 fertilizer producer and 5 refineries. 8 CO_2 conversion sites are involved: 3 urea, 2 e-methanol and 2 SAF facilities. Urea is produced in each country, whereas e-methanol and SAF are only made in the UK and Denmark. The Danish e-methanol facility is a project expected to be operational by 2030 (the E-Thor project), whereas urea facilities are currently operational and would have to decarbonize their processes by 2030. Similarly, SAF facilities are existing refineries expected to become more sustainable. The SAF plants simultaneously act as sources: they ideally provide CO_2 for their own conversion processes. Only 1 storage site is selected: the Rasnes (Bifrost project) onshore DOGF. This is the only site needed to store excess CO_2 from the Danish refinery as the rest of the CO_2 is utilized. The configuration composes 2 international CO_2 pipelines crossing the North Sea: Borssele-Cambridge and Kalundborg-Rotterdam. The former supplies an e-methanol plant whereas the latter provides CO_2 for a SAF refinery. In addition, 3 particularly long national pipelines are built: Cambridge-Ellesmere, Edinburgh-Ellesmere and Harlingen-Rotterdam. These respectively supply 1 e-methanol and 2 SAF facilities. The rest of the pipelines mostly stay within short distance of each cluster. Total CO_2 emissions captured with this configuration are 4,78 Mton out of 158,27 Mton possible emissions. This amounts to an insignificant 3,02% of total CO_2 captured, the remaining 153,48 Mton CO_2 is released.

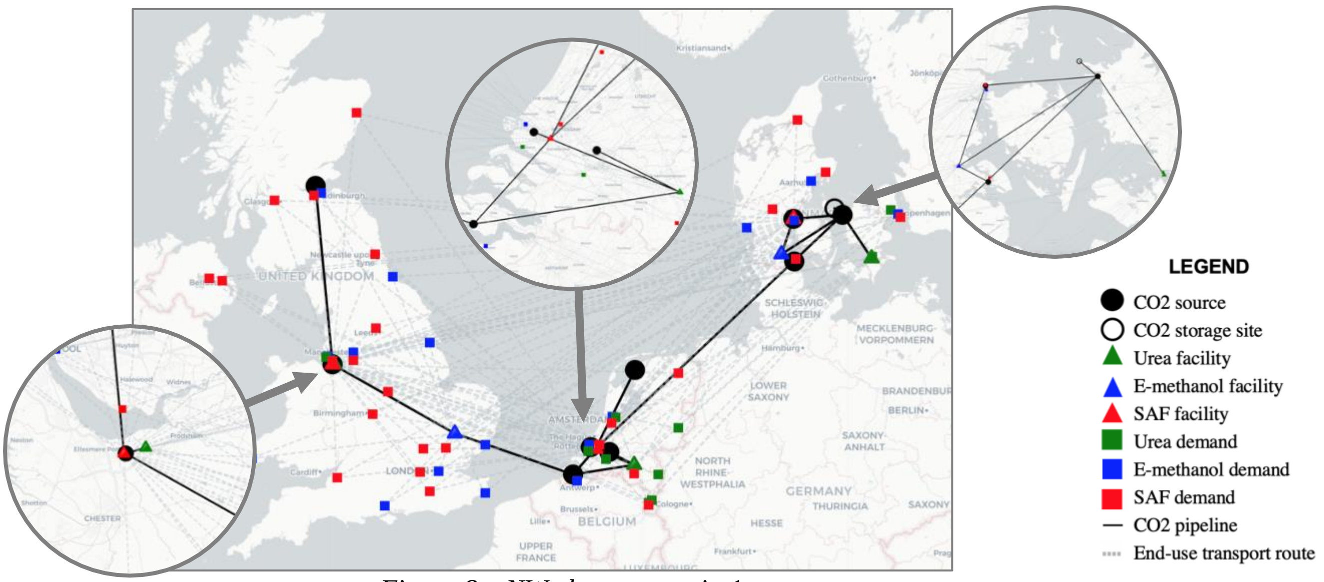


Figure 8 – NW cluster scnario 1

The SE cluster configuration shows that 2 industrial clusters are optimal: the Athens cluster and the Ploiesti (Bucharest) cluster. The setting contains 2 CO_2 sources, both of which are refineries. Additionally, there are six facilities required: Romania and Greece each contain one urea, e-methanol and SAF facility. All facilities are currentlty existing ones, meaning that they need to become sustainable producers by 2030. The Romanian SAF is provided by a refinery that is also an emitter, but it only supplies CO_2 for surrounding e-methanol and urea facilities, not for itself. Namely, this SAF facility is supplied with CO_2 through an international pipeline that springs from the Athens refinery. There is another significant pipeline that emerges at the Athens cluster, which supplies CO_2 for the Ploiesti e-methanol plant. These extensive international pipelines are present because the Athens refinery has almost twice the amount of emissions of the Ploiesti refinery, so the latter is only capable of supplying the two local facilities but additional CO_2 from the Athens source is needed for the other Romanian facilities. Storage is not optimal for this cluster: all CO_2 supplied by the two sources is reused by the six facilities. In this SE setting, 2,97 Mton emissions out of 45,86 Mton possible emissions are captured using this supply chain. The total percentage captured therefore becomes 6,48% and thus there is 42,89 Mton CO_2 emitted.

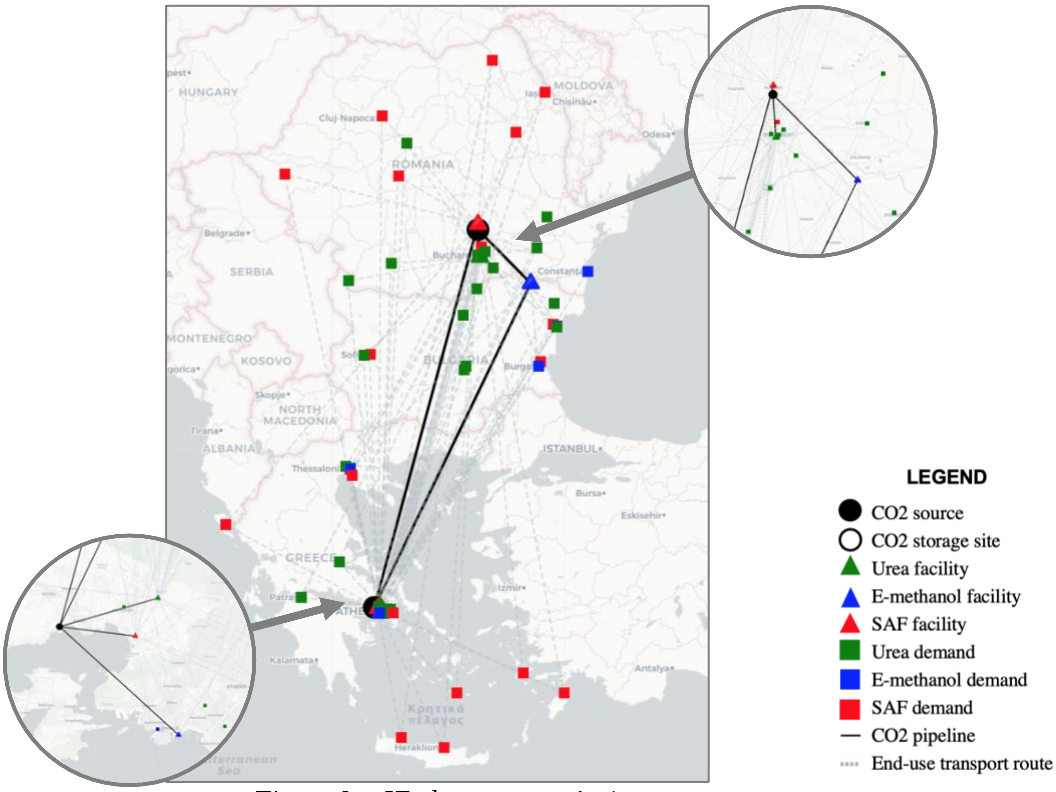


Figure 9 – SE cluster scenario 1

<u>Cost breakdown</u>

The supply chain costs for both clusters are presented by table 11. It shows that for both supply chains, conversion costs make up approximately 75% of total costs. This is not surprising as the cost data used for this parameter was the highest of all input data (especially for e-methanol). The other significant cost component aside from conversion costs is the truck transport of end-products, these are costly (linear) per-kilometer OPEX costs. Capture costs and CO_2 pipeline transport costs are negligible. The differences in the amount of construction decisions between the two clusters is emphasized by the conversion and capture costs. Specifically, due to lower end-use (and therefore CO_2) demand in the SE cluster, conversion and capture costs are considerably lower. Remarkably, truck transport costs are higher in the SE countries even though there is less demand. This can be attributed to their greater sizes which automatically imply greater distances between facilities and demand sites.

	NW (million €/y)	Percentage	SE (million €/y)	Percentage
Capture	80.82	1,85%	49.33	1,34%
Pipeline CO_2 (facility)	6.86	0,15 %	1.79	0,049%
Conversion	3346.67	76,73 %	2698.20	73,17 %
Truck transport	927.44	21,26 %	938.50	25,45 %
Pipeline CO_2 (storage)	0.031	0,0007%	0,00	0,00%
Total	4361.83	100,00%	3687.83	100,00%

Table 11 – Cost breakdown scenario 1

<u>Sensitivity analysis conversion cost</u>

The observation of high conversion costs requires further analysis. Interviews with Stamicarbon, European Energy and ISPT (see table 4) confirmed that these costs greatly depend on the levelized costs of renewable energy. Namely, renewable LCOE determine electrolysis costs and electrolysis is an important component of the conversion process. Scenario 1 assumed a fixed LCOE of 43.05 $/MWh for all countries. In order to show the influence of LCOE on conversion costs, a sensitivity analysis was carried out for the conversion cost parameter. Hereby the conversion costs factor was altered based on LCOE and other parameters were kept constant. In turn, the conversion share of total cost may be reassessed.

The altered values for conversion cost were calculated as follows. First, LCOE's share of conversion costs was detemined. This relative cost factor was gathered from Belotti et al. (2021). They present the production cost distribution for power-to-methanol and power-to-ammonia. It was found that electricity costs can make up 66,3% and 65,3% of total costs for methanol and ammonia plants respectively. For this sensitivity analysis, the share of conversion costs from electricity is set at 66,3% for e-methanol and SAF and 65,3% for urea. Given these percentages, conversion costs were adjusted by multiplying the LCOE fraction of converison costs with the expected LCOE grotwh (or reduction) factor and adding back the remaining percentage of original conversion costs. The LCOE growth and reduction factors are based on Statista (n.d.) and Reuters (2015) which estimate that LCOE costs may decrease as much as 58% by 2030. In the worst case, it is expected to drop by 25%. An unlikely 10% increase in LCOE is also included, though this is not predicted by any source due to the progress being made in the global renewable energy sector. The various conversion costs factors that were computed are shown in table 13. Their effects on the objective function are analyzed below.

	End-use	-58% LCOE	-25% LCOE	Scen 1 LCOE	+10% LCOE
Conversion	Urea	284.83	383.62	458.47	488.41
Cost c_f	E-methanol	431.21	584.50	700.63	747.08
(€/ton CO_2)	SAF	116.94	158.51	190.00	202.60

Table 12 – conversion costs c_f for different expectations of LCOE

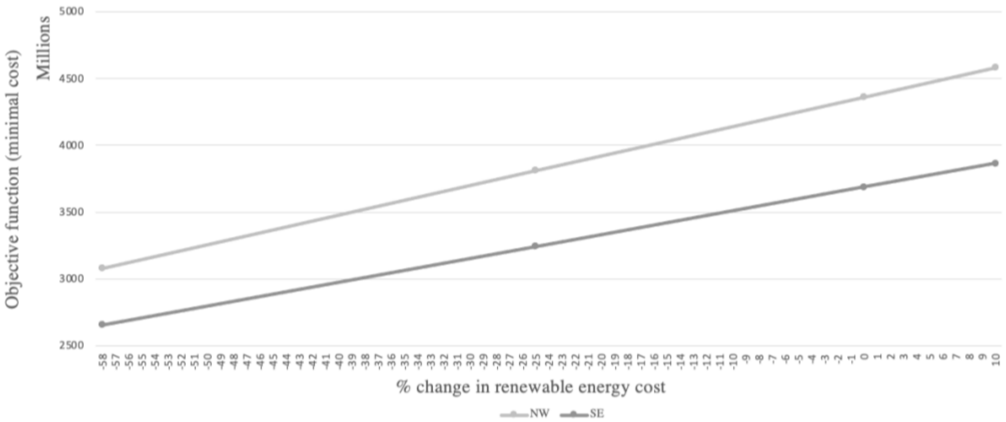


Figure 10 – impact of conversion cost on total costs

Applying the model with the cost scenarios given by table 12 results in varying construction decisions for storages and sources in the NW cluster. Specifically, for each increase in LCOE, more storages and sources are built. Namely, as conversion becomes more and more expensive, the model resorts to storages instead of facilities. This may also impact source construction decisions.

Logically, costs are also affected. The changes in total costs are represented by figure 10. The graph's slope is linear as costs are linear. Extra decisions do not have any effect on the linearity of the costs. That being said, there is a difference in slope observed between the two clusters. In the NW cluster, every percentage increase in renewable LCOE results in an increase of 894 million € total supply chain costs. For the SE cluster, this amount equals 755 million €. The difference can be explained by the fact that there are less facility construction decisions made for the SE cluster compared to the NW cluster (5 as opposed to 7). For the 3 renewable LCOE scenarios, conversion costs make up 67,11%, 73,36% and 73,18% of total costs in the NW cluster respectively. In the SE cluster, the shares are 62,73%, 69,48% and 74,40%. Finally, if the best case 2030 LCOE scenario (-58%) is realized, total costs will reduce by 29,36% and 16,45% for the NW and SE respectively.

This analysis shows that large decreases in renewable LCOE conversion costs may reduce total supply chain costs with each percentage decrease resulting in a cost reduction of 755-894 million €. Thereby the impact of conversion costs on the total costs may be reduced to just 67% as opposed to 75%. Thus, total costs may be reduced significantly, though conversion costs are still the largest factor.

<u>Discussion and takeaways scenario 1</u>

This section will comment on the above supply chains, their emissions captured, their costs and the sensitivity analysis performed. These findings were validated and criticized by ConsenCUS; their judgements are also expressed below.

This paragraph discusses scenario 1 supply chain findings. Firstly, SE countries require less constructions because end-use and CO_2 demand is lower. The ConsenCUS interview (see table 4) verified that there are indeed less on CCU activities as these regions mainly focus on hydrogen and CO_2 storage. Secondly, refineries are the preferred emitters as capture is least expensive for this industry (average industry costs are 57.22 €/t, refinery costs are 16.61 €/t). Thirdly, truck-transport edges are abundant as facilities only have a capacity of 1 Mton. Thus, demand is often satisfied with products produced abroad. The products are assumed to be transported by truck, however, realistically, they could also be shipped or flown in (though this affects total costs and therefore the optimal configuration). Fourthly, cross-country pipelines are included because close-by sources and shorter pipelines are suboptimal. Namely, capturing costs are higher than pipeline costs, at least from a long-term perspective. This naturally means that fewer sources are built (so CO_2 travels further). ConsenCUS confirmed that the pipelines in these settings are not in line with short-term goals as there are no currently existing ones that can satisfy present-day CO_2 demand. This holds especially for longer pipelines. At present, CO_2 is transported via truck and during the interview it was speculated that this could still be the case in 2030. However, it was stated that pipelines are feasible in the long-term. Fifthly, there are almost no storage edges, so facilities are more cost-efficient than storages in this scenario.

Scenario 1 supply chains are characterized by low amounts of CO_2 captured (7,75 Mton in total for both clusters, 3,80% total). The interview with ConsenCUS finds that this amount is not in line with the project's goals as ConsenCUS aims to achieve net zero emissions in a relatively short time horizon. It was questioned whether the construction of additional sources can be avoided simply because they are not needed to satisfy CCU demand, especially considering the associated ETS costs for these non-constructed sources. However, these considerations lie beyond the scope of this scenario and the model.

Looking at the cost for each setting, it was found that conversion makes up the largest fraction of total costs, though this was expected considering that input data was high for this parameter. This finding was not confirmed by ConsenCUS but it was considered highly likely. After conversion costs, end-use transport costs are the highest cost factor. CO_2 pipeline costs turned out insignificant.

The sensitivity analysis also provided insights. It showed that conversion costs are the largest cost factor regardless of LCOE, though its share of total costs may be reduced significantly (about 10%) if the best-case renewable LCOE is realized. For this scenario, a total cost reduction of 29,36% and 16,45% may be obtained for the NW and SE clusters respectively.

Finally, ConsenCUS confirmed that the international interactions shown in scenario 1 are not necessarily the goal of the project but they should be considered if they are feasible and increase the amount of CO_2 captured. Cost benefits of the international interaction attribute may only become clear when costs are compared with the following scenario.

4.2 Scenario 2 (only national interaction)

Results (optimal supply chains)

In scenario 1, international interactions were assumed to be feasible. This assumption is disregarded for scenario 2 as it presents the optimal supply chain for each of the 6 countries individually. The deterministic experiment settings are presented in appendix 5. They are the same as in the international scenario, except the cross-border facilities, emitters and storages have been excluded. The supply chains for each country are depicted by figures 11 through 16.

The optimal supply chain for Denmark as presented by figure 11 contains one industrial cluster in Kalundborg. One CO_2 source is constructed for this cluster, which is a present-day refinery. Three facilities are optimal: one for each end-use should be built. No projects were selected, merely existing facilities that have to convert. A pipeline across the Samsoe Belt should be assembled to facilitate the SAF plant with CO_2. A pipeline crossing Seeland to supply the urea plant should be constructed as well. No storages are involved as the facilities take up all CO_2. In this configuration, 0,54 Mton CO_2 captured out of 9,21 Mton total emissions, accounting for 5,86% of total emissions captured. The remaining 8,68 Mton is emitted.

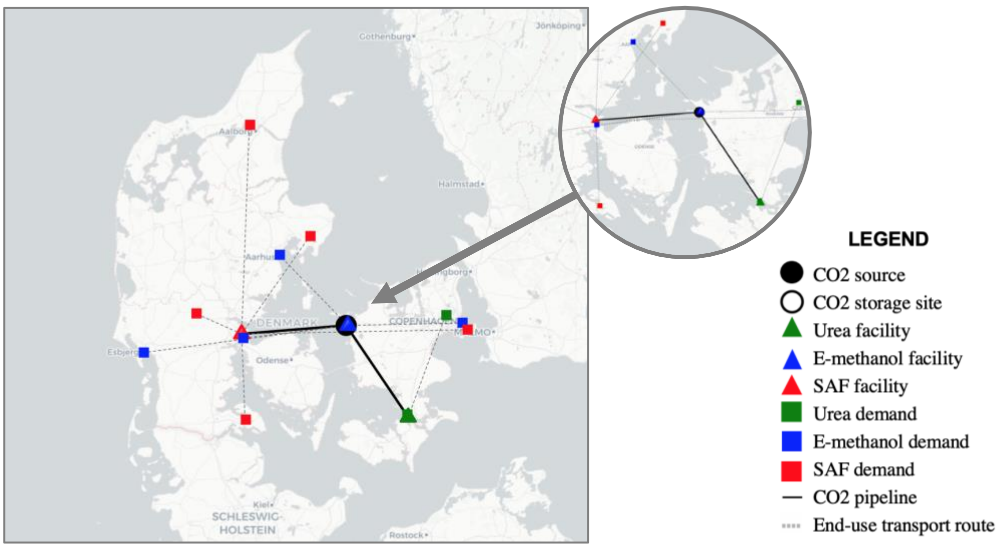


Figure 11 – Denmark scenario 2

Figure 12 displays the optimal supply chain for the Netherlands, in which there is one cluster situated near Rotterdam that extends east- and southwards to Den Bosch and Borssele. 5 sources supply the CO_2 needed, 2 of which are fertilizer producers and the remaining 3 are refineries. 1 facility for each end-use is necessary to satisfy all demand. All 3 facilities exist today and need to produce sustianably by 2030. 2 CO_2 pipelines emerging from Rotterdam supply the urea facility in Den Bosch. The other two pipelines start in the Borssele refinery and provide the SAF and e-methanol plants in Rotterdam with CO_2. There is no storage necessary for this configuration. It must be noted that this setting can be used to capture 1,65 Mton out of 78,32 Mton possible emissions. The resulting percentage of emissions captured is 2,11%, whereby the remaining 76,68 Mton is emitted.

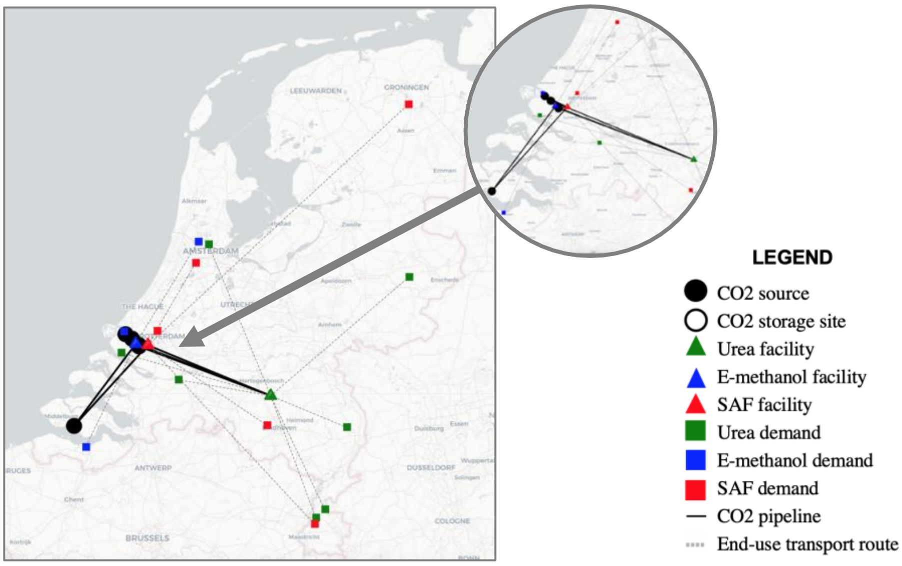


Figure 12 – Netherlands scenario 2

Figure 13 shows the optimal CCUS settings for the UK, whereby 1 industrial cluster should be located in Ellesmere. The CO_2 is supplied from outside of this cluster. There are 4 different sources needed which currently operate as refineries. In total, there are 4 facilities that need to be built: 2 for urea, 1 for e-methanol and 1 for SAF. The SAF facility in Ellesmere is an existing facility that needs to convert its operations to become supplier of its own CO_2. It should also receive CO_2 through a long pipeline that springs from the refinery in Flotta. Another striking pipeline construction is built around Pocklington, whereby the local urea facility is supplied with CO_2 from refineries in Middlesbrough and Easington. No storages are needed in this setting. Emissions captured amount to 2,66 Mton out of 70,72 Mton total emissions. In other words, 3,76% is captured and the remainder (68,07 Mton) is emitted.

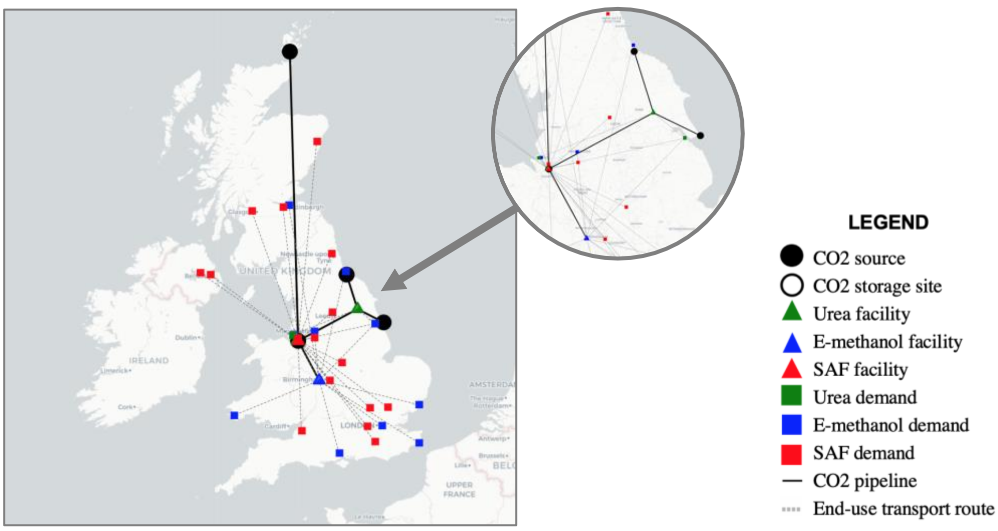


Figure 13 – UK scenario 2

For Romania, 1 industrial cluster must be built. It should be located in the surrounding area of Ploiesti and it has to include 2 sources which currently operate as refineries. The optimal configuration encompasses three facilities in total, implying that there is one needed for each end-use. As stated in the data description section, none of these are projects. Just like the above settings, there is no storage required. 2 pipelines emerge from the refinery in Făgăraş, they provide the SAF and e-methanol plant in Ploiesti and Bucharest with CO_2. There are also 2 pipelines stemming from the Ploiesti refinery which supply the e-methanol and urea facilities in Bucharest. For this setting, the total emissions captured equal 0,74 Mton out of 24,79 Mton total emissions. This implies that only 2,99% is captured; a surplus of 24,05 Mton is emitted.

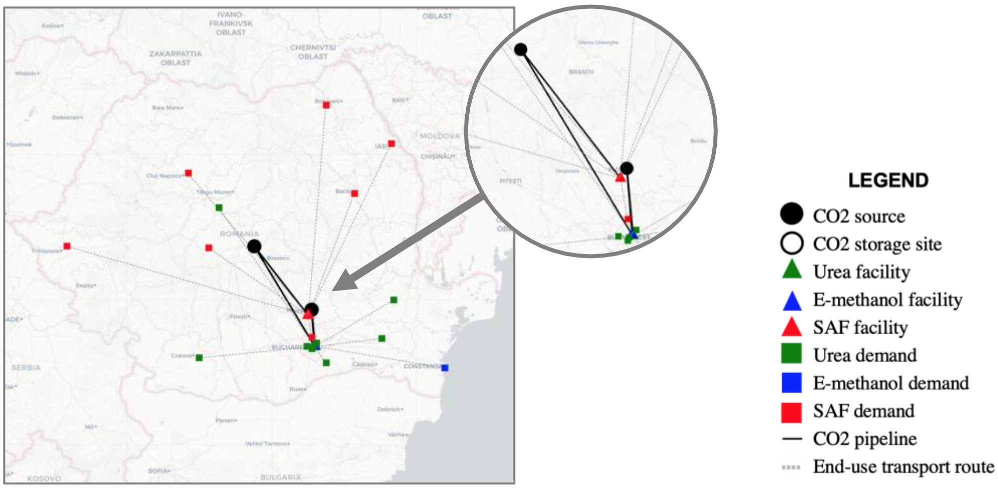


Figure 14 – Romania scenario 2

Figure 15 displays the optimal supply chain for Bulgaria. There is 1 industrial cluster to be built: the Bourgas cluster. This cluster contains 1 refinery which acts as the sole source in this supply chain. This emitter is also a facility that needs to become able to produce SAF. There are 3 facilities in total (1 for each end-use) which are all facilities that are currently operational. Just like in Romania, there are no projects being built. The cluster contains two CO_2 pipelines branching to Alfatar up north and westwards to Velika Tarnovo. These pipelines respectively supply the Alfatar e-methanol facility and the Velika Tarnovo urea facility with CO_2. Storages are not optimal for this configuration. Note that this supply chain captures 2,06 Mton CO_2 out of the 4,82 Mton that is emitted nationally. This adds up to a significant percentage of emissions captured, namely 42,74%. Therefore, only 2,76 Mton is emitted into the atmosphere.

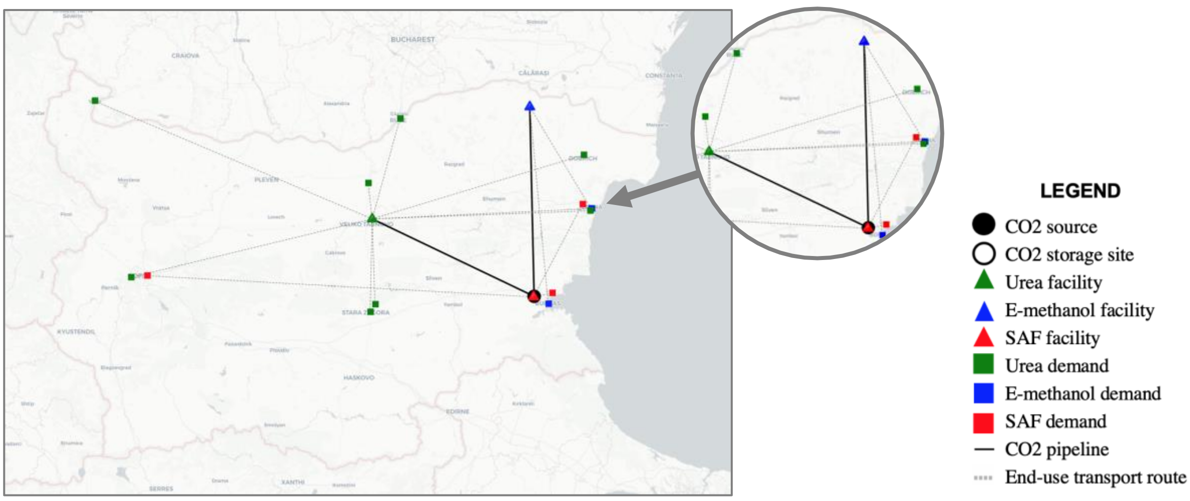


Figure 15 – Bulgaria scenario 2

Lastly, the optimal CCUS configuration for Greece is shown in figure 16. One cluster needs to be built, namely the Athens cluster. 1 source, a refinery, supplies all the CO_2 required for utilization by the 3 facilities. These consist of 1 urea, 2 e-methanol and 1 SAF facility, whereby only the e-methanol facility falls outside the Athens cluster. There are no storages built in this setting, though a pipeline needs to be constructed across the country to Thessaloniki in order to supply the e-methanol facility with CO_2. The 2 other pipelines supplying the urea and SAF facilities stay within Athens. In this supply chain, total emissions captured entail 1,92 Mton, whereby total national emissions are 16,25 Mton. Thus, 11,82% is captured and 14,33 Mton is emitted into the atmosphere.

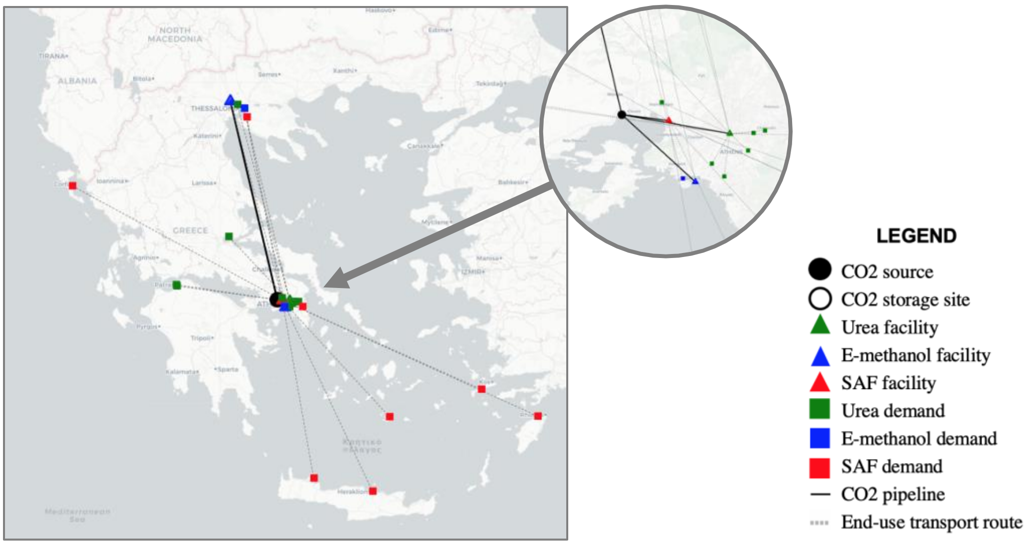


Figure 16 – Greece scenario 2

<u>Cost breakdown</u>

Table 13 below depicts the cost breakdown of the optimal supply chain for each country. It is striking that Greece has the largest total costs out of all countries. An explanation for this is the fact that it has the second largest e-methanol demand out of all countries which implies higher total conversion costs. It also has the largest urea and SAF demand out of the SE cluster countries. The UK leads when it comes to CO_2 capturing and transport costs as this country has the highest number of emissions captured (2,66 Mton) and the longest CO_2 pipelines. Shares of each cost component are quite similar to those of scenario 1, meaning that conversion costs are still the main cost component, followed by end-use transportation cost and capturing costs respectively.

Cost factor	Denmark	Netherlands	UK	Romania	Bulgaria	Greece
Unit (mill. €/year)						
Capture	8.98	29.45	44.13	12.30	34.18	31.89
Pipeline CO_2 (facility)	0.60	1.20	2.27	0.80	1.42	1.41
Conversion	1349.10	1349.10	1807.57	1349.10	1349.10	2049.73
Truck transport	107.49	120.19	569.94	261.32	194.20	348.66
Pipeline CO_2 (storage)	0.00	0.00	0.00	0.00	0.00	0.00
Total (national)	1365.71	1499.93	2423.91	1623.53	1578.90	2431.69
Total (cluster)		5289.55			4475.02	

Table 13 – Cost breakdown scenario 2

Sensitivity analysis conversion costs

Scenario 1 and 2 both showed that conversion costs make up a significant part of total costs. Following this, the sensitivity analysis of scenario 1 showed the different conversion costs for various renewable LCOE scenarios. However, only one value was applied to all countries for each renewable LCEO scenario. This might not give an accurate representation of renewable LCOE as individual countries might have different renewable energy markets (ISPT, European Energy, see table 4). Hence, this sensitivity analysis assesses the renewable LCOE for each individual country. Based on this, the previously used conversion costs were adjusted.

In order to compute the individual country conversion costs necessary for this analysis, the individual country renewable electricity costs have to be found. These costs were determined by means of load factors for domestic renewable resources (i.e., wind and solar). The idea for using load factors was brought up during the interview with Stamicarbon (see table 4). Load factor-based costs for PV were established by Bódis et al. (2019) and Ryberg et al. (2018) found the wind-based costs. These studies created load factor cost figures for PV and wind which are presented in appendix 8 and 9 respectively. The maps show that wind is more abundant in NW countries, whereas PV is more abundant in SE countries (an abundant resource tends to be less expensive). Based on the images, costs were determined for each country and added to table 14. Hereby variable renewable energy (VRE) represents the average of the 2 LCOE values (PV and wind) for each country. The conversion costs are alterations of the base case conversion costs (458.47, 700.63 and 190.00 for urea, e-methanol and SAF respectively) which are in turn based on the renewable cost of electricity used in scenario 1 and 2 (43.05 $/MWh). Denmark was found to have the lowest renewable LCOE, followed by the Netherlands and the UK. The SE cluster has much higher renewable LCOEs; Greece has the lowest renewable LCOE followed by Romania. Bulgaria has the highest renewable LCOE.

Country	Ren. LCOE (load factor PV, $/MWh)	Ren. LCOE (load factor wind, $/MWh)	Ren. LCOE (load factor VRE, $/MWh)	Conversion cost c_f (urea, e-methanol, SAF)
DK	21	41	31	[330,14, 504,52, 136,82]
NL	21	42	31,5	[335,47, 512,66, 139,02]
UK	24	41	32,5	[346,12, 528,93, 143,44]
RO	24	85	54,5	[577,21, 882,09, 239,21]
BG	23	87	55	[585,73, 895,11, 242,74]
GR	22	85	53,5	[569,76, 870,70, 236,12]

Table 14 – individual LCOE based on load factors from Bódis et al. (2019), Ryberg et al. (2018)

Table 15 summarizes the results of the sensitivity analysis. It shows that the other costs are constant with scenario 2 results but the conversion and therefore total costs differ significantly from the costs obtained in scenario 2 (see table 13) as a result of the altered conversion costs. Specifically, total costs for the Danish, Dutch and British supply chain are reduced by 20,29%, 24,13% and 18,11% respectively, whereas total supply chain costs in Romania, Bulgaria and Greece have risen by 21,70%, 23,72% and 20,46% respectively. This implies a total decrease in NW cluster costs of 20,38% and a significant increase of 53,26% SE cluster costs. In addition, these findings confirm that LCOE for each country should ideally be considered individually, as these costs significantly impact conversion and therefore supply chain costs. It also shows that locating operations in a low renewable LCOE country matter for total costs, given that the supply chains is domestic (i.e., it does not have international interactions).21,96

Cost factor	Denmark	Netherlands	UK	Romania	Bulgaria	Greece
Unit (million €/year)						
Conversion	971.48	987.15	1364.61	1698.51	1723.58	2547.28
Other costs	~	~	~	~	~	~
Pipeline CO_2 (storage)	0	0	0	0	0	0
Total (national)	1088.55	1137.98	1984.83	1975.79	1953.38	2929.15
Total (cluster)	4211.36 (20,38% lower than S2)			6858.32 (53,26% higher than S2)		

Table 15 – Economic analysis for changes in renewable LCOE

Discussion and takeaways scenario 2

This section outlines some general findings for scenario 2 supply chains. They concern the construction decisions for the supply chains, their emissions captured and their costs. The impact of the sensitivity analysis will also be assessed. Some findings were validated or criticized by ConsenCUS.

Findings on the construction decisions include the following. Firstly, similar to what was found in scenario 1, sources mainly consist of refineries. Some of these are selected as SAF facilities. Secondly, the supply chains did not involve any projects, nor did they contain storage decisions. Thirdly, there is at least 1 cluster built in each country for the scenario 2 supply chains. This contrasts scenario 1 configurations, which show that not every country needs to contain a cluster. Fourthly, similar to what was found in scenario 1, NW countries contain more construction decisions than SE countries. Again, this is explained by lower demand levels, which were also found by ConsenCUS.

The emissions captured were assessed as follows. In scenario 2, emissions captured by sources are higher than emissions captured by scenario 1 sources because the scenario 2 supply chains contain more sources in total. To be exact, emissions captured by scenario 1 sources amount to 7,75 Mton, whereas emissions captured by scenario 2 sources are 9,75 Mton (4,78%). ConsenCUS was critical of the emissions captured by sources in scenario 1. The same criticism was expressed for scenario 2 supply chains. From a ConsenCUS perspective, scenario 2 is better than scenario 1 as it captures more CO_2.

Conclusions can also be drawn from the scenario 2 cost breakdown. Similar to scenario 1, conversion costs are the highest cost attribute. However, this scenario allows for individual country cost assessments, shown table 13. Variations in individual country conversion, capture and CO_2 transport costs may be observed. Furthermore, total cluster costs for scenario 2 are higher than total cluster costs for scenario 1. Specifically, scenario 2 finds that the sum of NW country costs is 5289.55 million €, whereas scenario 1 NW cluster costs are 4361.83 million €. Similarly, scenario 2 shows that SE national cluster costs amount to 4475.02 million €; these were 3687.83 million € for scenario 1. Thus, NW cluster costs are 17,54% higher and SE cluster costs are 17,59% higher. This implies that international interaction is beneficial when trying to achieve the lowest supply chain costs if the goal is to satisfy all end-use demand. However, as was said in the scenario 1 discussion, the ConsenCUS interview implied that international interaction should only be utilized if it captures more CO_2.

The sensitivity analysis provides the following insights. It showed that total conversion costs may be lower than suggested by scenario 2 results (table 13). Namely, if operations are taken to a NW cluster country, actual conversion costs may be lower than suggested by this scenario. In contrast, if facilities are constructed in a SE country, conversion costs may be higher than scenario 2 results predict (see table 15). Specifically, total NW cluster costs decreased by 20,38%, whereas SE cluster cost increased by around 53,26%. This may occur due to the fact that scenario 2 assumes a constant conversion costs parameter across all countries. The sensitivity analysis emphasizes the fact that local renewable LCEO should be considered before CCU facilities are built. The ConsenCUS interview (see table 4) did not necessarily agree that local renewable LCOE should be the first thing to look at. Rather, ETS and local regulations and subsidy schemes are leading, though, again, these factors lie beyond the scope of this model and are not considered in the above supply chains.

4.3 Scenario 3 (international interaction with single end-uses, storage-oriented)

The above scenarios find no storage decisions and focus on CCU rather than storage. However, storage could be cost-effective in some scenarios, which will be demonstrated with this scenario. Perhaps storage could be an effective part of a CCUS supply chain that mainly focuses on utilization if utilization becomes expensive. This visualizes the idea that CCS will prevail over CCU, given some of the skepticism towards CCU that was noticed during interviews (CO_2 SmartUse, INEOS, see table 4).

This scenario is constructed as follows. In order for the model to select storages, sources that have excess CO_2 must be constructed as this has to be stored. The above scenarios found that the model excess CO_2 should generally flow into new facilities rather than storages. This can be explained by the fact that facilities carry the ability to satisfy demand (a model constraint) and storages do not. Additionally, storages are usually further away than facilities, making the storage decision more costly. Hence, to find a setting in which sources transfer their CO_2 into storages instead of facilities, the facilities must be made unattractive (i.e., more expensive) so that they will not be selected. This can be achieved by reducing total demand and increasing facility capacity. To reduce demand, this scenario will consider only individual end-products. Capacity is increased for all facilities. Hence, experiment data that was used before is altered significantly; experiment settings can be found in appendix 6.

<u>Results (optimal supply chains)</u>

Figure 17 shows the optimal supply chain for the NW cluster, whereby urea is the only end-use considered. In this setting, 5 sources are needed. These are all refineries apart from 1 fertilizer producer. The cluster requires 2 facilities to be built, 1 in Denmark and 1 in the Netherlands. Each is embedded in 1 of the 2 industrial clusters, the Rotterdam and Kalundborg clusters. These do not supply CO_2 for each other and are thus not connected through pipelines. There are 2 DOGF storages situated near the Kalundborg area. For this setting, total CO_2 captured by sources is 2,03 Mton out of an available 158,27 Mton. Thus, the percentage of emissions captured becomes 1,28%. The leftover 156.24 Mton is emitted.

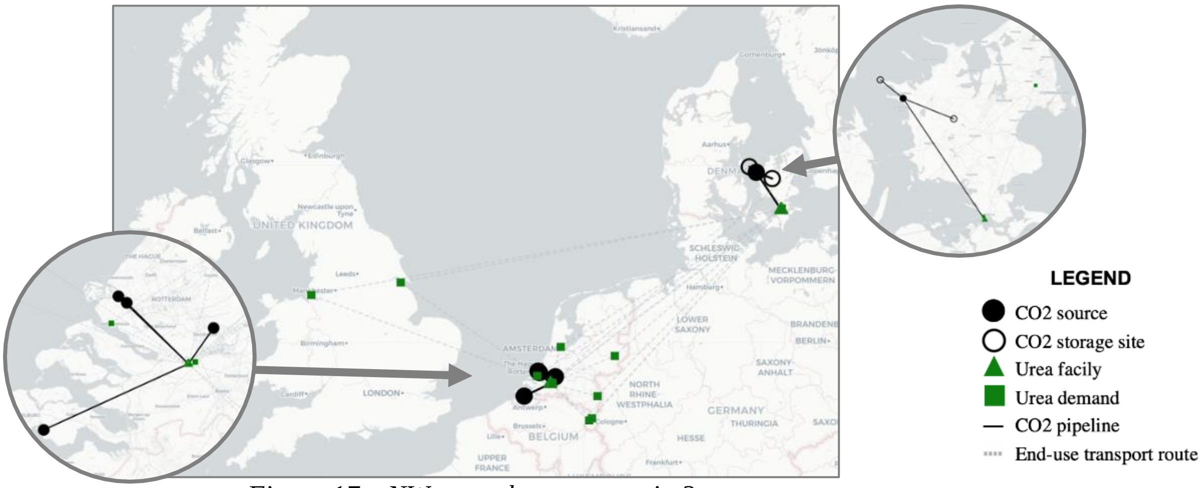


Figure 17 – NW urea cluster scenario 3

Figure 18 depicts the most favorable NW supply chain for just e-methanol production. This setting contains 5 sources which are all refineries with the exception of 1 waste incineration site. There are only 2 facilities needed, 1 in the UK and 1 in Denmark. They are spread among 4 industrial clusters: Newcastle, Norwich, Rotterdam and Sønderborg. CO_2 for the e-methanol facility in Denmark is transported by a pipeline emerging from Rotterdam, thereby it extends across the North Sea. Additionally, there are 2 pipelines from Rotterdam crossing the North Sea to get to the UK facility. Many storages are optimal for this configuration: 22 sites are built, 8 of these are DOGFs and the remaining 14 are SAs. They are dispersed around the UK coast and also appear offshore near Rotterdam. There are also a few onshore sites in Denmark. The sources in this configuration capture 1,61 Mton CO_2 out of 158,27 Mton total emissions, or 1,01%. Hereby 156,66 Mton CO_2 is emitted.

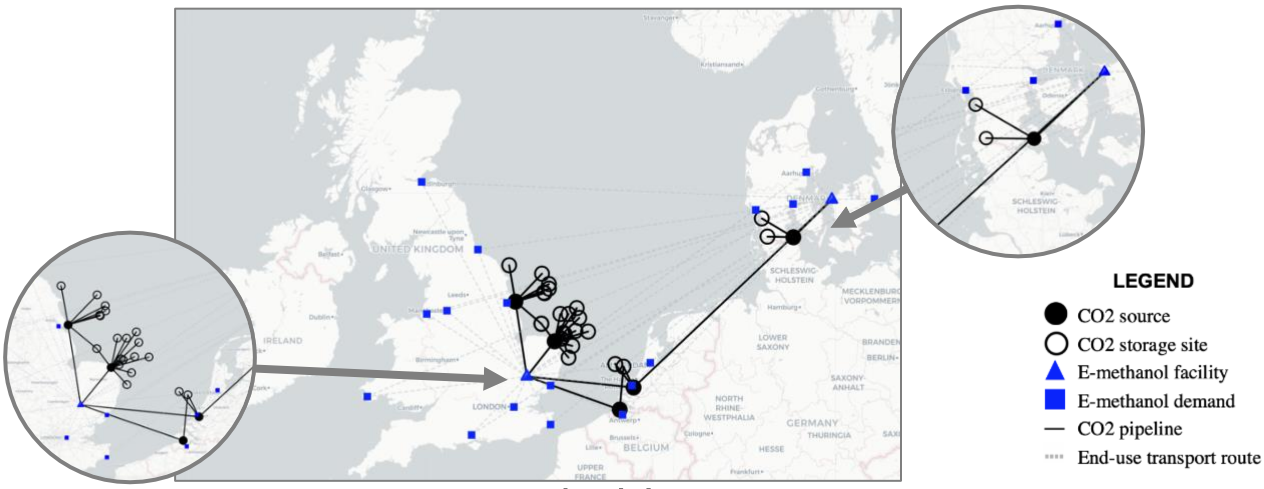


Figure 18 – NW e-methanol cluster scenario 3

Figure 19 depicts the optimal NW configuration in which SAF is the only end-use considered. 6 sources are required for CO_2 supply. They include 4 refineries, though a single fertilizer is selected from Harlingen, the Netherlands. Furthermore, 3 SAF facilities are optimal; 1 must be situated in each country. They are spread across 4 industrial clusters, 3 of which are in the UK: Newcastle, Ellesmere and Norwich. 1 cluster is located in the Rotterdam, the Netherlands and 1 is established in Fredericia, Denmark. All CO_2 demand for the SAF facilities in Fredericia is transported by 2 pipelines crossing the North sea. Additional pipelines that cross the North sea spring from Norwich and Newcastle. These supply the Rotterdam cluster with CO_2. 11 storages are included in this configuration which include 4 offshore DOGFs and 7 SAs. These surround the 3 UK clusters in offshore areas and there is also 1 near the coast at the level of Rotterdam. Sources in this setting capture a total of is 1,17 Mton CO_2 out of 158,27 Mton possible emissions, amounting to 0,74% captured and leaving 157,10 Mton to be emitted.

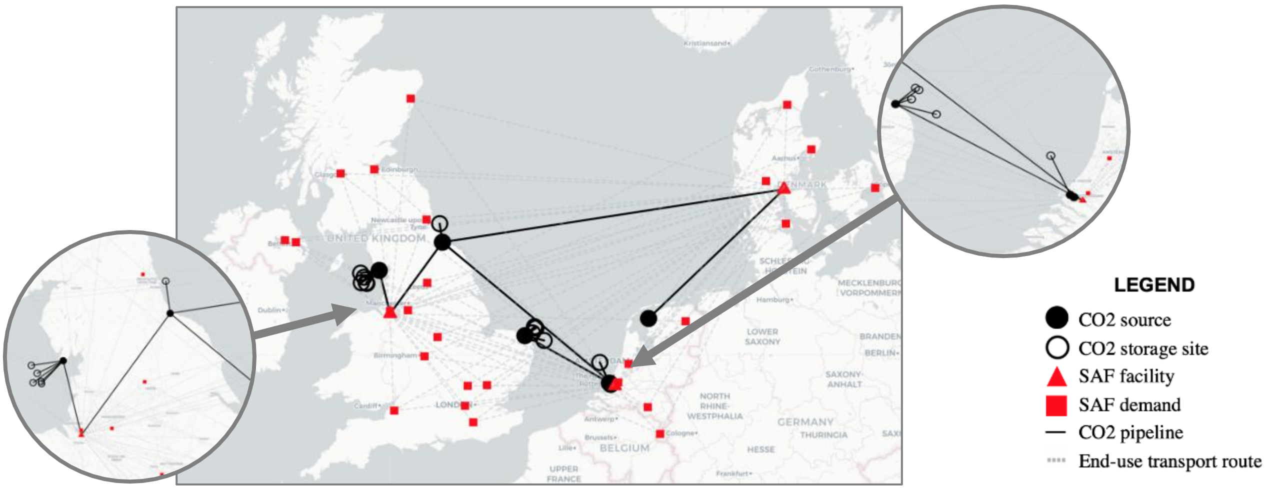


Figure 19 – NW SAF cluster scenario 3

The best possible SE cluster that solely produces urea is shown in figure 20. There are 3 sources to be constructed in this setting, all of which are refineries. Just 2 facilities are optimal, 1 is built in Greece and the other stands in Romania. There are 2 industrial clusters present in this supply chain, situated in Athens and Ploiesti. A pipeline migrates CO_2 from Thessaloniki to Athens and there is 1 extensive international CO_2 pipeline constructed from Ploiesti to the Athens facility connecting the 2 clusters. The Ploiesti plant is supplied by 2 sources by means of 2 pipelines, 1 of which stems from Bacau in the north, the other originates in Ploiesti. Only 1 storage is built in his arrangement: an onshore SA in Ploiesti. The supply chain manages to capture 1,60 Mton CO_2 out 45,86 Mton total emissions, thereby contributing to 3,49% emissions captured. Unfortunately, 44,24 Mton CO_2 is emitted.

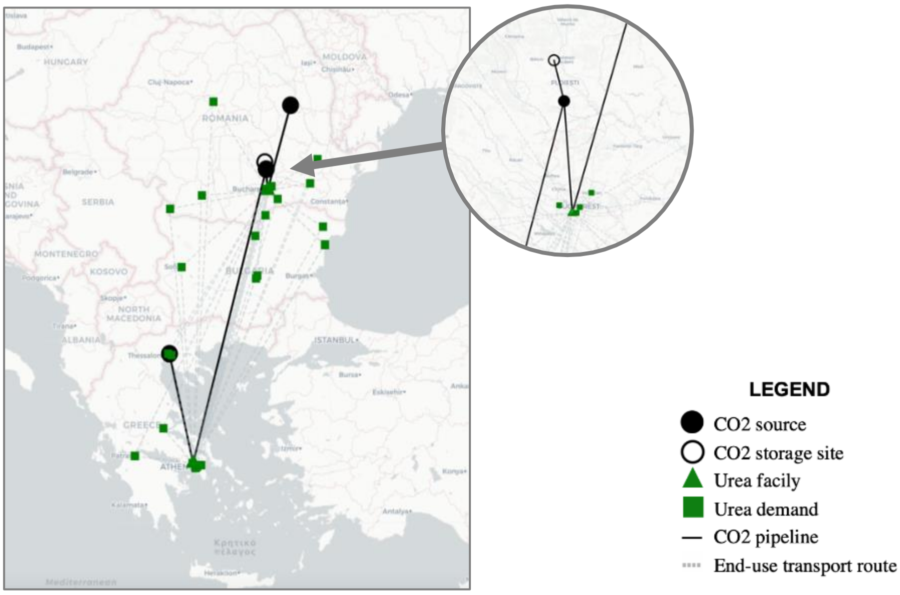


Figure 20 – SE urea cluster scenario 3

Figure 21 configures the optimal SE supply chain exclusively for e-methanol production. There are 3 refineries and 1 fertilizer plant supplying the CO_2. Merely 1 facility is constructed in Bulgaria and there are 4 industrial clusters. The facility lies at the center of these clusters. A cluster in Thessaloniki supplies the plant with CO_2, the other supply stems from the 3 clusters in Romania: Ploiesti, Bacau and Velika Tarnovo. There are 7 storages in total, 2 DOGFs and 5 SAs. They are located mostly onshore and surround Velika Tarnovo and Ploiesti. The 2 near Thessaloniki are offshore and placed in the same spot; it concerns 2 sites stacked on top of each other. Emissions captured by sources are 0,19 Mton out of 45,86 Mton total emissions. CO_2 captured makes up 2% of total emissions, 44,79 Mton is emitted.

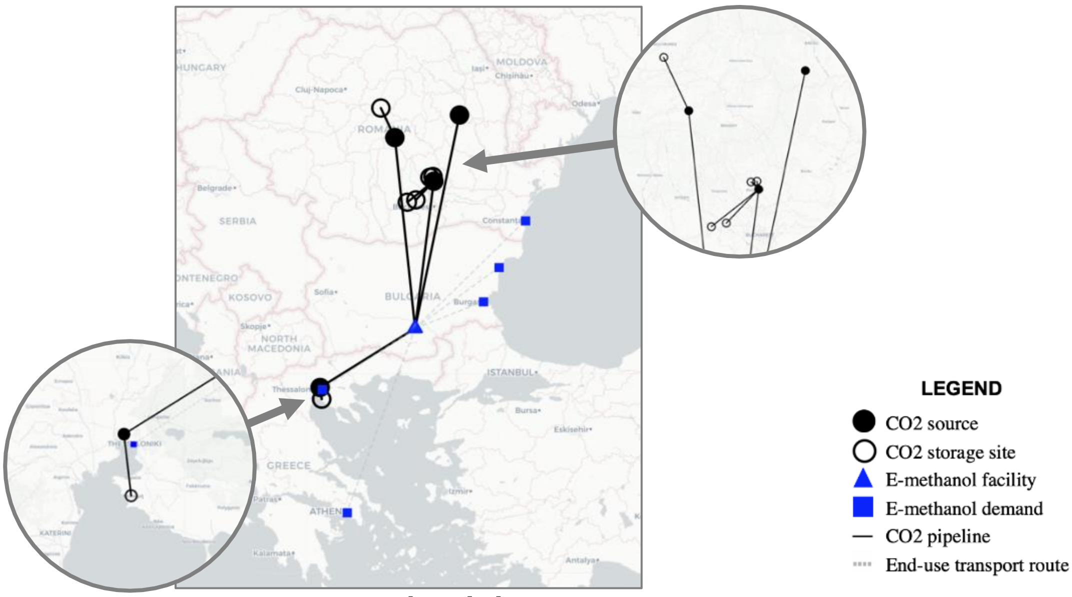


Figure 21 – SE e-methanol cluster scenario 3

Figure 22 displays the optimal SE supply chain that solely provides SAF. There is 1 refinery required to supply all CO_2 and there are 2 facilities constructed. These stand in Athens and Ploiesti. There is 1 industrial cluster in Thessaloniki containing the CO_2 source that connects to the facilities through cross-country pipelines. There are also 2 sites that store the excess CO_2 from the singular source. This concerns a DOGF combined with an SA which lie near the coast of Thessaloniki. That is, they are at the same location but 2 different storages. For this setting, the total CO_2 captured is 0,29 Mton out of 45,86 total emissions, or 0,64%. The surplus CO_2 emitted entails 45,56 Mton.

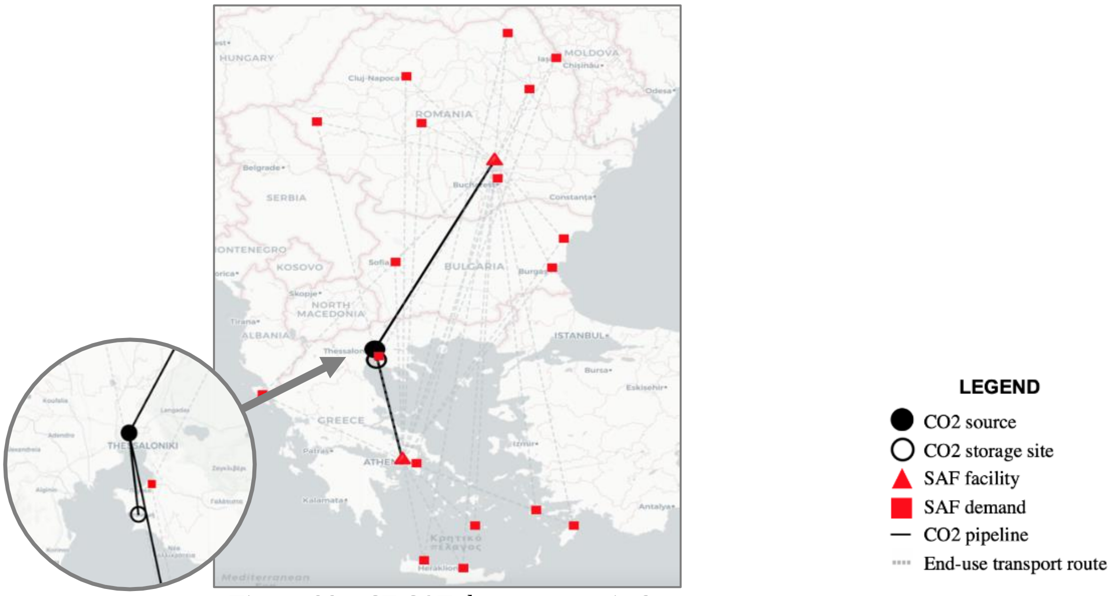


Figure 22 – SE SAFcluster scenario 3

<u>Cost breakdown</u>

Table 16 shows the costs associated with the above configurations. The share of respective cost components has not changed much from scenario 1 and 2. That is, conversion costs are still the most expensive component, followed by end-use transport. Surprisingly, CO_2 storage (pipeline) cost is still the smallest factor, though it has logically increased significantly because of all the added storage. Table 16 also reveals that each end-use has different total supply chain costs. Specifically, e-methanol is the costliest for the NW cluster due to its high per-ton conversion costs and high demand. Notably, e-methanol is not as expensive in the SE cluster because there is low demand for it in SE counties. In this cluster, it is urea that is most expensive. This is not due to conversion costs but due to its relatively high demand. Similar to what was found in scenario 1 and 2, total costs are lower in the SE cluster due to less end-use demand. Therefore, fewer nodes are constructed and total costs are lower.

Unit (mill. €/year)	NW			SE		
Cost factor	Urea	E-methanol	SAF	Urea	E-methanol	SAF
Capture	34.22	27.42	19.43	26.61	18.67	4.85
Pipeline CO_2 (facility)	1.78	3.65	1.07	3.10	4.23	0.50
Conversion	916.94	1401.26	570.00	916.94	700.63	380.00
Truck transport	185.24	355.53	446.68	363.82	149.66	481.03
Pipeline CO_2 (storage)	0.071	1.25	0.70	0.049	0.34	0.083
Total (per end-use)	1138.25	1789.12	1037.88	1310.52	873.52	866.46
Total (cluster)	3965.25			3050.50		

Table 16 – Cost breakdown scenario 3

Sensitivity analyses

The above supply chains make use of all storages identified by ConsenCUS (2022B). It was confirmed by BGS (see table 4) that these are the most up-to-date storages to use for analysis. However, the scenario 3 configurations may suggest storages which will unlikely be built by 2030. Namely, storages may have characteristics making them less suitable for storage. Hence, various sensitivity analyses were performed that show the impact on scenario 3 supply chains when storages with certain attributes are excluded. Thus, the assumption that all storage sites identified by ConsenCUS (2022) will be operational by 2030 is disregarded. The first sensitivity analysis looks at the effect of excluding onshore storages. Namely, onshore storages might not be used for political reasons identified during the interview with GeoEcoMar (see table 4). For the second analysis, sites with an SRL higher than 5 ("validated by detailed analysis in real-world settings", see appendix 1) will be used exclusively. The third and final sensitivity analysis only includes DOGFs (onshore and offshore sites) as they are the least expensive out of storage types according to Van den Broek et al. (2010) found in appendix 7).

Table 17 presents the results of the first analysis. It includes the changes in supply chain costs after all onshore sites were excluded. The other components are similar to the storage scenario described by table 16 (represented by "~"). Note how CO_2 transport costs are significantly higher; they have risen with 298,93% for all uses on average (up to 1147,06% for e-methanol individually). However, this does not significantly affect total costs, because the storage cost component remains small, total costs go up with 0,01% and 0,15% for the NW and SE cluster respectively. The lower percentage for NW can be explained by the fact that most storages in the NW are generally offshore in the first place.

Unit (million €/year)		NW			SE	
Cost factor	Urea	E-methanol	SAF	Urea	E-methanol	SAF
Other costs (table 16)	~	~	~	~	~	~
Pipeline CO_2 (storage)	0.23	1.29	0.70	0.15	4.24	0.26
% of scenario 3 CO_2 storage pipeline costs	223,94%	3,20%	0,00%	206,12%	1147,06%	213,25%
Total (per end-use)	1138.43	1789.15	1037.88	1310.64	877.85	866.64
Total (cluster)	3965.46 (0,01% higher than S3)			3055.13 (0,15% higher than S3)		

Table 17 – Sensitivity scenario 3 (only offshore)

Table 18 presents the results for the analysis that was performed after excluding SRL levels lower than 5. It only shows results for the NW storages as there were no SRL levels available for the SE storages in the ConsenCUS (2022B) database. It was confirmed by GeoEcoMar (see table 4) that Eastern European countries do not have high SRLs, so excluding them seems valid. 16 sites across the UK and the Netherlands were identified as having a SRL of 5 or higher. Table 18 shows that the storage costs for each configuration increase with 209,51% on average. For urea individually, it may be up to 322,54% as expensive as the scenario 3 settings above suggest. The total supply chain costs are only 0,09% higher than the scenario 3 NW configuration suggested. It appears that the high SRL storages are generally located further away from optimal clusters and supply chain costs increase as a result.

Unit (million €/year)		NW	
Cost factor	Urea	E-methanol	SAF
Other costs (see table 16)	~	~	~
Pipeline CO_2 (storage)	0.30	2.20	2.31
% of scenario 3 CO_2 storage pipeline costs	322,54%	76,00%	230,00%
Total (per end-use)	1138.49	1790.06	1040.10
Total (cluster)	3968,65 (0,09% higher than S3)		

Table 18 – Sensitivity scenario 3 (only SRL ≥ 5)

Finally, table 19 shows the scenario 3 supply chain costs after solely including DOGF storages. Costs increase by 169,55% for each end-use on average. Again, the other components stay roughly the same as in table 16. However, when assessing storage construction cost (which are not considered by the model) total costs might be significantly lower. These additional costs are given by appendix 7. Table 19 shows that constructing the pipelines solely for DOGF storage types is inefficient from a total supply chain cost perspective. Instead, SAs should be included as they are often closer to optimal CO_2 sources, meaning that the pipeline construction costs will be lower. Total supply chain costs become 3966,79 and 3051,91 million € for the NW and SE cluster respectively. This translates to increases of 0,04% and 0,05% in total costs for each cluster respectively when compared to table 16 costs.

Unit (million €/year)	NW			SE		
Cost factor	Urea	E-methanol	SAF	Urea	E-methanol	SAF
Other costs (see table 16)	~	~	~	~	~	~
Pipeline CO_2 (storage)	0.071	1.90	1.56	0.13	2.04	0.23
% of scenario 3 CO_2 storage pipeline costs	0,00%	52,00%	122,86%	165,31%	500,00%	177,11%
Total (per end-use)	1138.25	1789.80	1038.74	1310.63	874.74	866.61
Total (cluster)	3966,79 (0,04% higher than S3)			3051,98 (0,05% higher than S3)		

Table 19 – Sensitivity scenario 3 (only DOGF)

Discussion and takeaways scenario 3

The upcoming section presents some findings based on the above supply chain layouts, the emissions captured, the costs and the sensitivity analyses. It also specifies comments made by BGS.

Observations for scenario 3 supply chains include the following. Firstly, the supply chains show that selected storages are located as close as possible to sources as their optimality solely depends on distance. It was confirmed during the BGS interview (see table 4) that these selected sites are ones that CCUS stakeholders (such as BGS) are currently interested in. BGS also recommended storages along the Scottish coast, though these were not optimal according to scenario 3 results. Secondly, there are generally more storages built in e-methanol supply chains because e-methanol (and thus CO_2 demand) is low. The opposite is true for urea (there is more CO_2 demand and end-use demand). Thirdly, most storage pipelines are short, clustered and close to emitters. BGS confirmed that such pipeline constructions are feasible, tough quite expensive. According to BGS, existing pipeline infrastructures should be assessed first as these may already exist (this holds for DOGFs). Finally, BGS brought to the attention that selected pipelines may pass through restricted areas, including windfarms and protected areas present along UK coastlines. Such elements have not been considered as direct routes are assumed.

Emissions captured by sources for scenario 3 were evaluated as follows. The sources in both urea clusters presented by scenario 3 capture 3,63 Mton emissions in total. For e-methanol and SAF, these amounts equal 1,80 and 1,46 respectively. Individually, these numbers are much lower than scenario 1 and 2 emissions captured (7,75 and 9,75 for scenario 1 and 2 respectively). Adding the scenario 3 emissions captured together results in a total of 6,89 Mton captured (3,38%). However, that would mean that supply chains are combined. The resulting supply chain would not be optimal from a total cost perspective. In short, emissions captured are unsatisfactory from a ConsenCUS perspective.

Scenario 3 supply chain costs are evaluated in this section. Table 16 concludes that the total costs for each cluster have reduced compared to the international base case by about 25.03% and 31,84% for the NW and SE clusters respectively. This can be explained by the fact that the capacity settings of individual facilities have been increased in order to obtain a low number of facility construction decisions. The costs of storage edges were also assessed by BGS. It was confirmed that distance matters, but it is likely not the most important factor to base storage decisions on. It was suggested that faraway sources usually provide a good starting point for clusters: if a storage capacity of a faraway site is reached, operations can always be moved to a site that closer to the emitter.

The sensitivity analyses may also be used to infer conclusions. It showed that when certain storages are no longer available, supply chain costs could go up by 0,01-0,15% depending on the storages excluded and the cluster that is considered. Looking solely at the NW cluster, costs increase most significantly when there are only high-SRL storages available. In contrast, the analysis that excluded onshore storages for the NW cluster had the least effect on total costs because NW countries barely have onshore sites to begin with. The analyses impacted the SE cluster configurations differently. For this cluster, excluding onshore sites had the greatest effect on total costs because these countries almost exclusively offer onshore storage. Excluding SAs barely showed any effect in the SE cluster because there is usually a DOGF nearby that can replace the initially selected SA. This also holds for the NW cluster. In short, all different storage types should be included if cost optimization is the goal. BGS agrees with this finding: during the interview, they confirmed that storages of all types should be included: it does not matter if it is a SA or a low SRL storage. Namely, according to BGS, a higher SRL only implies that emitters might prefer them over other storages as is just an indication of how much financial resources are still required. BGS also denied that storages with higher SRLs will become usable sooner than sites with lower SRLs because the former might run into an issue that stops progress completely, whereas the latter might not. Finally, according to BGS, preferences between SA and DOGF are site-specific and it is not true that DOGFs are always preferred. The point was made that average costs might be higher for SAs, but some SAs might be much more suitable to store large amounts of CO_2 in. In other words, SAs might be a better long-term investment.

5. CONCLUSION

This thesis aimed to find the optimal CCUS supply chains for the NW and SE ConsenCUS clusters in which decarbonized urea, e-methanol and SAF are produced and excess captured CO_2 is stored. In order to achieve this, 3 scenarios were constructed. Scenario 1 provided the optimal supply chain whereby international interactions are in place, whereas scenario 2 showed the optimal configuration for individual countries. Finally, scenario 3 presented the optimal supply chains for both clusters in which single end-uses were assumed. Results for scenarios 1 and 2 were validated by ConsenCUS and scenario 3 was validated by BGS (see table 4).

The optimal configurations for NW and SE supply chains were the ones presented by scenario 1 as these allowed for the lowest total costs whilst satisfying all demand. Total costs for these configurations are 4,36 billion €/year and 3,69 billion €/year for the NW and SE clusters respectively (see table 11). Scenario 2 costs amount to 5,29 billion €/year for the NW cluster and 4,48 billion €/year for the SE cluster (see table 13). Finally, the optimal scenarios for single end-uses shown by scenario 3 amount to 3,97 billion €/year and 3,05 billion €/year. Scenario 3 showed the lowest costs for individual end-use supply chains, though settings were altered making it difficult to compare to scenario 1 and 2. These findings correspond to Zhang et al (2018), who obtained a total cost of 2.30 billion $/year for a supply chain in China. Similarly, Leonzio, Foscolo and Zondervan (2020) optimized a CCUS supply chain and found total costs of 77.3, 98.0 and 1.05 billion €/year for Italy, Germany and the UK respectively. Although these costs are somewhat similar to the ones found by this thesis, different outcomes are to be expected as the studies do not consider the same end-uses nor storage. They also used different optimization models and data. Additionally, not all of them analyzed multiple countries.

Emissions captured were found to be low in the aforementioned scenarios. Scenario 1 configurations are able to capture 3,80% of total emissions, whereas supply chains from scenario 2 have the capacity to capture 4,78%. Scenario 3 supply chains capture the least amount, namely 3,38%. These results compare to Hasan et al. (2015), who performed a similar optimization and managed to find a supply chain capturing 3% of the total CO_2 emissions in the US. This differs significantly from the network designed by Zhang et al (2018), who managed reductions up to 50% in China. When comparing the 3 scenarios, it may be concluded that scenario 2 supply chains are able to capture most emissions. This setting corresponds best with the ConsenCUS goal which is to achieve net zero emissions.

Managerial takeaways were implied by the above findings and supply chains. Firstly, international interactions are beneficial if the goal is to obtain the lowest costs whilst satisfying all demand. As a result, scenario 1 shows that demand sites should be supplied with products produced internationally. If the objective is to capture a high percentage of total emissions, national supply chains are optimal. Secondly, if supply chain costs are intended to be minimized, CO_2 capturing should be exclusively performed by natural gas and oil refineries as the majority of constructed emitters were of this industry type, no matter their distance from facilities. This was observed across all scenarios due to their low capture costs. Thirdly, as conversion costs were found to be the main cost factor, the reduction of conversion cost should be prioritized. In scenario 1, an attempt was made to reduce conversion costs by assessing the impact of reduced renewable LCOE. Should the best case renewable LCOE scenario develop, total costs for the NW and SE supply chains could be reduced by 29,36% and 16,45% respectively. Scenario 2 extended this by assessing the impact of individual country renewable LCOE on total costs. It was found that total costs may reduce by 20,38% for the NW cluster and increase by 53,26% for SE cluster, given the lower renewable LCOEs of the former. Thus, expected renewable LCOE scenarios as well as the location of the planned conversion facility should be considered if the goal is to minimize costs. A fourth takeaway to note is that supply chains become more storage-oriented when end-use demand is reduced. Namely, scenarios 1 and 2 had high demands and barely utilized storage, whereas scenario 3 had the lowest end-use demands and promoted lots of storages. The latter scenario showed that, in order to obtain the lowest costs, all storage types should be included. Namely, when storages are excluded based on their SRL, onshore setting or type (SA or DOGF), distances between sources and storages become larger, pipelines become more expensive and total costs increase. In was shown that excluding low SRL storages had the greatest effect on NW supply chains as they experienced a 0,09% cost increase. Contrastingly, excluding onshore sites affected SE supply chains most significantly as they experienced a 0,15% cost increase. BGS verified that SRLs or storage types are not major determinants for an optimal supply chain: it is better to look at sites individually.

Limitations should be recognized for the scenario analyses that were performed. After discussing results with BGS and ConsenCUS, the following limitations stood out. First of all, end-uses are assumed to be transported by truck, though in reality they cannot always be trucked and should be transported by ship or plane (for edges crossing the sea for instance). Hence, further research is required to investigate whether shipping transport cost are just as expensive as the assumed truck transport. Secondly, ConsenCUS argued that CO_2 transport is currently done by truck and not by pipeline. Hence, new research should perhaps assume that CO_2 is transported by truck instead of by pipeline. Thirdly, ConsenCUS argued that instead of looking at (national) renewable LCOE first, it might be better to look at local rules, regulations and subsidy schemes first. ETS might also be useful to consider. All these factors were not considered by this thesis. Future research should account for them and find cost parameters that have these elements factored in. Fourthly, emissions captured by the above configurations are quite low (3,38%-4,78%). These amounts are not in line with the short term ConsenCUS goal of obtaining net zero emissions. Future research must aim to find a net zero supply chain using a different model. Namely, the model used in this thesis is not constrained to capture all emissions. Fifthly, as pointed out by BGS, existing pipeline infrastructures and obstacles such as wind parks and protected areas were not considered for storage decisions. Future research may focus on applying a model that accounts for prohibited areas and existing pipeline infrastructure. For instance, new research may include edge restrictions that stop them from making certain connections. Sixthly, the model used in this thesis only looks at distance and the associated pipeline costs rather than actual storage costs. Upcoming research should take these costs into account. Finally, data used for most parameters was considered deterministic and uncertainties were thus not accounted for. This may have resulted in inaccurate supply chain representations. Uncertainties include the linearity of costs, emissions staying constant over time, future demands and the selection of existing facilities (these might not be able to convert). Logically, the cost parameters are also uncertain. Future research should make use of feasible scenarios (which are embedded in the model by Wouda, Romeijnders and Ursavas, though not applied by this thesis) to account for the uncertainty of scenarios.

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APPENDIX

SRL number	Description/title of SRL	Stages and thresholds in the storage site permitting process	Stages and thresholds in technical appraisal & project planning
SRL 1	First-pass assessment of storage capacity at coutry-wide or basin scales	Gathering information for an exploration permit, if needed*	Technical appraisal
SRL 2	Site identified as theoretical capacity		
SRL 3	Screening study to identify an individual storage site & an initial storage project concept		
SRL 4	Storage site validated by desktop studies & storage project concept updated		
SRL 5	Storage site validated by detailed analyses, then in a 'real world' setting	Exploration permit Planning & plan iteration for a storage permit ♦	Well confirmation, if needed* Outline planning for development
SRL 6	Storage site integrated into a feasible CCS project concept or in a portfolio of sites (contingent storage resources)		Technical risk reduction completed Project planning & permitting iterations
SRL 7	Storage site is permit ready or permitted	Storage permit ♦ application & iteration	
SRL 8	Commissioning of the storage site and test injection in an operational environment	Storage permit ♦ required Injection permit application, if needed	All planning work completed Construction & testing
SRL 9	Storage site on injection	Injection permit	Site construction completed Operation & monitoring

Appendix 1 – storage readiness level legend (Akhurst, 2021)

Country		Share of revenues per country	Total fertilizer consumption (kg/year)	Demand + CAGR (Kton/year + 1,2%)
NL	Van Iperen B.V.	39,96%	279190000	111,58
	Van De Reyt Meststoffen B.V.	10,34%		28,87
	Triferto B.V.	7,79%		21,74
	Mertens B.V.	6,62%		18,48
	Borealis Plastomers B.V.	6,32%		17,63
	Icl Europe B V	27,18%		75,88
	OCI Fertilizer Trade & Supply B.V.	1,79%		5,01
UK	Nw Trading (Commodities) Limited	4,69%	1394000000	65,38
	Yara Uk Ltd	95,31%		1328,62
DK	Yara Danmark A/S	39,71%	342935980	136,19
	Basf Agro	60,29%		206,75
RO	Alcedo SRL	34,37%		253,79
	Kwizda Agro Romania SRL	13,77%	738453000	101,71
	Adama Agricultural Solutions SRL	10,67%		78,76
	Archim Fertil SRL	9,42%		69,57
	Toros Agroport Romania S.A.	9,36%		69,15
	Agromas Grup Srl	8,27%		61,07
	Ecoplant SRL	5,84%		43,09
	Holland Farming Agro SRL	4,36%		32,18
	Chimagri SRL	3,94%		29,12
	Afer Bulgaria	56,03%		272,41
BG	Sembodja	9,32%	486187330	45,32
	F+S Agro	9,10%		44,25
	Bulagro	7,46%		36,26
	Tedi	5,02%		24,41
	Agrochemicals	4,65%		22,61
	Agroexperts	2,14%		10,40
	Agrostil	1,86%		9,06
	Eurochem Agro Bulgaria Ead	4,41%		21,46
	Hellagrolip Commercial And Industrial S.A.	33,12%		105,88
	Aegean First Company Afco S.A.	17,80%		56,90
GR	Yara Hellas S.A.	15,97%	319715110	51,06
	Eurochem Agricultural Trading Hellas S.A.	7,74%		24,74
	Teofert S.A.	7,39%		23,63
	Compo Expert Hellas S.A.	5,71%		18,24
	Nitrofarm S.A.	3,24%		10,37
	New Trade Fertilizers Ltd	3,14%		10,05
	Medilco Hellas S.A.	2,31%		7,38
	Agri.Fe.M. Ltd	1,66%		5,31
	Active Agro S.A.	1,62%		5,19
	Eurochemicals Ltd	0,30%		0,95

Appendix 2 – Urea demand

Country	TEU/y & CAGR (UNCTAD, 2021)	Port	Cargo handled (Mton/year)	Reference	Share of tons handled	Ships/port/y (with CAGR TEU, relative to country)	E-methanol required per port 2030 (Kton/year)
NL	15781756 (+2,80%/y)	1. Rotterdam	434,8[1]	[1] Marine Insight, n.d. from: https://www.marineinsight.com/know-more/ports-of-the-netherlands/#:~:text=Zeeland%20Seaports&text=It%20handles%20different%20kinds%20of,handled%20at%20the%20port%20annually.	83,0%	3358,93	815,68
		2. Amsterdam	74,8[1]		14,0%	566,57	137,59
		3. Zeeland Seaports (Terneuzen)	15,0[1]		2,9%	117,36	28,50
UK	9844540 (+1,51%/y)	1. Southampton	27,6[2]	[2] GOV.uk, 2021. From: https://www.gov.uk/government/statistics/port-freight-annual-statistics-2021/port-freight-annual-statistics-2021-overview-of-port-freight-statistics-and-useful-information	9,1%	205,86	49,99
		2. London	51,8 [2]		17,0%	386,35	93,82
		3. Felixstowe	21,5[2]		7,1%	160,36	38,94
		4. Milford Haven	30,3[2]		10,0%	225,99	54,88
		5. Grimsby &	50,0[2]		17,0%	372,93	90,56
		Immingham				257,32	62,49
		6. Manchester	34,5[2]		11,0%	199,89	48,54
		7. Liverpool	26,8[2]		8,9%	148,43	36,04
		8. Tees Hartlepool	19,9[2]		6,6%	148,43	36,04
		9. Dover	19,9[2]		6,6%	147,68	35,86
		10. Forth Ports	19,8[2]		6,6%		
DK	1055262 (+3,50%/y)	**1.** Copenhagen	15,0[3]	[3] Marine Insight, n.d. from: https://www.marineinsight.com/know-more/6-major-ports-in-denmark/	31,0%	89,17	21,65
		2. Fredericia	16,9[3]		35,0%	100,67	24,45
		3. Esbjerg	4,7[3]		9,8%	28,19	6,85
		4. Aarhus	11,29[3]		24,0%	69,03	16,76
RO	631964 (+1,06%/y)	1. Costanta	90,0[4]	[4] Marine Insight, n.d. from: https://www.marineinsight.com/ports/10-major-ports-in-romania/#1_Port_of_Constanta	100%	138,97	33,75
BG	245160 (+4,62%/y)	1. Varna	7,72[5]	[5] Marine Insight, n.d. from: https://www.marineinsight.com/know-more/7-major-ports-and-harbours-in-bulgaria/	53,0%	39,02	9,48
		2. Bourgas	6,77[5]		47,0%	34,60	8,40
GR	6069480 (+14,61%/y)	1. Piraeus	46,9[6]	[6] Eurostat, 2021, from: http://aapa.files.cms-plus.com/PDFs/WORLD%20PORT%20RANKINGS%202011.pdf	73,0%	3023,48	734,22
		2. Thessaloniki	17,4[6]		27,0%	1118,27	271,56

Appendix 3 – Methanol demand

Country	Total yearly consumption (thousand tons/y)	Airport	Share of traffic units (2021)	Reference	SAF demand (Kton/year, + CAGR + blending ratio, 13,7%, 5%)
NL	2378 (2021)	1. Schiphol	89.15%	CBS, n.d., from: https://opendata.cbs.nl/#/CBS/en/dataset/37478eng/table	331,23
		2. Eindhoven	7.82%		34,83
		3. Eelde	0.36%		0,84
		4. Maastricht	0.29%		8,23
		5. Rotterdam	2.39%		10,35
UK	4677 (2021)	1. Heathrow	30.12%	CAA, 2021, from https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/uk-airport-data-2021/annual-2021/	223,68
		2. London Stansted	11.10%		82,42
		3. London Gatwick	9.72%		72,21
		4. Manchester	9.45%		70,16
		5. London Luton	7.26%		53,91
		6. Edinburgh	4.70%		34,88
		7. Birmingham	3.85%		28,57
		8. Belfast	3.61%		26,84
		9. Bristol	3.24%		24,06
		10. Glasgow	3.22%		23,89
		11. Liverpool (John Lennon)	1.81%		13,44
		12. Aberdeen	1.67%		12,41
		13. Newcastle	1.59%		11,79
		14. East Midlands International	1.29%		9,55
		15. Belfast city (Gorge best)	1.26%		9,37
		16. Leeds Bradford	1.14%		8,48
DK	462 (2021)	1. Copenhagen	84.20%	Statistics Denmark, 2023, from: https://www.statbank.dk/FLYV31	58,68
		2. Billund	9.80%		8,73
		3. Aarhus	1.35%		0,87
		4. Aalborg	4.44%		4,90
		5. Sønderborg	0.21%		0,18
RO	185 (2018)	1. Henri Coandă	61.50%	Airportaar, 2022, from: https://www.airportaar.ro/traficul-de-pasageri-pe-aeroporturile-din-romania-in-trimestrul-i-iii-2022/	18,07
		2. Cluj Avram Iancu	13.02%		3,83
		3. Iași	5.71%		1,68
		4. Traian Vuia	5.62%		1,65
		5. George Enescu	3.39%		1,00
		6. Ștefan cel Mare	3.09%		0,91
		7. Sibiu	2.50%		0,74
BG	258 (2018)	1. Sofia	63.13%	Eurocontrol., 2021, from: https://www.eurocontrol.int/sites/default/files/2022-05/eurocontrol-lssip-2021-bulgaria.pdf	25,86
		2. Varna	18.96%		7,77
		3. Burgas	17.91%		7,34
GR	893 (2021)	1. Athens	12.20%	CAA, 2021, from http://www.ypa.gr/	57,89
		2. Heraklion	11.71%		17,30
		3. Thessaloniki	7.74%		16,61
		4. Rhodes	4.83%		10,97
		5. Corfu	3.97%		6,85
		6. Chania	3.54%		5,62
		7. Kos	2.87%		5,02
		8. Santorini	2.14%		4,06

Appendix 4 – SAF demand

Cost parameter	Cost (in €/ton CO_2/year)	Capacity parameter	Capacity (ton *R*/year)
c_u (variable per industry)	95.79 (C), 99.97 (IS), 25.95 (F), 16.61 (R), 79.02 (PG), 25.95 (WD)	σ_u	Respective emissions for each source node in set V^u.
c_{uf}, c_{us} (variable per *d*)	24.7*((c_{uf},c_{uf})^0.35) * (d^1^1.13) + 0.02 * d^1	σ_{uf}, σ_{us}	σ_{uf} is based on σ_f and the yield for each product: 0.73, 1.37 and 3.00 for urea, e-methanol and SAF respectively. σ_{us} is equal to the average yearly injection rate (3,52Mton).
c_f (variable per *R*)	458.47 (urea), 700.63 (methanol), 190.00 (SAF)	σ_f	Average yearly production: 1 Mton for each end-use.
c_{fv}	0.10*d (distance is represented by *d*, which is calculated for each edge based on φ and λ).	σ_{fv}	The demand at respective demand node V^v, as truck capacity is unlimited (1 truck carries 20 t but more trucks can be called on demand).
N.a.	N.a.	$d_j(\omega^s)$	demand at demand node locations (base case, see table 10-12). ω^s is one.

* For each cost or capacity parameter, cross-border locations are included for scenario 1 and excluded for scenario 2.

<u>Appendix 5 – Experiment settings scenario 1 and 2*</u>

Cost parameter	Cost (in €/ton CO_2/year)	Capacity parameter	Capacity (ton *R*/year)
c_u (variable per industry)	Base case setting: 95.79 (C), 99.97 (IS), 25.95 (F), 16.61 (R), 79.02 (PG), 25.95 (WD)	σ_u	Base case setting i.e. the respective emissions for each source node in set V^u.
c_{uf}, c_{us} (variable per *d*)	24.7*((c_{uf},c_{uf})^0.35) * (d^1^1.13) + 0.02 * d^1	σ_{uf}, σ_{us}	σ_{uf} is based on σ_f and the yield for each product (0.73, 1.37 and 3.00 for urea, e-methanol and SAF respectively). But as facility capacities are increased 50%, edge capacity is also increased 50% to 1.10, 2.06 and 4.50 for urea, e-methanol and SAF respectively. σ_{us} is still equal to the average yearly injection rate (3,52Mton).
c_f (variable per *R*)	458.47 (urea), 700.63 (methanol), 190.00 (SAF)	σ_f	Yearly production capacity, increased by 50% from scenario 1 and 2 to 1.5 Mton for each end-use.
c_{fv}	0.10*d (distance is represented by *d*, which is calculated for each edge based on φ and λ)	σ_{fv}	Base case setting, i.e. the demand at respective demand node V^v,. truck capacity is unlimited (1 truck carries 20 t but more trucks can be called on demand).
N.a.	N.a.	$d_j(\omega^s)$	Separate demand for each end-use. Still equal to the demand at demand node locations (base case, see table 10-12). ω^s is still one.

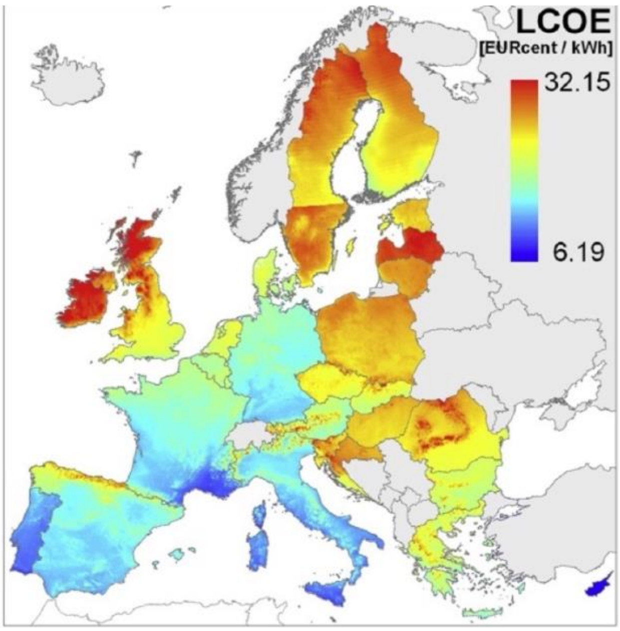
* All locations for each cluster are included but for the sensitivity analysis some storage locations were excluded.

. <u>Appendix 6 – Experiment settings scenario 3*</u>

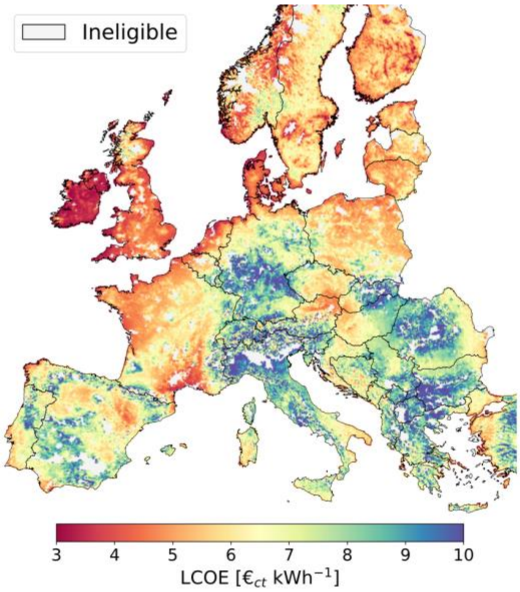
	Parameter	Unit	DOFG onshore	DOGF onshore (re-use)	DOGF offshore	DOGF offshore (re-use)	SA onshore	SA offshore
CAPEX	Drilling costs (*Cd*)	€ per m	3000	0	5314	0	3000	5314
	Fixed well costs (*Cw*)	M€/well	0	1	8.2	2	0	8.2
	Site development costs (*Csd*)	M€	3.3	3.3	3.3	3.3	25.5	25.5
	Surface facilities costs (*Csf*)	M€	1.5	0.4	61	15	1.5	61
OPEX		% of investment per year[1]	5	5	5	5	5	5
Typical storage[2]	Depth + thickness (*H*)	m	2500		3600		2500	3000
	Injection rate per well	MtCO/yr	1	1	1	1	1	0.5
LC		€/tCO_2	1.7	1.0	12.5	6.4	9.4	30.1

[1] As a fixed percentage of the investment costs for the development of the sink from scratch (also in the case of re-use of equipment).
[2] The model by Broek et al, storage costs are calculated individually depending on type, CO_2 storage capacity, depth, and injection rate of the sink. LC is shown for a sink with a typical depth and injection rate and a lifetime of 25 years for the storage facilities, based on a 7% discount rate.
[3] For DOGFs, injection wells are assumed to be in place (i.e., "DOGF with re-use" values assumed). No reduction in costs are assumed for 2030 setting.

Appendix 7 – Storage costs of CO_2 according to various studies, from Van den Broek et. al. (2010)



Appendix 8 – PV LCOE per country



Appendix 9 – Wind LCOE per country

Appendix 10 – interview transcripts

Appendix 10.1-7 are excluded in this version for fraud detection purposes!

Appendix 10.8 – ISPT interview transcript

Interviewer: Pelle Meuzelaar (P)

Interviewee: Antonie de Haas (A)

P: Yes. Now the questions. Could you please tell us about ISPT and explain your role within the organization?

A: Yes, sure. ISPT is a network organization, so we collaborate with various companies as well as universities, including the RUG. Together, we organize projects, innovation projects. Some of them come from researchers or PhD students who come to us because they want to conduct certain studies. Some are driven by what the government wants in terms of innovation, but primarily it's about what industries/companies want in order to become more sustainable and/or circular. An example is using sources other than oil or gas to produce materials. So, yes, we sit in between as a non-profit organization to connect people and organizations and establish new projects. We also act as the lead partner in such projects, which means we represent the government in those projects because the government is not directly involved. Instead, we communicate with the RVO (Netherlands Enterprise Agency) or other parties that provide subsidies or track the progress of a project.

P: Okay, so you play a mediating role.

A: Yes, as for myself: we are a small group, and the work is not very well defined. I'm simply involved in the organization, such as events and setting up and guiding new projects.

P: And that includes PROVE IT, right? Are you still actively involved in that?

A: Yes, we started in September 2021, and I was already involved at that time. It runs until 2024, if everything goes well. We are currently working with the RVO to extend it until 2025. So, it will continue for a little while longer.

P: I saw that you have certain "result areas," I read that on the PROVE IT page. You have completed the initial phases of the research. I want to discuss that later. First, let's delve into the details of the PROVE IT project. The challenge is to produce methanol competitively. In my opinion, this is still a challenge. Is this the reason the project was started? Do you have a concrete idea of how to produce methanol competitively from CO_2 from waste?

A: Well, research is being conducted on what you just mentioned. Currently, people are exploring smart ways to make this process more efficient. It involves catalysis. I'm not sure how much I can delve into the technical aspects. But in any case, to maintain the stability of the reaction for a longer time, the catalyst must function properly, and research is being done on that. Also, there is ongoing research on how to deal with heat. The University of Twente is conducting research in this area.

P: University of Twente; are they the main partner with whom you're conducting the research? How did this collaboration come about? Did the university approach you, or was it the other way around?

A: I wasn't fully involved in the project's inception. I wasn't part of setting up the idea. I joined when the project received funding and we were about to start. Often, there is a process leading up to a project. So, I missed that part. But I believe it originated from industries. Nobian, currently known as ICC, produces a specific chemical, namely dichloromethane. Methanol is used as a raw material for that. And of course, they also need to make their products and feedstocks greener. They are simply looking for green methanol for their chemistry. That's where it started, and the University of Twente has expertise in process development, catalysis, and related areas. They also want to conduct research, so it's a way for them to contribute to an industry-driven question. That's how it all came together.

P: And you have Twence there, right? That's the company that actually produces methanol from CO_2, I believe.

A: Yes, they are waste processors. So what they do is burn waste, which generates CO_2. They capture that CO_2, and they have recently built a larger-scale capture facility. With the captured CO_2, which is quite clean, you can convert it into green methanol using hydrogen. Yes, they have the methanol to use for various purposes.

P: Right, and do you have an idea of how they capture it? What is the technique they use to capture it?

A: I don't know the details, but I think they use a specific solvent that contains an amide, which readily attaches to CO_2. It is transported by a liquid, and then you can separate them. I don't know the exact technology behind it.

P: My impression was that there is already a market for sustainable methanol. You mentioned Nobian earlier, right?

A: Yes, I mentioned Nobian. You see, methanol is a product that can be converted into various other products. We call it a platform chemical, a base chemical. It can be used for many things, so there are also many buyers for it. Additionally, it can be blended with gasoline, and there is ongoing research and implementation in that area. So, there are different applications for it.

P: I'm currently doing my preliminary research on this topic. I have read about the uses of methanol. Since I'm optimizing the supply chain for methanol production, I need some values, ranging from production capacity to demand. But because there are so many end-uses, it's quite difficult to precisely estimate the demand. Are you conducting any research on that?

A: Within this project, we are not conducting market research. I know that IRENA does that. Detailed market research is not part of this project. However, our partners are interested in gaining better insights into the demand.

P: I happened to read about PROVE IT, and it mentioned that the demand in 2018 was derived from sources like Petrochem and Bilfinger. Does that ring a bell to you as well?

A: Bilfinger is a consultancy firm, and Petrochem is a medium/website/trade magazine.

P: So, potentially, this could be a source that I could use?

A: Yes, definitely.

P: Looking at the bigger picture, carbon capture and utilization, it's often a question of whether it's more attractive to store the captured CO_2 instead of reusing it. Think of Saline Aquifers and DOGF. How do you view this? Has it been more often attractive to store CO_2 rather than reuse it?

A: We also want to do CCS here in the Netherlands, for example, with the Porthos project. The point is that you have to create new materials, as you mentioned earlier. Methanol can be used to create new chemistry. It is currently mainly produced from oil and gas, but now we can produce it using CO_2 emissions. If you can capture it all, you might be able to continue that indefinitely, but we also believe in the fact that you can do new chemistry with that CO_2 again. It does require new energy, and that is indeed an economic question of whether it is viable. There is ongoing research in that area. And it's interesting to see how the supply chain will look like. A significant portion of the costs is related to the green energy needed for hydrogen production. So, perhaps we will have situations where we capture CO_2 here, maybe do something with fossil fuels as well. But you can also capture it here and transport it to a location where green energy is cheaper. And there you can produce methanol. Because there is definitely a market emerging for green chemistry since capturing CO_2 also incurs costs. If you don't have to capture it because it's already green or you have a product that is inherently greener, that makes a difference. So, ultimately, time will tell how these things will evolve. It's not competitively available yet because it requires further research. But if you ask me, I also see CCS as a temporary solution to bury our fossil waste somewhere and forget about it. You can reuse carbon to do something new. We know that we cannot rely on fossil sources forever; they will eventually run out. Moreover, there is also a level of dependence on other countries for our gas or oil supply, which can be problematic. So, finding something feasible for us to produce would be highly desirable.

P: Yes, you have already mentioned a lot about the future of CCS and CCU. The ultimate goal is, of course, to have a carbon-neutral industry...

A: Yes, and circular, so that we reuse things instead of letting them end up linearly in the atmosphere.

P: I read certain projections for 2030 and 2050, by which time the climate goals should be achieved. How do you see that in relation to CCU and CCS? Do you see it as a temporary solution?

A: I think CCS is a temporary solution that buys you time. What we are currently researching is not yet market-ready or feasible. We may already be able to capture and store it underground, but the power needed to do this is not currently available. I think this is temporary. I believe that the circular aspect we are exploring, the reuse of waste for chemistry, can be the ultimate solution. The question is whether it can be realized in time and whether it is the ultimate solution.

P: Let me see, we have discussed the project, the market, and the future of CCU. Are there any other topics you would like to discuss?

A: I am curious about your perspective, such as the cost of electricity. It is naturally high and not yet sufficiently available. Have you looked into any options for green energy? For example, using green energy in places where it is more affordable. Have you looked into this?

P: Based on my research, obtaining green energy is currently very expensive. And it is easier to obtain in certain countries than in, for example, the Netherlands. My research focuses on specific countries in Northwest and Southeast Europe, namely the Netherlands, Denmark, the United Kingdom, Romania, Bulgaria, and Greece. So far, I haven't really observed any differences. I know that in Eastern Europe, not much is being done with CO_2 reuse. It is mainly stored there. But I know that Denmark has many projects using hydrogen from green energy. I think that's the case in Scandinavia in general. Apparently, it is more competitive to use there.

A: Indeed, in Sweden and Norway, they generate electricity with the lowest emissions, green energy. And there is a lot of hydropower available there. If you have green energy, you also have a lot of potential to produce green hydrogen. Here in the Netherlands, we are mainly focusing on wind energy, and the same goes for Denmark. This is happening in the North Sea, so there is a lot available. This does create some room for green energy, but we still have a long way to go in terms of transportation, heat pumps in homes, etc. So, the question is to what extent green energy will be available for the industry. But it remains to be seen how this development progresses. We currently have quite a significant industry in the Netherlands, so the question is whether it will still be the same in the future. It depends on the circumstances.

P: I am also researching the interaction between these countries, so I will also see if it is possible to combine a supply chain from different countries. I am using a conceptual model for this. With this model, I calculate the optimal supply chain. But comparable research shows that domestic interactions are optimal.

A: What do they exchange then?

P: The captured CO_2 and the end products it can be used for, in my case urea, methanol, and SAF. Pipeline transport is assumed for this. I have also looked into transport by ship.

A: What I find interesting is that you mentioned England and Denmark. I don't know to what extent the electricity prices there differ from those in the Netherlands. I can imagine that in Spain or Portugal, or Southern Europe in general, cheaper green energy is available because there is more sunshine. If you were to transport it there, with lower prices, would you potentially have a better business case? I don't know how Denmark or England differs from the Netherlands in that regard. Maybe you know better?

P: What you're saying is, you would have to see if you can work with other countries. The reason I am researching these countries is that they are part of the ConcenCUS project. Does that ring a bell to you?

A: No.

P: It's an initiative that collaborates with the aforementioned countries. There are CO_2 emitters and utilization facilities participating in the project. That's why I'm researching those countries. It would be nice to study it for the whole of Europe, but then it would become a very broad research. It's challenging enough to derive certain values, let alone for the entire Europe.

A: Yes, I understand.

P: Let me see, regarding the interview, I will transcribe the text later. Then I can refer to it if necessary. Is it okay if I send it to you so that you can review it and see if you agree with it?

A: Yes, that's fine!

P: Then I have no further questions. We have covered everything. I have more interviews scheduled, and now I can proceed with the research.

*Closing remarks

Appendix 10.9 – European Energy interview transcript

Interviewer: Pelle Meuzelaar (P)

Interviewee: Alexander Reumert (A)

P: Let's start, I guess. So is it okay by the way, if I record the interview and use it for transcription later so I can refer to it?

A: Absolutely perfect. Perfectly fine.

P: So could you tell a little bit about European energy and your role within the organization?

A: Yeah, sure. Well, so, as you also correctly identified from your research, we're a developer primarily, who recently and quite aggressively have moved into the Power-to-X space. So we have a long tradition of producing, developing, operating, constructing and having the technical asset management of wind and solar projects in general, primarily in Europe, hence the name. Specifically very much in Denmark, which is where I'm sitting. And in 2021, we took the strategic decision to take more scope of the value chain, and that specifically included power-to-x. And so we are currently in construction with two projects that are, that are slated to, to be operational within the year. That's the Måde and the Kassø project. One producing green hydrogen for the port of Alberg and other off-takers and one producing as you've correctly identified methanol primarily for the shipping industry.

P: Right.

A: But also for the plastics industry, which we are very excited about and have recently announced.

P: Great. And as you said, you have two projects going on right now for the power-to-x. So that is just for e-methanol, right?

A: Yes, sir.

P: Well based on green hydrogen, I guess. And then is that also using captured CO_2 or is that using CO_2 from fossil fuels or CO_2 from biomass?

A: Excellent question. Very good question. So, the only CO_2 that we are using, going to be using and have any interest in using is CO_2 that does not prolong the lifetime of any fossil assets, which means that we have limited ourselves exclusively to biogenic CO_2 for the moment, and we are looking into using what's known as technogenic CO_2. That is CO_2 occurring naturally from processes that release CO_2 that could not be avoided any other way. But that is a longer term scope. And so for our Kassø projects and for all projects that we will be announcing, biogenic CO_2 is the only CO_2 that we'll be using.

P: Right. I'm asking this because I'm also looking into the supply chain. And I was wondering how you organize these projects. What does the value chain look like? Because you mention that you're solely using biogenic CO_2. How is this supplied in the supply chain? And then how does it get to the well, to, to the conversion stage and become methanol?

A: Yes, oof. That is a very good and very complicated question. There are quite a few players in this, and we're gonna, we're gonna be breaking it down to people who are selling CO_2, CO_2 producers, we won't call them emitters because they actually will not emit anything in this value chain. So we will, we will call them CO_2 producers and then there are CO_2 consumers that would be us. And then there are end users that would be our customers. And so we are in a part of a value chain where we approach and go to, say, biogas plants. Biomass plants waste incineration plants, cement works, steelwork, so on and so forth.Anywhere where you have a chimney or a point source of CO_2 that is able to be captured, liquified, stored, treated, and transported. And so we approach these companies and we go as a one-stop shop to these point sources and say, hey, if you want us to do so, we are able to finance, install, operate, and take care of all of your carbon capture needs. We have strategically acquired competencies, companies within the space. We are a one stop shop for CCU. We would also like to buy your CO_2 if you would like to own and operate your own CO_2 capture plant. And then of course we are expecting the price to be different. The more scope we take, the less overhead there is for you. The more scope you take, the more overhead we're willing to accept, right? That is, that is the risk sharing involved. And so this essentially becomes what's known in economics as pass through cost for us, right? Because if you charge me a hundred Euros per ton of CO_2, I have to charge my customer 140 Euros a ton for methanol because it takes 1.4 tons of CO_2 to make a ton of methanol. And so this is not one of our core competencies, right? We have acquired competencies within this but we are essentially a pass through between our suppliers and our customers.

P: Okay, so you do actually work with companies that offer the capture technology? Or do you have the capturing technology in house at European Energy?

A: Yes. They're there. So we have acquired a company known as Amand Gas which is a carbon capturing and carbon capturing electrification company. And I think we bought a minority stake and we became co-investor. There's some complicated financial matters that I'm not entirely sure of. But they are sitting in our building.

P: Okay. Okay.

A: And we are working very closely with them. So we are not exclusively working with Armand Gas, but these are competencies that we want to be able to offer to our suppliers.

P: So considering that you have this technology close to you, do you also work with so-called carbon clusters? Are the CO_2 supply operations close to the conversion and end-user sites? Or does it not matter really where the CO_2 comes from?

A: So that's a very interesting point. We are essentially agnostic on that point. So we go where the economics are the best, right for us and for our customers.And so that might very well in the future be places like carbon clusters behind the meter setups, energy hubs, stuff like that. That might very well be the case. But, right now we have a concept that is replicable throughout the world. That's simply just, you need three things for methanol.

You need water, you need power, and you need CO_2. That's it. Yeah. Right? And so you can associate a transport cost with all three, right? Yeah. So you need to find the spot where that three-dimensional matrix has the lowest value. Yeah, exactly. And wherever that is. That's where we build. Yeah.

P: That's very logical as well.

A: Of course. So water is relatively abundant and rather easy to move. CO_2: a little bit harder. And there's a fourth element, right? You need to export your methanol somewhere. And so we would like to be at a deep sea port site with a local biogenic CO_2 emitter next door that also houses all of the cheap renewable power right next to it, behind the meter that is also fed by a freshwater river. And there are exactly zero of those spots in the world: we checked. And so you always have to move something, right? Something has to be transported. In some cases that's the CO_2 and in some cases that's the methanol.And in some cases that's the power. Very, very seldom you truck water anywhere. Usually you just dig a hole and then you take it up. And of course you have transport costs.

P: And how does this transport work? Because I'm in my model, I'm kind of assuming that CO_2 and end uses are going by pipeline, which is not always feasible, but it's the cheapest. And so, do you also use pipelines? Or is it all going by truck currently?

A: There are many thoughts on this issue. Right now we're at a scale where there's no issue in trucking. We can truck 32,000 tons of methanol with around 800 trucks, which is three trucks every weekday. One at one at eight, one at two, and one at six.

P: Okay, that's not much, right?

A: No, that's a lot of downtime. You can drive a truck five kilometers to get CO_2. Similarly, you need 45,000 tons. That's around 1100 trucks a year, right? I mean, like, that's a, that's a lot of truck trips, right? But that's also something you could do with one, maybe two trucks. But it's not an oppressive amount. Like, it's not like we're hiring like a distribution company to handle that and only that, but as scales get larger, you run into logistics issues. One of these issues is, say you wanna move from the size we have to something that's 10 times that. That's still a small methanol plant. That's not a large methanol plant. But that scale would be the largest renewable energy methanol plant that has ever been proposed, incredibly large. Butin terms of logistics, in terms of the traditional methanol market, it's small. And so as you move to these scales, you have to start thinking about logistics. At this scale you cannot just simply truck this around, right? And then you begin ships, pipelines, and drains. That is not really an issue right now, right? The issue you're going to hit before logistics is that chemicals are relatively dense. That's the entire point of making chemicals, right? That's the reason for the energy carrier being what it is, right? The issue that you get into is: if you are going to build a plant of 10 x the scale of Kassø, that's gonna be gigawatts of renewable energy. And so do you wanna, do you wanna build gigawatts of onshore wind near industrial sites? No, God no. Because that'll be hundreds if not thousands of hectares. And so that triumvirate of problems, power, water, CO_2. But it leans very much towards the power side. Once you reach larger and larger scales, that leans very heavily towards the look I need 1.2. I need three terawatt hours a year of renewable energy. And that's a lot of wind turbines. Where will I place these turbines? Right? Once you have your power, you have your logistics solution because everything else will figure out, right? Whether it will be pipes, trains or trucks. But right now we've hit a scale and we've hit an infrastructure where it justifies building a road for this plant. So this is the “pipeline” or this is the “train” line for this plant. It stops only here and it goes from here. So compare this with different plants. For instance, we're buying CO_2 from biomass plants. And we need, say, a hundred thousand tons a year in order to make a hundred thousand tons of biogenic CO_2, you need millions of tons of biomass. That also needs to be trucked in from the surrounding sites. So compared to that, we're a drop in the ocean. And so the math sort of shakes out differently. None of this is secret, this is public knowledge. This is just chemistry. Yeah, you can look that up. And so once you start thinking about the logistics of this, it all really depends on your size. As a methanol plant, you can move from say 10,000 tons a year of methanol plants to a hundred-thousand-ton year methanol plant to a million tons a year methanol plant. You look at the numbers and go from there. Six gigawatt renewable projects exist. None have been finalized and built, but they exist.

P: How does plant expansion like this sit with the people living in surrounding areas?

A: Am I gonna build a large plant near people? Nope. Hell no. Right. So if you are building six gigawatts, that's either offshore or it's very remote. Western coast of Australia, the southern tip of Chile in the middle of nowhere, Northern Lithuania, very far up North Sweden. Excellent places for wind. And there is a lot of land very cheaply. Not a lot of people are bothered by bulldozing 2,500 hectares for wind turbines to make methanol and so it all depends on the scale essentially.

P: Right. So I now understand it, the focus is really on optimizing the location for the supply of renewable energy, right?

A: Yes. Using the turbines and or solar. Yes sir.

P: So about that, you focus on these power costs. And I assume (because that's also what I read from other research) that the electrolysis process that generates hydrogen is the most expensive part of the process. I'm not sure if that's correct in all cases, but is this also true for European Energy?

A; Yeah. Yeah. How would, how would you describe it? The devil's in the details there. Yeah.

P: Because I'm using the conversion cost as well in my model. And previous studies have found that it could be up to like 1400 euros, per tonne of production and half of that could be the energy cost for electrolysis.

A: So you mean the levelized cost of methanol?

P: Yeah, yeah. As I understand it, the transport costs that we talked about before will be modest compared to these electrolysis costs, right?

A: Yeah. It'll be modest. Yeah. So many questions there. Let's, let's, yeah, let's start somewhere and then let's see where we end. Is electrolysis costs the dominating cost factor of a facility? The answer is blatantly no. But depending on what you're really asking, the answer might be yes. So is the total cost of producing green hydrogen dominating in the equation of how much a methanol costs? Yes. Depending on your scope.So if I have to make methanol, I have to build a turbine and some solar panels, I have to turn that through conversion into direct current power. I have to put that into an electrolyzer. Depending on my setup, I either have to have storage or compression or compression and storage, and then I have to feed that into a chemical plant. Now, if we just cut the cost of the equation, that is green hydrogen. At the input to the chemical plant and the turbines at the end, then this will be the dominating cost factor, right? And so that's often what we talk about when we talk about the levelized cost of hydrogen. And that'll often be between two euros of kilo, five euros of kilo, even higher. And so this is again, like basic math. Wind turbine costs a million euros, a megawatt. It has a 40% capacity factor, and a hydrolyzer costs 800,000 euros. A megawatt storage is another 400,000 on top of that. That's 2 million euros at a 40% capacity factor for a discounted continuity of 20 years, which is 10 foot load years, blah, blah, blah, blah, blah, blah. That's around a couple of euros, three euros, let's say. Yeah, and so if you have three euros/kilogram, That's 3000 euros a ton, right? You can divide it then. It takes one ton of hydrogen to make about five tons of methanol. That's chemistry. Like it's, it's a simple balance equation. You can look that up. So you divide by five and you get 600 euros. Okay? 600, 700 euros, right? That's the majority of your levelized cost of methanol, right? Pretty much. If I sell it for, for a thousand, right? Of that, 600 euros of that is the cost of producing hydrogen. Then yes, the electrolysis process is the dominating cost factor. However, there were a lot of numbers. There were a lot of costs in that, and only one of those costs was the cost of the electrolyzer. So depending on how you figure the answer could be yes or no.

P: And to power electrolyzer here, you mentioned you have a choice between multiple sources, including wind turbines and solar panels. How do you decide between those two? Is there a preference? Right now you use both?

A: Yes. Yeah. Okay. So are you familiar and comfortable with the term levelized Cost of energy?

P: Not to the extent I think that you might require.

A: excellent. So if you go to a wind turbine manufacturer, a solar panel manufacturer, they will tell you: my levelized cost of energy at this specific site under these specific conditions is “this much” euros per megawatt hour. Now what are they actually telling you? Well, they're telling you, a wind turbine or a solar panel is a machine that takes money up front and then gives you power down the line. And depending on how much money your, your internal rate of return, like how quickly you would like to be paid back, you would have to sell your power more extensively or more cheaply. And so depending on that specific factor, what the levelized cost of energy tells you is what do you need to sell your energy for in order to break even, which means that if your levelized cost of energy is, say, 25 euros a megawatt hour. And you go out into the market and you say, “hey, I've got a turbine over here I'd like to sell that to you. How much are you willing to pay?” And I say “30”. Then you're in the win, because my buying price is higher than your levelized cost of energy, which internally should be your selling price. If I say 20, you're in trouble. You've lost money, right?

P: Yeah.

A: Sp there is a similar argument to the levelized cost of hydrogen, which is just one step removed from the story above. Rather than having somewhere where the wind blows, that gets turned into power, that gets sold, it gets turned into power, which then gets turned into hydrogen that gets sold. And so, sorry, I think I trailed off. What was your initial question?

P: The initial question was how you decide between sources of renewable energy.

A: Ah, yes, yes. So if you're only making power, then your levelized cost of energy is king. That's what you base your case on. But if you're making power-to-X projects, you have a lot longer value chain. My electrolyzer is more efficient at lower load, which means that if it runs a partial load a lot, like I'd rather have my wind turbine running at half load for two hours, then fully loaded, one hour, and then no load in the second hour because I'm more efficient at partial load, right? So there are considerations here about efficiency and part load and uptime and downtime, yada, yada, yada. I also have some backend processes that can't be stopped quite easily, which means that the more evenly the wind turbine or solar panel produces, the less storage I need. And then there are the seasonal conditions that we have here in Northern Europe. The wind blows a lot in winter and very little in summer. But let me simplify it for you. How do we decide? We decide by doing complex energy simulations of the entire systems and the techno economics optimization of the different components within the system, and the answer is always that you need a mix of solar and wind. That’s the answer; there is never a time where that is not the answer. However, we will put a premium; It might not be so simple as I want the turbine that brings me the lowest levelized cost of energy. Namely, there might be someone who is more expensive at producing energy but produces energy at more useful times.

P: Right.

A: Imagine, imagine a turbine where I make a bigger rotor that costs money, that's equipment. It's more expensive, it has a bigger rotor, it needs a larger foundation, it needs a stronger tower, it needs a stronger now, so on and so forth. But with the larger rotor, it rotates more often, more frequently, and more evenly, which means that I have less downtime on my electrolyzer, on my compressor, on my storage and on my methanol plant. This means I can save money on all of these bits, right? So it's not always, I want the cheapest possible energy. I want the cheapest possible energy to supply me with the cheapest possible methanol, right. Or ammonia or urea or hydrogen or whatever I'm making. Right? Yeah. I need the levelized costs to be as low as possible, the levelized cost of whatever I make.

P: Right. So as I understand it, you need the security of constant supply. And you need a combination of solar and wind. Is this useful for weather fluctuations? So, if there's a little less wind but a little more sun or the other way around, you can fall back on the one that’s there.

A: Yes. You are correct. Okay. So there are two effects which are anti-corollary effects. One is that it is due to meteorological reasons that I don't fully understand, but there are some people who tell me it's true that the sun is not shining and the wind is not blowing. Simultaneously at full power due to complicated reasons that I don't understand. When it's very sunny, it's usually not windy, and when it's very windy, it's very rarely, also very sunny. Summer is good for sun, bad for wind. Winter is good for wind, bad for soda.

Which means you get this smoothening out, everyone, everyone agrees on this. Yet no one has built a power project that utilizes hybrids. Everyone either goes solar or wind and it's, it's infuriating, but it's because it's just simpler and it needs to happen quickly. So everyone knows what the correct answer is. It's just so happened that at least I don't know of any large projects that utilize the hybrid approach. But we are working on it and we will, we will do it.

P: Alright, so right then I'm hoping you could also tell me a little bit more about the methanol market as well.

Absolutely. So the methanol market has been quite shaken up by the emergence of power-to-X, specifically the choice of Maersk to, to like touch the stove, so to speak, and go, well we'll buy e-methanol. Just produce it. And so what, what we are seeing is the stratification of the market, meaning that the lower your carbon impact of production, the less CO_2 emission that is associated with your product, the higher the price you're able to charge. And this is due to the IMO, the International Maritime Organization and the. IECCP, the Institute for European Energy and Climate Policy. They have set classifications for methanol. These are based on the varying levels of carbon in methanol. These are different classifications of methanol. Mm-hmm. Right? For instance, you have IECCP plus, IECCP plus plus. All of these classifications means that we have a certification to go to our customers: Maersk primarily. Or H&M, Total Energies. We can say, "look, this methanol that you're buying from us. You're not just buying a chemical. You're buying a a a a fuel that is certified green. Here, take the certification. And when you burn this when sailing in the ocean you
are able to say that the IMO and the IECCP were burning green fuels. There is zero carbon emission associated with this and these governing bodies, which are self-governed. It's not a, it's not like an internationally, uh, ordained order by the UN or something like that. It's an interest organization within the Maritime Association. Right. So it's essentially voluntary, but it's good for business that everyone agrees that we follow some certain rules, right? Because if you're, if you are an international shipping company, there is not one set of laws that can be beyond international law, right? If you're in international waters, Danish law doesn't apply, European law doesn't apply, American law doesn't apply. So they have this governing body and this governing body has said "you need to phase out this and this much dirty fuel and put in this and this much clean fuel by x year". And so that push has led to the methanol market being very fragmented because you can solely buy zero carbon fuel or you buy methanol, with 50% of the carbon intensity of diesel. So then why not just get the diesel and buy more of the green stuff? So it's all a matter of bringing down CO_2 emissions. It's called from well-to-wake. So, well, you're pulling it out of the ground, wake means using it on a boat.

P: Okay. Right.

A: Did that make any sense?

P: Yeah, it did make sense. And you mentioned a lot of things that I was gonna ask anyway, so that's good. I also want to talk a little bit about what kind of customers you have for methanol. Because a difficult part of my research is that methanol is a product that can be used in quite a lot of situations.

A: Yes.

P: And as I understand from you, it's mostly used for freight shipping fuel.

A: Right. And plastics. Yeah, you're absolutely correct. That is how I'm making it out to sound. Okay. Good question. So methanol is the second most traded chemical in the world by weight. The first is ammonia. And so methanol is incredibly useful at tons of things. And so if you look at the walls behind you, the paint that you put on those walls were suspended in methanol, right? Classic methanol made from, from natural gas. And so if you look at like, like any sort of, any sort of wood glued together, Laminates. Any sort of laminate, any sort of glued wood together, is made by formaldehyde, which comes from methanol. And so methanol is the starting chemical of so many different things. And the reason it always gets so diffuse is that it's not that you use methanol for any one thing. It's sort of like describing what you use water for? And you can say, well, you drink it and you irrigate with it, but it's also essential in every other chemical process, right? And so there are millions of tons of methanol being traded globally today. But the reason we keep mentioning the shipping industry and to a lesser degree the plastic industry is that these are industries that have voluntarily chosen to pay a green premium in order to become carbon neutral. So that's the reason. Generally, methanol has three purposes. It's a fuel, like you can burn it for heat or power. Second, it's a chemical ingredient in chemical processes in general. And finally, it's a solvent for chemical industries, which means you can put paint in methanol and then you can paint with it. Then the methanol evaporates, and then you're left with the nice paint particles behind, right? And so each of these uses are millions of tons of methanol a year. And the methanol market is so large that it's sort of tough to talk about as a single thing. But the thing that I really wanna impress on you is that it's a global market. So the fourth utilization that we don't talk about, but will become generally more and more true as this market develops, is that it can be used as an energy vector. So in the same way that power is an energy vector. You have, you have torque on a wind turbine and you use electricity to term the blender in your house, right?

P: Mm-hmm.

A: That is essentially a transference of torque, like Yeah. The mechanical concept of torque. You transfer through an energy carrier, which is electrons, right? And so, We can do the same thing with fuels like I coal out of the ground and then I send you coal and then you burn coal and they send you energy in the form of fuel. So you could imagine production of methanol in high surplus areas of green energy which gets shipped to areas of high demand. And then it is burned there for fuel or some transference of energy, and that would essentially make a loop where you send CO_2 one way and methanol the other way. So you're charging and discharging your battery. I hate that term because it's not at all accurate and it's entirely different economics, but it's a, it's, it's a good framework of like methanol is the charge state of a battery and CO_2 is the discharged state of a battery.

P: Yeah, that makes sense actually.

A: And so there are those four usages, but all of these four usages are global. If you look at your electricity market, that's local. For instance, if it's windy in China, it does not affect the price of power in Europe. And so electricity markets are very locally spread. We will definitely feel it if the French nuclear industry trips, say if five gigawatts of French nuclear power is disconnected from the grid. In just 12 minutes, you will feel it on your electricity bill. However, it is not entirely certain that I will feel it on my electricity bill.

P: Right. Okay. Probably I will.

A: But for explanatory purposes. But if it's a bit windier in say the southern tip of Chile and we have a very integrated energy system through power-to-x project products. You will feel it on the global price of say, ammonia or methanol or whatever. Right? And, we did see that when natural gas prices rose in Europe, ammonia prices shot up. Like 1200% or something. Like, it was completely ridiculous. Yeah. We've never been called by ammonia producers so much. They said: “we'd like some green hydrogen please”. Because their opex was killing them. And so the market mechanisms of the things that we’re producing are very local. Take electricity markets, subsidy schemes make a huge difference in installed capacity of wind turbines or solar projects. Huge. That's why the Germans have all the solar in the world and the Danes have all the wind in the world. Because we have had different subsidy schemes. But when we're talking about these power-to-X products, they will be traded globally. And that's an interesting conundrum sort of to think about.

P: Yeah. It definitely is. And like to go back a little bit. The reason that you sell the green methanol to freight shipping and plastics companies is because it has the certification. But in reality there are a lot of more end uses. But would I be correct to consider freight shipping companies and plastics companies as main end-users of e-methanol? Consider freight shipping and maybe plastics as well.

A: Absolutely. And, and it's just important for me to emphasize that the point of this is an accident of willingness to pay. There is absolutely no reason why fresh shipping or plastics should be the first areas of the methanol value chain to decarbonize. It's simply because they're willing to pay the premium. And I think that has to do with the IMO setting targets and everyone going, well, okay, I guess we have to decarbonize now. And plastics, the plastic producers that are decarbonizing are the ones that have the closest business to consumer relationship. Okay. Would you pay an extra Euro for your Legos being carbon negative?

P: Ah yes, I saw the Lego collaboration.
A: I don't know about you. I would, yeah. Would you pay an extra set on your medicine to know that the plastic tip in your insulin injector is made carbon neutrally? I mean, yes, I would. But would you, would you pay a 40% markup if you were a competing business in a very cutthroat market to allow your customers to claim carbon neutrality down the line? Let's say the solvent maker on an industrial scale for a paint producer. That gets tricky.
The more times I have to say "your customer's, customer's, customer", that's a harder sell to make. And so it has to start with the consumers. It has to start with also people understanding where my paint comes from?

P: Going back a little bit further as well, about your story, about the Energy. So the, the, what you said about the nuclear plants in France as well and the subsidizing of certain energy solutions. I gathered from previous interviews that people requiring renewable energy take their business to places where it's cheapest. How is this in Denmark? Because you said that Denmark is the cheapest for the wind?

A: The best wind sites in the world are in the western part of Denmark. Plain and simple.

P: So, are there a lot of people wanting to buy the energy or take their business close to the wind energy source that is in Denmark?

A: So, the entire thing shakes down to economics. So, If there is a government or any sort of regulatory body that's able to guarantee the stability of the grid and the offtake of your power for a long period of time you will see renewable projects happening. That's what we saw in Germany. That's what we saw in the Netherlands for that matter. I'll take a step back. So, the energy system is built up like any grid is built up under the assumption of production hubs and consumption hubs and wires to connect the two. Now, once that production becomes decentralized, there's a lot of overhead in building and maintaining those wires, right? It's a lot easier to make. So a 100 megawatt coal plant will produce year on year, about the same as a gigawatt of installed solar, because solar has a capacity factor of 10%. But I need wires able to carry a gigawatt away from that solar plant and only wires to carry a hundred megawatts away from the coal plant. Right now, I also need battery mechanisms, and I mean that in the most abstract way I can, to allow that demand and production from the solar facility to even out. If someone is willing to say, look, I don't care. I just needed carbon neutral. Then you see renewable energy projects happen. So we had about 50% wind power in our electricity system in 2017 or 18 in Denmark. That hasn't moved much in the last six years. It's beginning to move now because there are a lot of people announcing power-to-X projects. You're building some flexibility into the system, but in order for these renewable energy projects to happen, you sort of need the political will for it to happen. And so the renewable energy projects are very local. You hear me saying the Danish energy system? Yeah. Or maybe even the Western Danish energy system or like the fourth Swedish system has decarbonized various successes. You're not hearing me say the "world". And so when you go from these local systems to a global market, you need to be very careful. If the American Induction Inflation Reduction Act promises very, very heavy subsidies for Power-to-X projects, that'll definitely affect the viability of the European Power-to-X projects because as you've, as you've already noted, transport costs are marginal.

Production costs are everything. That means, if my ammonia costs 800 Euros per tonne in my backyard, but it costs 400 euros a tonne in Western Australia and 50 euros per ton to move it anywhere in the world. Now you're going to Australia. I'm building it in Australia. And I'm saving 350 Euros a ton.

P: Right. But I wanted to ask, is that also what European energy does? Aren't most of the operations in Denmark?

A: Yes, that is true. But we're also in Australia, we are in the US, we're in Brazil. We are in the Baltics. We're growing into a very global company on the back of our success in power. And so the emergence of these global markets have really allowed us to leverage sort of our global footprint. We can build four gigawatts of wind and solar in Australia, but there is no place in Australia that needs four gigawatts of wind and solar. Australia's a very dispersed country. It might need 20 gigawatts of power in any given place at one given time, but that's distributed over thousands of kilometers. Take Perth for instance, there are no wires connecting Perth in Brisbane. Those are separate systems. So I can build 20 gigawatts in the middle of the desert, but I actually can't get that power anywhere. Which means that if you're interested in very, very large gigawatt projects in Australia, I guarantee you all of them will have some element of cars, of power-to-X and transport, if not export.

P: Yeah, I understand as well. Do you also notice the renewable energy market becoming more competitive and more available and are there more Power-to-X projects because of this?

A: You have correctly identified half of the equation. Half of the equation is that we're building more and more wind and solar, which means you need some way to take the surplus. And that's power checks. The other part of the equation is that fossil fuels are becoming more expensive, which means we're simply becoming more competitive. 10 years ago, no one was really worried. Like there were niche applications like personal cars. You would drive your car on hydrogen. There are still a couple of crazy people who think that'll be reality. But I mean, like, there is no way, there is no way to electrify your steel industry, it's simply chemically impossible. Like take that up with chemistry if you think that.

P: Yeah, right.

A: And there is no feasible way to do it using biofuels. I mean, like you would need to cut down every forest of the world every year on end. it's not impossible, but it would require a drastic shift of the entire eco chain. Or you could use hydrogen. How big of a market is steel? If you would need to decarbonize, say, half of the world’s steel production, you would need to install three times the global current renewable capacity. It shows that this market is huge, right? I mean, like, it's, it's three times more than anything we've ever built. And so it's inevitable and I feel like a lot of people are treating it like an economic exercise rather than going: “this will be real”. I don't know when, no one knows when, but whoever has the best competences in making the best projects and the best steel using hydrogen will win. There's no doubt about it. No one disagrees. Every major steel plant operator has power checks. Yeah. And so it, it, it gets bonkers when you think of it at that scale. So it's, it's, it's really interesting to think about the logistics. Will we truck it? We need to think about hydrogen pipes and infrastructure. And CO_2: are we going to capture and reuse it or are we going to get it from air? Like what, what are we gonna do with all of that? Like what are the major sources of energy flow that will happen using chemicals over the next, say 10, 15 years? No one knows, but it, it's, it's coming just over the horizon.

P: Yeah. And as well, like that's what I want to ask about to round off the interview. We have these future goals, like the 2050 goals. And as you said, no one really knows how everything is going to play out in the coming years. Do you have any idea of the role that CCU and Power-to-X will have in 2050? Let me rephrase. Do you expect the role of power-to-X to continue growing? Or will we use other sustainable practices to help us reach climate goals?

A: It has to be ended. We have to reduce, reuse, recycle, but we also have to decarbonize the processes within the chemical world. There's no one who sees a world without concrete. There's no one who sees a world without steel. There's no one who sees a world without plastics. But there is also no one who sees the world running exactly as we do now. For instance, I think it's criminal to burn methanol in an engine rather than using a fuel cell, which has double the efficiency. And so I think at that time (20 years is a long time), I see no way of continuing to take our high value chemicals and burn them. I see it as thermodynamic crimes against humanity. There are people talking about putting hydrogen into your gas networks to burn it for heat, and I think those people should be taken to thermodynamics jail. You’re taking your highest value chemical in turn it into the lowest value of energy you possibly could, which is heat. You could use it to make jet fuel! Anyway, I think I want to leave you with one point. There are a lot of different use cases and I think often people in my field get hyper focused on fuel. For good reason, for good reason. People get very focused on fuel. However, facilities like large scale steel producers, ammonia producers, plastic producers, grid balancing facilities, renewable electricity plants, energy storage plants, and so on and so forth. All of these plants, if you look at them from a chemical angle, start with water and turn it into hydrogen, and if you can move that hydrogen, you can move all the energy. And so the example I gave you earlier of a, of methanol being produced, driven where it's burnt to CO_2 and CO_2 moving back. What we're doing there is we're moving hydrogen. And the CO_2 is just a carrier. It's just carrying the hydrogen and we're burning the hydrogen. Why not put a pipe pipe of this size (*makes a hand gesture) at 70 bars, which is usual for pipe networks? It carries the same energy capacity as 14 gigawatts. In one pipe! That is all the offshore wind capacity of the entire North Sea, Denmark, Sweden, Netherlands, England, Germany, all of them together. One pipe fit into this pipe if you turn it into hydrogen. And so once you realize that, hydrogen networks begin to make a lot of sense. It doesn't matter what you're going to use it for. Do you wanna turn it into methanol and accept a 20% thermodynamic loss of burning capacity just to make it easier to handle, to send to you, to make steel? No, I've, I've wasted 20% of all the energy I just produced. I'll send it to you as hydrogen. Because it's tough to move that much electricity. I'll send it to you then you do whatever you want with them. Do you wanna make methanol? Fine. Do you wanna make ammonia? Sure. Fine. You wanna make steel? Yeah, sure. Go for it. Yeah. You see the early stages of this happening now. Where you are, right? There are hydrogen pipes crossing right now. We've just announced a connection and refurbishment of our old national gas pipeline to Germany. And so we see the early stages of this infrastructure being built and expanded out and. Note that this is a prediction that will never come true because all predictions turn out false, right? But I think that the major breakthrough in this is the understanding of the versatility of hydrogen, and that all of these very local renewable energy markets, all of those will collapse into: "get me the cheapest energy so I can make hydrogen, put it into a pipeline and we'll deal with it later".

P: So hydrogen is gonna take over the world?

A: Hopefully. Take that from a man with a PhD in hydrogen, right? Like, I have a vested interest in this, right? I'm not a neutral observer in any way. And of course you can't have accurate predictions because no one has.

* Closing remarks

Appendix 10.10 – GeoEcoMar interview transcript

Interviewer: Pelle Meuzelaar (P)

Interviewee: Alexandra Dudu (A)

P: Awesome, well, let's start. About myself, I am a student at the University of Groningen, the Netherlands and I study technology and operations management. And for my thesis, I am optimizing a CCUS supply chain. So I look into the capturing of CO_2 and how that can be utilized, utilized in various manners. So I look into end-uses urea, aviation fuel as well as methanol. I came across your organization and I sent out an email. So could you tell a little bit about the organization, GeoEcoMar and maybe your role within the organization?

A: Yes. So GeoEcoMar is involved in the research for CO_2 Geological Storage. and utilization, but we refer mainly to geological utilization and enhanced hydrocarbon recovery options and we are involved since 2002. In this research, we have participated in many international projects. Maybe you have heard about EU GeoCapacity, a pan-European project that estimated the storage capacity in Europe. And we have done many other projects since then. I'm a geophysicist by trade and I've been involved in the research for CO_2 geological storage since 2008, when I was hired by GeoEcoMar and started working on this EU GeoCapacity project. And since 2017 I lead a small department focusing on CO_2 geological storage.

P: Okay, 2002; that's quite a long time already. So you mentioned that you specialized mostly in geological utilization, so the storage of CO_2.

A: Just the enhanced hydrocarbon recovery using CO_2. So we are geologists and geophysicists and we are focusing on geological aspects only. We do not have studies on CO_2 utilization like you do. Not anything like turning CO_2 into fuels or other products. No, just injecting CO_2 to retrieve more hydrocarbons.

P: Okay. So, yeah, that was indeed my question because I have read one paper about it that was published by GeoEcoMar and it was about utilization but it was more stating the possibilities. Right? There are currently any projects going on with utilization of CO_2 in Romania, or is there?

A: No, no, I think I know the paper that you are referring to and I think I'm one of the coauthors of the paper. Yeah, but we have made a short review of the utilization options and I think we focused then on EOR, enhanced oil recovery.

P: Yeah, exactly. Yeah. I want to ask something about EOR later as well. You emailed me yesterday as well about the subjects, I think you mentioned there's no CCS going on right now, what did you mean exactly by that?

A: I mean in Romania we do not have an operational CCCs project at the moment. We have made several studies for different potential sources for CO_2 and storage operators. We have made research but we do not have an operational CCS project in Romania, not even an EOR project in Romania right now. There are some preparations made for a project but it is still in the feasibility phase. We have made a feasibility study as well; we have led the CO_2 storage part of the feasibility study for a demo project in Romania a long time ago in 2010. It was called the Getica CCS Demo Project but unfortunately due to some financing issues and due to the loss of governmental support, the project was stalled indefinitely and, yeah, we did not realize that project.

P: Yeah. So, you mentioned that the lack of government support and financing options stalled the project. I also read one paper that was published. It mainly concluded the same thing that you just said that the legislation and the financial support is lacking and it's one of the main bottlenecks. Is that correct?

A: Yes. Yeah. We are referring to Romania only, right?

P: Yeah, right now I'm referring to Romania.

A: Okay, just to be sure. We currently have legislation for CO_2 geological storage, we have implemented the CCS Directive view, CCS directive, if you know this directive for CO_2 Geological Storage. I can send an email with a link if you don't know. So we have transposed this directive into Romanian legislation. There are currently issued procedures for granting the exploration permit for a site and for the CO_2 storage permit. But, there are some difficulties in harmonizing the petroleum law with the CO_2 Geological Storage Law.This is what the Agency for Mineral Resources is doing now, together with some potential storage operators. And I think they will come up in the near future with a solution to that because right now the CCS legislation in Romania is focusing mostly on deep Saline Aquifer options. So sites that have not been used for hydrocarbon recovery. So this is the issue now and the financing; this is another story. So, there are private companies that could invest and would like to invest in this. This could be a business like in the US, for example. In the US they have some tax deductions. There is a law for this and we would appreciate a law like this. Not only in Romania, but in Europe. This could be stimulating the CCS businesses. It’s very important but not present in Europe. We are a little bit behind, let’s say. Especially compared to the US, who have been at the top of the CCS business for a long time.

P: Yeah, so they already have an implemented system with subsidies and financing methods?

A: Yes, yes.

P: I don't know exactly how that is in the other parts of Europe because I study Eastern Europe, so that includes Romania, Bulgaria and Greece. And I also study the northwest of Europe, so that includes the Netherlands, the United Kingdom and Denmark. So I look into those countries and I try to find some differences as well. But I think procedures are pretty similar across Europe. So, next question, does the term storage readiness levels mean anything to you?

A: Yeah, it means a lot to me. I don't know,if you heard about the Strategy CCUS project, the research horizon 2020 project?

P: The name rings a bell but I don't know the exact content.

A: So we have assessed that in eight regions in Europe, one of the regions is in Romania, the Galați region. We have also made a techno economic assessment of the implementation of CCUS in these regions and in this project we addressed the storage readiness levels.I Romania this is quite low because we have made an estimation of storage capacity from EU GeoCapacity project time in 2009. But, this is mainly theoretical. It was done solely on public data. And in order to increase the precision of this estimation, we would need more data. We have another issue here, and this is another bottleneck in Romania. Because data related to potential reservoirs to hydrocarbon fields is classified.

P: Oh, okay.

A: So, it is very complicated to get access to this data in order to increase the precision of our estimations.

P: So there's no incentive to give that information for storage? They don't want to cooperate?

A: No, no. This is a major issue and we have put some effort into acquiring existing data from the government. But it was very slow and it is a very complicated process. Especially since you cannot share this data with anyone. So this is a tough, tough situation.

P: And it's probably also one of the reasons why there's not an actual storage project running right now.

A: No, I don't think that. This is not an issue because hydrocarbon operators have this data so they could become storage operators and make CCS projects. So this is not an issue.

P: Okay, clear.

A: But there is another thing that is very important. When you think about storing CO_2 underground, especially onshore (because Romania has a lot of onshore possibilities). During a research project a while ago I made some assessment for offshore storage but options were very limited because of the data, of course. And this could be a bottleneck. It is about public acceptance of CO_2 geological storage. So, people do not have a problem with CO_2 capture, don't have a problem with transport or utilization but could have a problem with storing CO_2 underground, especially onshore. In Europe there are no CO_2 storage projects onshore, so there have only been successful pilots onshore, the rest of the projects are offshore.

P: Okay, I didn't know that.

A: Many projects have been stopped because of this public opposition. In the Netherlands as well. A while ago, I think.

A: I think I know what you're referring to. I've read about the public acceptance and it's one of the main bottlenecks as well. Do you think this is going to get better in the future, or are we just gonna have to rely on offshore?

A: Mm. I don’t really know. It depends on how information on CCS will be communicated to the people and the companies that initiate these communication project processes. So it is very easy to get the opposition of people and opposition of mass media. So, it depends, it depends. I think this is a critical moment because there are projects planned on shore and if they succeed it'll be very good. People are arguing about projects onshore. Why do you want to make a CO_2 storage project beneath our homes?

P: Yeah. Right, “not in my backyard”.

A: Not in my backyard! Yeah. This is an experiment.

P: But maybe if there's a successful project it could act like a snowball, right?

A: Yes, yes. But I think that the best way to do that is to build a pilot first and then upscale. Because you can demonstrate to people this is safe; this is good. These are the advantages for your community. We want to upscale, but we base our plans on the success so far. I think this is the best way.

P: Yeah. Yeah, I agree. Well, we talked about onshore and offshore, but we have not discussed the type of storage site. So if it's, it's a SA or a DOGF. I've read a GeoEcoMar paper that states that there's quite a lot of depleted oil and gas fields in Romania that could be used for CO_2 storage. What is the main advantage of depleted oil gas fields versus saline aquifers? Are you looking into both?

A: We try to look into both but the main advantage of depleted hydrocarbon fields is that there is a lot of knowledge associated with them. So there are studies from exploration, data from exploitation. These are very well-known structures. You do not go into the unknown, like in deep saline aquifers. SA's were never the target of some exploration. Maybe they were discovered by accident, but no efforts were made to get more knowledge on them. This is a great disadvantage because you need a very high financial effort to explore SAs and you need to demonstrate that the aquifer is there, that it is suitable for a CO_2 storage and that no leakage will occur. So it'll take a lot of time and a lot of money. But, there is another aspect related to this. Because usually it may happen - not in Romania because on Romanian territory there was drilled a lot, so there are a lot of wells – but in other countries I have seen that on a deep SA surface there is usually one or no wells. But in hydrocarbon exploitation, you have a lot of wells that you need to address. You need to check whether they are abandoned. If, the structure of the well and the materials that compose the well are compatible with a CO_2 enriched environment. You must demonstrate that this well will not be a leakage pathway for CO_2. This is another cost and it depends on how many wells you have on the structure. We have also made a project investigating the usability of hydrocarbon wells for CO_2 storage. So in some cases with some additional work (because you cannot just reuse hydrocarbon wells for CO_2 storage, you have to do some work) that well could become at least a monitoring well, if not an injection well, so you can save some money there too.

P: Yeah. Yeah. So it would be more cost effective I guess.

A: In some situations, not in all. It may happen that you have a lot of wells that were not abandoned properly and you need to re-abandon them. This costs a lot of money.

P: It might even mean that you don't use it at all, probably, right?

A: Sometimes, yes. You may not want to use it at all because they pose potential leakage risks.

P: Mm. And I've also read something about the enhanced oil recovery that could also be used in the oil and gas fields. How is that currently progressing in Romania? Are there any…

A: No, I told you we do not have an EOR project. There were some experiments done some while ago that I do not know much about. But I don't think someone considers this option right now. There is opposition to this enhanced recovery and it is not considered a viable option for storing CO_2. It is true that when you inject CO_2 and you retrieve hydrocarbons, there is a part of the CO_2 that is coming back to the surface that must be circulated but there is another part that stays underground. And the public perception on this is that we prolong the life of hydrocarbons. So this has become a controversial thing in Europe, but in the United States you get credits even for enhanced recovery. They have been doing business on enhanced oil recovery for a very long time. From the seventies on, they have built 5,000 kilometers of CO_2 pipelines for enhanced oil recovery. So they are doing a lot of projects. Have you checked the Global CCS Institute facilities database?

P: No not yet. Not the same one that you are referring to. I work with a project called ConsenCUS. They also have data on storage that I will use. So that's where I get most of the data from. But what is the one that you said exactly? What does it show?

A: So, let me try to find the database and put it here in the chat. It is very interesting. I don't know if you have heard about Global CCS Institute. They have a lot of resources that are good. I recommended taking a look. And of course, the International Energy Agency, IEA.

P: IEA, Yeah.

A: They have a greenhouse gas control program that is also very good. Very good reports in general. Let me try to find the global CCS Institute. I think I have a bookmark on it.

P: Yeah, take your time. It will be helpful I think. I will save the link so I don't lose it.

A: I can send you, if you want, just send me, drop me an email and ask for it. In the first link you can see all the facilities that are planned and that were closed and that are operational right now from pilots to demonstration and commercial projects as well. And you have also some links to the project. Very interesting database. It is made in regions, countries, etc.

P: And you can select projects based on region and country?

A: Yeah.

P: I will look into it after the interview. Let's move to the costs. These depend on so many things. But in general, is it true that CO_2 storage costs are much less compared to the cost of capture? Because what I've read is that capturing costs quite often incur the highest costs within the supply chain.

A: Yes, you are right. The capture costs are more than half usually and the other half is just split between transport and storage but, transport is cheap compared to storage. But the storage costs are site specific, very site specific, and depend on a lot of things. First of all, it depends on the solution that you choose for storage. In terms of SA, depleted hydrocarbon fields or mineable coal seam. But there are not many examples of mineable coal seams. Not in Romania at least, for as far as I know. So this comes first because when you are considering a deep saline aquifer you have to put a lot of money into exploration to get all the data that you need to demonstrate storage, integrity and performance. So you have that data usually for hydrocarbon fields. In many cases, if you start the hydrocarbon exploitation and you want to go directly to storage, you may not need exploration at all. Exploration could be around, I don't know, like 40 million. I'm remembering this from the Getica project when we did some financial estimations. But this was just a start. And it depends also if you are considering a site onshore or if it is offshore. Offshore is much more expensive than onshore. At least two, three times more expensive. Everything cost aspect of offshore is more expensive; from exploration to drilling wells, to facilities, to everything. So, I don't really know if you are familiar with the CO_2 storage project phases?

P: No, I don't think so.

A: Considering that, feasibility studies were done (we are talking about regional site selection) and you have selected one site for further assessment. If it is deep in an aquifer, you must go to the exploration phase, which is also site specific and could last for two, three years. After the exploration, if everything is okay, it may happen that the site is not suitable. It's not considered suitable after exploration. This is a risk for someone who invests money. But after the exploration, you go to construction of the site. You drill wells. At the exploration phase, you have also drilled at least one or two exploration wells (if you don't have wells to retrieve data from). You may choose that these exploration wells are transformed into monitoring wells or injection wells. So within the construction phase, you may have to drill and equip injection wells, shallow monitoring wells, deep monitoring wells. You have to construct the surface facilities, there are the compressors and pipes and manifolds that are connected to a site. And after the construction phase has ended, you may begin injecting CO_2. This is the operational phase. In the operational phase. You mainly have OPEX. So you need to invest some money into keeping the site running, but also to make some workovers to the wells every five years. So this is another cost, mainly an operational cost. After you end operations, you begin the closure of the site. This is considered the closure phase and post closure phase. In this phase, you need to conduct some operating activities until the site is transferred to the state. Now, this depends on the legislation but at least 20 years after the closure and end of injection. And in all these phases, starting from construction, you need to do monitoring. This is another cost. This is also site specific because the monitoring is planned based on a risk assessment that should be done for the site. And you need to implement some methods prior to injection in order to make sure that after the injection you have some data to compare with. During all this time, there is another thing to consider, which is modeling, constant periodic modeling of the site and of the process. Because every new datapoint that you get from monitoring and from operation, you need to include in the model and re-do some studies.

P: Okay. About the model, how do you go about modeling? Because I also do modeling but for the entire supply chain. So I also look into capturing, transport and then storage. But I think you're talking about something else right now.

A: Specifically, I'm talking about geological models. If you are not a geologist, it’s maybe hard to explain. You need to try to get an image of your storage complex as near to reality as you can. The more data you have, the closer to reality is this image of the storage site. And also you need to model the process of injecting CO_2 and what happens to the CO_2 in the reservoir, how does it evolve over time. You have some risks; CO_2 tends to migrate along the fault along the well.

P: And so you monitor that and you model it and you can monitor it better that way.

A: Yeah, the more data you have, the better the model.

P: Yeah, exactly. I still want to ask a little bit about the capture and transport because you mentioned that transport is quite cheap compared to storage.

A; Compared to storage, yeah.

P: But do you think that if the capturing costs at an emitting facility were not so high, CO_2 storage would be implemented more often? Do you think it's a bottleneck?

A: I don’t know if I got this right, you mean the cost of storage?

P: No, the capturing I mean. Have you researched carbon capturing a lot?

A: No. Not, not at all. I did some techno economic assessment on the entire CCUS chain for a Strategy CCS project, but I got a lot of help from people that are focusing on capture and transport. So I cannot discuss that in great detail.

P: Ah, okay that's fine. I also have different interviews with people that focus more on utilization and capturing, so I could ask them as well. It's not a, not a problem. I want to discuss one more thing about the entire CCUS supply chain. So my research focuses on the capturing stage, the transportation stage and utilization or storage. And I have a model that optimizes the supply chain for costs. So in the end it shows the interactions between capture and utilization facilities and storage facilities. But, as said, I focus on some countries and I configure the supply chain in those countries. So I also look into cross-border interactions. Do you have any expectations on whether it is feasible to create a cluster that, for instance, captures CO_2 in one country and then transports it to another country and then it's stored in that country, or it's utilized.

A: Yes, there are many discussions around this subject and I think it is not only feasible, but it is a must because there are some countries where you don't have storage possibilities or there is strong public opposition. So this could be a business for everybody. But there are some legal issues to be clarified there. But I think you know about Northern Lights Project Aurora. They want to create a hub CO_2 storage hub for Europe, offshore. And I know some emitters who are very enthusiastic about the option of just knowing where to send the CO_2 (not in Romania because we are very far east and transport would be an issue). So the emitters want to capture CO_2, but they do not know what to do with the CO_2. It is very important to have a storage site or a utilization site or something very well planned. Especially if you want to submit a project for financing. You need to come up with a storage solution. And I don't think that in large quantities of CO_2 you can utilize it. You can’t utilize all the CO_2 captured. So maybe you need to combine utilization with storage.

P: Exactly. And,that's also what I want to look into. Right now, what I find is that there could be quite a lot of CO_2 captured but the part that is utilized is very small right now. In the northwest of Europe, I can find quite a lot of facilities and projects that do utilize CO_2, but in general there is not a lot of utilization going on right now. A lot of end-products are still produced using fossil fuels and captured CO_2 is not prominent in the market yet. But as I understand it, you do think that you could make an entire supply chain across Europe. You could make that feasible?

A: Right, yes. I don't think it is a good solution to have one emitter and one storage site. I think we should think about clusters, everywhere. Because in that way we could perform large scale implementation of captured CO_2 and ultimately CCS.

P: Yeah. I work with the ConsenCUS project and they have done other thesis projects with students and I've also seen that they optimize using clusters. In those theses there were not a lot of international interactions going on. Most of them found that the supply of CO_2 could already meet the demand of all the CO_2 utilization sites and storage sites. So in terms of optimization, they found that it could be just within countries and not across borders. But I think that I could find a scenario that uses international interaction.

A: Yes, available storage opportunities are everywhere, almost everywhere in Europe. The problem lies with the storage readiness levels. This is the issue.

P: And so to conclude, I want to ask you about the future of CCS and CCU. Do you think that we will achieve the climate goals that are set for 2050 using CCS and CCU? And do you think we will use CCUS after that point? Or is CCUS just temporary?

A: My personal point of view is that we have an urgent need for CCS in order to meet the climate goals. At least until 2050. All the estimations I performed stopped in 2050. I don't know how it will be after that. But science is progressing a lot. We need to get rid of the CO_2 now and CCS is essential. You cannot do it without CCS. The numbers will not match if you calculate it without CCS. No, you cannot do it without. And it's not about the energy production industry. Let's say somehow they solely use renewable energy. There are other industries that cannot replace carbon with other things. This includes the cement industry, for example. What do you do with those emissions? You do not have another choice. Also in the steel industry, you can make some changes in technology used, but from our analysis, there is a share of the CO_2 that cannot be removed by other means. So we should use CCUS. You cannot do it otherwise.

P: I would agree. And eventually you would want to get rid of the emissions at the source; the process would have to be neutral. But as you said, that's for some industries like cement, that's impossible right now. Do you also think that the focus should be more on CCU in the future as opposed to CCS, or do you think that CCS will always be more prominent?

A: I don't really know; I do not tend to look after 2050. Maybe, there is a lot of pressure to go into utilization. This is seen everywhere. People are talking more and more about utilization, not storage, because storage is somehow problematic from different aspects. Public opinion for instance. This public attitude could lead to removal of the storage option maybe. Or maybe people could understand that this could be a business model; the CO_2 can stay underground, like in natural CO_2 reservoirs. There are natural CO_2 reservoirs in the world. And this is a way to fill the void (referring to depleted hydrocarbon fields), I don't know what to say about hydrogen. There is a lot of pressure to switch everything to hydrogen. And we are also involved with hydrogen; geological storage of hydrogen. Yeah, I think we should focus on meeting the climate goals right now. This is most urgent.

* Closing remarks

Appendix 10.11 – Stamicarbon interview transcript

Interviewer: Pelle Meuzelaar (P)

Interviewee: Joey Dobrée (J)

P: Can you introduce yourself and tell me about StamiCarbon?

J: Yes, I can briefly tell you about myself. I have been working here for almost 16 years now. I also studied at the University of Groningen, specializing in technical business administration. It was a hybrid program combining technical chemistry and technical business administration. Eventually, I ended up at StamiCarbon. I started as a technologist, which I did for a few years. Then I worked as a licensing manager, which is more on the commercial side. That's essentially the sales aspect. And now, I am the product portfolio manager, which means I am responsible for the entire technology portfolio on behalf of StamiCarbon. We license technology, and you can think of us as the architects of fertilizer plants. We focus on urea, but also nitric acid, and recently, green ammonia. This involves various stages, from urea production to the melt (liquid) phase, finishing, granulation, and prilling. We also provide services, such as proprietary equipment, including high-pressure apparatus, digital products, simulators, and process monitors, all developed in-house. Together with my colleague, who handles new product development, I ensure that we identify new market trends and commercialize them. So, we develop new products and, when we find something interesting, we develop the technology, patent it, and bring it to market. That's my main role, providing guidance in these processes.

P: I see, understood.

J: Urea is our main product, and we are the global market leader with a market share of 50-60%.

P: Impressive. I came across Stamicarbon in an article I read in Setis, which also discussed urea. At that time, I hadn't realized it was written by you, so I was pleasantly surprised when you responded.

J: Yes, I am also the focal point for new technologies, and the reason you chose urea is that urea consists largely of CO_2. This poses a challenge for the future. But the most important thing is that urea cannot simply be eliminated. If you consider all our plants, accounting for a market share of 50-60%, urea is a crucial fertilizer. If we were to exclude our plants, imagine that one-third of the world's population would no longer be able to survive because there would be insufficient food. A significant portion of the global population depends on fertilizers, and it's easy to say, "Let's reduce CO_2." While that may sound good, it has direct consequences for food supply. This makes it a fascinating problem as it links environmental issues, emissions, and climate with demographic challenges.

P: That makes it one of the most important CO_2 end products that I'm researching (I'm also investigating methanol and SAF). And now we're talking about food.

J: Yes, that's historically our strong suit, and it's a problem that many people deny. We operate in many countries where our plants are seen as strategic assets. As a result, our plants are often guarded during times of crisis (such as the Arab Spring). Tanks are stationed at our plants, and the military protects them. This is the case in many countries because fertilizers mean food. This brings to mind the ancient Roman saying: "bread and circuses keep the people content." It still holds true in many countries.

P: If we delve deeper into the sustainability issue, as far as I know, ammonia is used as a precursor, which can react with CO_2 under certain conditions. Is it correct to say that hydrogen is needed to produce ammonia?

J: Yes, that's possible. Ammonia has traditionally been produced from two raw materials: coal through coal gasification, which produces syngas used to make ammonia, and natural gas, which is the more common route. Essentially, you have a process where you go through two steps. This is a bit complex. The CO_2 comes from gas and coal, and then we convert it. When the urea granule reaches the land, it immediately decomposes into CO_2 and ammonia. The plant absorbs the ammonia as nitrogen, but the CO_2 simply goes into the atmosphere. That's just how it is. CO_2 acts as a binder and isn't retained. As a result, for every ton of urea produced, approximately one ton of CO_2 is emitted, on average, in a reasonably efficient plant. When it comes to sustainability, we have made significant progress. Essentially, for every ton of urea, you need about 733 kg of CO_2, roughly 73% of the weight. Per ton, you require 0.73 tons of CO_2. That's simply how it is, determined by nature. You can't change that. With that in mind, you can still reduce the footprint we have, for example, 1 ton of CO_2 per ton of urea. However, at some point, you can't avoid the CO_2 required to produce urea; it's a reaction mechanism. We can still lower it to some extent, for example, by using green ammonia. This involves producing ammonia from green electricity, generating hydrogen from nitrogen in the air, and then producing ammonia. We're currently working on this approach, setting up a pilot plant. This may further reduce emissions by around 30%, but you still have the CO_2. The big question now is whether you can obtain that CO_2 from elsewhere or make it circular. Carbon capture is one sustainable option, and there are even ideas about direct air capture, although it's currently a step too far. We're exploring these possibilities. Additionally, you can further reduce the CO_2 footprint. We have a European project called Initiate, subsidized by the EU. It involves a large consortium in which we participate. The project aims to reuse the emissions from the steel industry. They emit CO_2, and we use it to produce urea.

P: So, if I understand correctly, you already have pilots and projects where emissions are captured and reused from various industries. Then you react it with ammonia. Ideally, you would prefer to use green ammonia, but it's quite expensive.

J: Yes, because urea still requires CO_2, which needs to come from somewhere. And then the question is: can you use CO_2, which is already available, in a more sustainable way? Look, I think it should be clear that urea is a problem, and that problem is not going away. But the problem is linked to the fact that we have such a large global population. What we are trying to do is make the problem smaller. The alternative route we are pursuing is to produce nitrate fertilizers from ammonia. This is based on nitric acid; you go from ammonia to nitric acid, and from there, you go to Ammonium Nitrate. This can be used for explosives as well as fertilizers. And from there, we produce MPK fertilizers or Calcium Ammonium Nitrate (CAN). And this is a route that can be done without carbon. We are actively working on this; we are building the first factories in the relatively near future. These factories will be able to produce carbon-free fertilizers. However, this approach also has some agronomic disadvantages. You would be producing fertilizers based on hydroelectric power plants, solar energy, and wind energy. I am actually going to Copenhagen soon to discuss a green ammonia plant that will run on solar energy.

P: So, you could argue that this route is better than the route where you capture and reuse carbon in urea production.

J: Definitely, but it is a capital-intensive industry, so you can't just say, "everything will be energy-neutral by 2030." Forget it, it won't even happen by 2050. Because you can't simply shut down a factory all at once. When you start closing factories - this is what happened with the whole situation in Ukraine - the grain doesn't leave the country anymore. No more fertilizer comes from Russia, this was a side effect. And what happens then? The prices of all the items in the supermarket go up because fertilizers are used everywhere. You should not forget that everything related to food contains fertilizer. Therefore, it is one of the main drivers of food prices. So, you can't change it easily. But what we are showing is that the technology is ready. There is also another disadvantage when you replace urea with something else. Urea has the advantage of having the highest nitrogen content per ton.

P: So, urea is a very efficient fertilizer?

J: Exactly, when you look at other nitrates, the fertilization efficiency is lower. This means you need more of it. That can be solved, but the reason why it is so efficient also explains why it is used so much: urea allows for the transportation of large amounts of nitrogen.

P: Does it also reduce transportation costs?

J: Exactly, urea has a nitrogen content of n=46. When you look at other substances, you're already at n=30-32. So, that's a substantial difference, you would need more product. This is only about nitrogen, but many plants also need phosphorus and potassium. Blends can be made to compensate for some of the efficiency, but for many of the major crops, they mainly use urea.

P: My research mainly focuses on urea and captured CO_2. So, I would like to ask some more questions about that. In the projects you currently have with captured CO_2, how does the supply chain work? How is the CO_2 captured, transported, and converted?

J: Well, normally CO_2 is produced in the factories. Natural gas is burned, and the CO_2 is captured using Pressure Swing Adsorption (PSA) or amine washing. Then it is converted into liquid CO_2. Nowadays, they also capture the exhaust gasses using stoves and amines to remove all the CO_2 (99.x%). The factory itself is not the main problem. The biggest issue is that the CO_2 goes into the product, and as soon as it reaches the land, it goes back into the air. So, CO_2 acts as a transport medium for nitrogen. What is currently being done is that CO_2 is captured as gas and then liquefied. It is then brought to high pressure and used in our synthesis. This happens at around 150 bars. With high-pressure vessels, we combine the CO_2 with ammonia to produce urea.

P: Exactly, and when you receive that concentrated CO_2, can it be transported through pipelines? That's what I'm looking into in my research.

J: Yes, they exist, but there are almost none. I know that there is a factory in New Orleans that we work with, which receives CO_2 through a pipeline. They are used on a large scale for enhanced oil recovery. So, they pump CO_2 into the ground to extract more oil. In Europe, we have the Porthos project, you're familiar with that, I think?

P: Yes, I know about it.

J: We have been looking, together with the Initiate project, at the possibility of building a pipeline with ArcelorMittal in Ghent that would go via Terneuzen to Rotterdam, but it doesn't exist yet. And then you could store it there (Porthos). Currently, the only place where it is being done is in Geleen. They produce CO_2 for beverages, but it also goes directly into the atmosphere. Then there is the project, which is not yet commercial. There is CO_2 storage capacity underground, there is a lot in Eastern Europe, but the first major one is Northern Lights. It's in Norway, where they capture CO_2 and transport it underground using a ship. But if you ask about the infrastructure, it's practically zero.

P: So, the CO_2 is mainly generated in the factories using natural gas and then used to produce urea. It's not transported via captured CO_2.

J: Yes, in principle, everything stays within the factory, but that's only a limited part. Or it goes back into the atmosphere with the end product.

P: I would like to touch on the cost aspect because my research focuses on the supply chain, using a model that optimizes it through cost calculations. From other sources, I have discovered that electrolysis of hydrogen to produce green ammonia is a significant cost factor.

J: I could show you what the ammonia price is. These are challenging times, so it's difficult to say exactly. We've seen the price of ammonia drop in April this year. The price in Miami is currently $410 per ton, and the price in the Middle East is $380 per ton. Normally, we look at the price in Odessa, but it's a bit difficult now. We've also seen green plants; the most competitive ones can go up to $450 per ton, but those are initial models that haven't even been built yet. What you see is that the problem with green plants is that sustainable urea is relatively expensive. And that is mainly due to the cost of electrolysis required for hydrogen production. Firstly, electrolysis is not readily available, and it's expensive because there is no economy of scale behind it yet. Additionally, sustainable electricity is simply expensive; in Europe, it's not profitable to do this because renewable electricity prices are too high.

P: And do you have an idea of how prices are outside of Europe?

J: Yes, you see, a wind turbine in the North Sea operates on average for 5000-5500 hours per year. When we go to other locations (we're also working on a project in Kenya), the wind turbines there operate for 8000 hours per year. Almost continuous when you look at it. This significantly lowers the price. This also has to do with taxes. You can relatively build wind and solar cheaper, but the problem is that old projects are more expensive than new projects. What we are seeing now is that prices are coming down. We are now reaching the order of magnitude where you can say: with some taxes (CO_2 ETS, CBAM, and premium or green resources), we can produce green ammonia and other green resources profitably.

P: Right, I also want to discuss your future perspective later, which you're already talking about. I want to go back to prices for a moment. Do you have any idea of the cost of producing sustainable urea now?

J: Let me show you (*shows screen with urea prices). These are all the prices of urea in the global market. Urea is a commodity. It's a granule that you can throw in a ship and deliver anywhere in the world. It costs almost nothing. So, the price is typically determined by the one who produces it the most expensive. Another thing; we all want green in Europe, but in Nigeria, they don't care about that at all. They also have very cheap gas, so you're competing with parties that are simply in the global market. If you look at Nigeria, they have so much gas, and it's so cheap that they can continue for another 100 years (figuratively speaking). If you look at China, they also produce relatively cheaply but for different reasons. They do everything with coal. So, it's very polluting; a lot of CO_2 is emitted. But eventually, you have to compete with them.

P: From previous research, I gathered that it can be sold for around $230 per ton. What do you think of this amount?

J: That strongly depends. We use a cost curve, so what you have is the cheapest and the most expensive. And depending on supply and demand, the most expensive may or may not survive. So, when prices are high (and they are still high now), they can continue producing in China with coal, even with a little emission tax. But if the price continues to decrease due to decreasing demand, you have the situation where the most expensive producers cannot survive anymore. If they close, the demand increases again because there is less supply. This leads to an increase in price, and expensive producers can resume production.

P: And is this a significant part of your daily practices? Looking at how prices compare to each other?

J: Yes, we know the cost price of almost all factories in the world. In Europe, for example, factories were shut down for a while last year when gas prices went up due to the war in Ukraine. People made a fortune just because the news that some people were going to shut down their factory caused urea prices to skyrocket as people started buying in bulk. This continued until the farmers thought, "I'm not going to buy fertilizer anymore because it's getting too expensive." And then the demand collapsed because you had high prices and no demand. As a result, more factories stopped operating. World mechanisms have a significant influence here.

P: I'm looking, for example, at 2030. But it's going to be difficult to determine prices for 2030 given the uncertainties in the world economy.

J: Yes, we do that too, forecasting. But you're always off, actually.

P: Another question. Is it true that emitters in the fertilizer industry can easily capture emitted emissions during production because they are purer?

J: Well, if you look at that little table I showed you, you can also see the ETS price on carbon. This gives you a bit of an idea about the background of the market. Previously, emitting was cheap. Nowadays, you need an end-of-pipe solution. This is expensive because it costs money and doesn't add extra capacity. What's happening now is that the CO_2 ETS is at 93 euros. Not long ago, it was below 30 euros (2 years ago). Storing CO_2 is profitable at an ETS price between 70 and 80 euros per ton. So, what you have now under the current ETS model is that it's already profitable to store CO_2 instead of emitting it. And what they are going to do with that ETS is that every company has been given rights. But what will happen now is that after 2035 or 2040, those rights will move towards zero. Let's say in 15 years, a penalty has to be paid for everything. Because as the supply of ETS rights decreases, they automatically become more expensive. If you look at the current ETS price of 94 euros, and I mentioned that there is approximately one ton of CO_2 in one ton of urea (through the whole life cycle assessment). So, in 15 years, that ton of fertilizer alone will become a quarter more expensive due to the increasing cost of CO_2 rights. I've seen that regulation, and I don't think it's realistic. But we'll see. I expect that factories will have to close, and food prices will rise. Then we'll have to pay 5 euros for a loaf of bread.

P: I see. Another question: when you license your technology, you also categorize the supply based on the age of the factories.

J: Yes, we offer the Launch program for greenfield factories, which are factories built from scratch. We provide the technology, and then a construction company builds the factory. "Evolve" is the revamping program where we modify existing factories to produce more energy-neutral.

P: Okay, my question was actually, when it comes to implementing captured CO_2, completely green, carbonized urea. Is it true that you need to set up an entirely new factory to meet the required technologies?

J: Yes, that's correct. What you see is that with electrolysis, factories look completely different now. So, it's very challenging to apply electrolysis in existing factories. It's practically impossible. The reason for that is that many of those factories, because they burn gas or coal, release a lot of heat, and that heat is often efficiently used to produce steam. And all the equipment, compressors, pumps, often operate on a steam turbine. So, they are powered by steam instead of electricity. This is highly efficient and works very well. But if I start removing the steam that I generated through heating, then I can no longer power the equipment. And those are the main investments in the factory. So, we see that existing factories can still make about 10-20% more sustainable, but not much more. So, if you really want to make it sustainable, you need to set up new types of factories that produce green ammonia.

P: I can imagine that, and I also want to look at where it's best to locate those factories to create an efficient supply chain for green ammonia production.

J: There are maps for that, which we also use in our charts. It has to do with load factor. There are maps that indicate where green energy is the cheapest. The green factory where I'm going tomorrow and where we're also building another factory is located in this region (Central North America). That's where we see projects. We're also working in the north of Sweden. Your location is actually determined by one thing, and that's the cost of your electricity. So, you produce where your load factors are the highest. Solar becomes the cheapest source of electricity, and then you have wind.

P: That's something I'll look into. Actually, I want to conclude with your future perspective. You mentioned earlier that the demand for urea only keeps increasing because urea is directly related to our food. How do you see the demand for urea in 2030?

J: That's in the presentation I sent you.

P: Ah, okay, then I'll look into that.

J: I should mention that it's an estimate, but it gives an idea.

P: And finally, do you see the demand for green fertilizers (other than urea) only growing in the coming years?

J: Yes, I think that mainly depends on the ETS prices, as I mentioned earlier. I'll send you some information. If you have any further questions, feel free to send me an email. The forecast is there, but we expect the demand for urea to remain steady. The growth for fertilizers remains roughly the same, around 1%. But for ammonia, we expect the demand to double until 2050. This is because it will be used as fuel for ships, as fuel for power plants, and eventually, it can be used for hydrogen transportation.

P: Transportation for hydrogen?

J: Yes, in the Sahara or in Australia, you have a lot of solar energy with which you can produce hydrogen, but transporting it becomes challenging. So, the primary case is to convert it into ammonia. This can be transported and then converted back to hydrogen. So, the growth of ammonia will mainly come from hydrogen.

*Closing remarks

Appendix 10.12 – ConsenCUS interview transcript

Interviewer: Pelle Meuzelaar (P)

Interviewee: Kate Harboe (K)

P: Thanks again for meeting me. Is it okay if I also record the session?

K: Yeah.

P: Okay, good. Great. So I prepared a little visual presentation.I have some results and I want to ask you some questions about them.

* I provide the model and data explanations and give an image of the optimal supply chain for scenario 1.

P: I have these two instances for the first scenario, these two supply chains for each cluster. And so as you can see, there's industrial clusters in the northwest one and they're all connected with pipelines. Most countries contain one, maybe two clusters. So the first question I want to ask is, how many clusters are necessary per country to achieve the ConsenCUS project's goals to reduce emissions. Because My results optimize for costs and show one or two clusters per country. But it does not optimize for emissions and so I want to know if they differ in any way. Would that generally be a feasible CCUS construction to just have one, maybe two clusters in each country? Or are they expected to be more? What is your opinion on that?

K: Okay, I first have a question about the results. Is this without storage? And how many sources are there? That is the black dots, right?

P Yeah. There is some storage, the hollow points. In Denmark there is one to be built, but that's the only one.

K: And on the other map you have several emitters?

P: Yes.

K: So what is, is it that you're actually connecting here? It looks like it's only one source?

P: Oh, yeah. Right. I've a lot of emitters and the thing is that they're not selected. There's only a few of these selected in the model because the model selects the minimum amount that is required to be used if the amount for all end users is to be satisfied. So that is why it doesn't include all the emitters, but just some and those provide all the CO_2 necessary for the utilization of the three end users.

K: And why are the sources connected?

P: It kinda looks like that, but they're connected to producers. It's a little small to see that.

K: Okay. So what if, if I understand correctly, what you say is that, so the demand for urea is known and is covered and it is easily covered by one source?

P: Yeah. So there's usually like one, maybe two emitters going into one facility. And the other way around. The facility usually needs one or two pipelines from emitters that we have.
K: So we have too much CO_2 to use, basically.

P: Yeah. And if it's too much, it's stored by my model.

K: So, why if there's enough CO_2 for production of urea methanol and SAF in each country. Why are the countries interlinked?

P: That has to do with the fact that the pipelines are considered cheaper to make. In my experiments at least, it's cheaper to make the pipelines so they go across the sea. The one in Denmark, it goes into a facility in Rotterdam because, well, it decides that because it's cheaper than building another source and capturing those emissions close by. So that is why sometimes you get these long international pipelines. There’s one for the UK as well, it goes the one between the Netherlands and the UK.

K: Is that because carbon capture is so expensive?

P: Yeah. Do you think it's feasible to connect such pipelines internationally or only would you say that it is more realistic to see pipelines being built nationally, in the cluster areas? Assume that there would be short pipelines within each cluster.

K: But it's just in the big picture, in the broader picture. We need to get to net zero in 2050. So I’m just questioning if you can just avoid capturing CO_2 because it's expensive.

P: Yeah. That's true. And it has to do with the model. Nodes are selected and there's a lot of emissions not being captured and if I found super high demands for each of these end users, which I didn't really, I would've likely had much more emitters, facilities and much more carbon captured.

K: Okay, interesting. So it's flipping everything because from my perspective, we are working with transportation and we see a demand. That came to us saying, we want your captured CO_2, could you please move it the cheapest way possible? But it's nice to know that it's so cheap enough to make pipelines, according to your model.

P: Yeah. About that, will CO_2 generally be transported by truck or shipped and end-used? Like how would you personally visualize that?

K: So in the short term, there are some projects that really need to have some funding and can get started right away, basically. So in the short term, it will be transported by trucks, and then in the longer term, hopefully there'll be CO_2 infrastructure too, right? And then we see that that's the same story for offshore (with container ships), basically.

P: So I'll just go on a little bit here about a few of the economics behind this. And I find that out of all the costs in the supply chain, the conversion costs for the end use facilities are the most expensive. It amounted to around 70% or 75% in my supply chain. So, could you confirm that that is usually the case? Or is it would you say that capturing the CO_2 is generally a more expensive cost element?

K: And you found this to be the case for all the products?

P: Yeah, it's it's, if you look at the entire supply chain for all products, it's 75%. And if you look at them individually, it differs a little. So one may be a little higher, some will be a little lower.

K: I don't have the numbers at hand right now. But you have them here. I don't know about the conversion. I think there's some studies saying for capturing, it's around, what is it, 150 Euros per ton of CO_2?

P: Yeah, something like that. In these, the conversion goes into the 200, 300 plus, especially for methanol and urea.

K: So this could be possible, if it’s also according to your calculation.

P: Okay so I did this analysis for the LCOE because from other interviews and the literature I found that it's cost of renewable electricity is usually a main cost factor of this conversion costs. And so I looked at it. These ranges in the table below represent the increase in the levelized cost and on the left scenario there is a very high decrease in LCOE, 58%. And so my question is do you expect cost reductions of renewable electricity as well? And do you have a sense like how much is gonna decrease? Could it drop by 50% (2030)?

K: I don't know. We're also using more, more energy every year.

P: Am I right to assume that LCOE does determine how much CCUS will be happening in the future? Like, if it ends out being very expensive, then there will be less CCU and CCS?

K: Well it's linked to the hydrogen industry, so yeah.

*I show the supply chain for scenario 2

P: Okay and so this one is just the national clusters. I'm quite satisfied with these results. Itit looks similar to the international experiment before, just not connected with any very long pipelines. So what you see here is that there's usually one cluster. In the UK, there's some more but Denmark is a really nice example of having just one cluster Kalundborg. And there's only one facility for each end-use. It's, it's a, it's a simple, it's a simple overview. And did you also find that there are less clusters in the SE countries than in NW countries? In the southeast, there's generally fewer emitters and facilities, so you should use one cluster, whereas in the Netherlands or the UK which have also the most emissions in general, you will have more clusters?

K: Yeah, yeah, yeah. We didn't find much about CCUS in the southeast region, though they're very much into hydrogen, so everything should run on hydrogen basically over there. And they find that the CO can be stored, if that is really necessary. And also we have one partner in the ConsenCUS project from Bulgaria confirming that that is the focus for now.

P: Okay, so I think this is a little more feasible as well then. However, if I compare this scenario with the previous one I do find that costs are about 17.5% higher, if you add all countries together and keep the same demand. This is easily explained though. Because in the UK and in the Netherlands, there's more building decisions. So there's more sources constructed and there's more facilities constructed. However my question is, is this in line with ConsenCUS? Because it aims to connect everyone, right?

K: No I'm not sure if that's always the case. No, I think you want to do what is feasible. I don't think you need to connect all the countries. So the clusters can be small or big, they can be interconnected. You have the freedom to decide what is most feasible. So I don't think the aim necessarily is to connect the countries.

P: Good. Okay. But it’s good to have the possibility. For this scenario, I did somewhat of a sensitivity analysis for the cost of electricity as well. And of course, the conversion cost is still the most expensive cost factor. So what I did was, I changed the individual country cost of renewable electricity. And I found, for instance, that Denmark came out on top with the lowest renewable electricity cost, followed by I think the Netherlands and then the UK. And then for the southeast Greece was best followed by Romania, followed by Bulgaria. And then I found the differences in supply chain costs based on these initial costs. So basically, the question I want to ask you is, should costs of renewable energy be the first thing you look at, when you want to start a CCUS project? Can you expect that these all go into the countries with the lowest LCOE?

K: Yeah. I don't know. I don't know. I find that it should be considering subsidies and regulations and funding as well right? So those things should also be considered, the lowest cost contracts. Did you also look at ETS? What is the solution when they reuse the CO_2 in your model? Do they not pay ETS?

P: So for my configurations, the access that is not captured isn't really taken into account with the cost. But it's a nice continuation.

K: So the carbon capture gets cheaper because they don't need to pay the penalties for letting out CO_2 because they actually capture it. CCU is basically just a reuse of CO_2. At some point you would end up with CO_2 in the atmosphere.

P: And so if you look at the ETS market in Europe, there is just one ETS market?

K: Well, its regulated, so that's also where we found the emitter database and how much each emits because they have to tell how much they emit. So all the databases we used from ConsenCUS was based on this. They need to give the numbers for how much they admit so they can pay the right amount. And then there's all kind of schemes about how, how much discount they get, depending on multiple things. But in the end, there is a penalty for, for emitting.

P: Ah, okay. I don’t have any further questions.

* Closing remarks

Appendix 10.13 – BGS interview transcript

Interviewer: Pelle Meuzelaar (P)

Interviewee: Karen Kirk (K)

P: Thanks so much for taking the time for this meeting. So I prepared a short presentation to show the idea of the research and then present the results. And I want to just ask you some questions about the results. Is it also okay if I record this session so I can refer to it later during my thesis. Is that okay with you?

K: Yeah. Okay.

P: Okay, great. I'll just briefly introduce what I'm doing. I'm researching an optimal CCUS supply chain. And I research the end uses methanol, urea and aviation fuel, but I also look at storing the excess CO_2 from emitters that are not utilized. So if the emitters selected emit access CO_2 that is not utilized, I aim to store this in storage sites. The model I use for this is a mathematical model that minimizes the total costs of investment decisions. It's not really important for the questions I'm about to ask, so I'll just hop through them. The scope is the Northwest of Europe as well as the Southeast. And I've just provided here a short image of the emitters that are selected in my data as well. So these are from various industries, have various emissions and yeah, so these are the emitters. But then there's the sites as well. It's kind of similar, but as you can see, I've used the green ones for the, for the urea and the blue ones for the ol and the red ones for the aviation fuel. But what is important as well, and what I want to ask you, is these are the storage sites that I selected. And they are from ConcenCUS. I think you're familiar with ConcenCUS, right?

K: Yeah, I've been involved in Consensus.

P: Good. So well this is the storage database and storages projected on a map here [image of sites is shown] and the hollow circles represent the saline aquifers and the fully black dots are the depleted oil and gas fields. I want to ask you: to your knowledge, would this be a sufficient and accurate representation of the storage sites for these regions?

K: Yes. So if it's the data from Consensus, then that is going to be the most up-to-date information from all the countries that are involved. Because it's quite recent, so it will be the most accurate version.

P: Right. That's good because I've used that for the results that I'll show you in a second. What I also looked at with these was the readiness levels. Because that is also provided by consensus. So a lot of them right now, especially the southeast, have either no available readiness level or the readiness level ranged from like three to six-ish. And that goes especially for the northwest. In my research I included every storage no matter the readiness level, but according to you, is this a good idea? Or should you only include the ones with the highest readiness level?

K: I would include the ones with the lower storage readiness levels as well because although obviously they aren't as high in terms of how well they are known it doesn't mean that they're not going to be, they're not going to have potential. So it just means that they need more work, right? Basically. So, it's an indicator to the regulators and to industry of how much additional effort is required to work the site up to know, to understand it fully. Obviously the higher the number the better in terms of the fact that less you, you're going to have less financial input.

P: Right.

K: So, yeah, obviously industry will probably look at the higher numbers on that storage register level, and be more attracted to those sites because they're obviously better known in terms of CO_2 storage, right?

P: Yeah. Would you say that the levels that are somewhat higher right now, do you expect those to be operational sooner? Like, could it be that others having low or no level still end up opening sooner than the ones?

K: I mean, that's quite difficult to answer obviously. You may get to a point where they get to a stage where they've done some further investigation to try and get the site to the point where it's ready. They may discover something that hadn't already previously been discovered because they didn't have some specific data that highlighted an issue that implies: maybe this isn't the best site to start with. And it also doesn't necessarily mean that a site is not suitable or it is a showstopper completely. It would mean that, possibly at that point, they wouldn't want to commit the extra funding at that point. And it could be that it is. So you, you know, if you think in terms of having a cluster of sites, it might be that one would be useful to use later on, if you know what I mean.

P: I do. Yeah.

K: So you start with another site and then that could be sort of the next site or the site after that once you filled that site. Or maybe you came across an issue and that site needed to close for a certain amount of time, you may then move to the other one in a cluster. Does that make sense?

P: Right. It does. Yeah. Then that’s great to hear because then I know I made the right decisions in terms of data selection. So just onto some of the results that I had for my supply chain. They’re for each end-use. So the red one is aviation fuel, the green one is urea, and the blue one is methanol. But then there's also the storages in which the access CO_2 flows into. So what I find is that the CCU is more prominent or more so used in the high demand end-uses and not so much in the low demand. CCS is more prominent in the latter as there's more storage space. On the right, the methanol and SAF chain, there's quite a lot more storage, especially for the methanol chain. This is explained by the fact that the urea simply has more demand. So there's more CO_2 used for production of urea compared to the other two where there's much less amount. There's less CO_2 needed for the utilization and more for the storage. The question I want to ask is what is your vision on CCS vs CCU. Would you say that one is more effective than the other in terms of emissions reductions?

K: I would say there's a preference. I think the two actually go nicely hand in hand together really. Obviously down the line, one of the things we're hoping is we are not going to have to be doing CCS because, we've maybe become more sustainable in terms of our energy production. But I would say basically that CCU and CCS probably need to work together, right? Personally I wouldn't say that one is better or more prominent than the other. Maybe, maybe CCU in the future is going to be more prominent if we do manage to get rid of all our fossil fuel power plants and things like that. But at the moment I think that they sort of work hand in hand together.

P: Right. Yeah. So that's also what these results represent. I want to ask some questions about the selected storages in the UK. Because, well, that's your area's expertise, right? Or am I wrong for assuming this?

K: That's correct. Yeah.

P: Okay. So, the images on the right, there's like the storage clusters at the mid-east and there's one in the north of Manchester area as well. The data shows that they're offshore. Looking at the red and the blue images with those storage clusters, would you say that these clusters are feasible to build? Could they be ready in 2030, like 10 years from now, scenario?

K: Yeah, so you're very much hit on the areas that are of interest in terms of what industry we are looking at. So I would say that you are looking in the right areas, basically. Okay. And then one other area of interest is actually off the Scottish coast, so further north. And there's a lot of interest in and around the captain area.

P: Okay, good. So, my model just calculates based on distance and right now it chooses the ones that are closest to the emitters, which is what I want to ask you about. Is it a good rule of thumb to choose emitters and storages that are close to the emissions? Or would you say that you base those decisions on other factors, say storage type? Does distance matter basically is what I'm asking.

K: Yeah, I, yeah, I mean, distance is, is always a factor. When you are looking at where to store it is always considered. It doesn't necessarily mean that the closest store to where you are looking at transporting your CO_2 from is going to be the most optimal site. So it is a factor. But don't be afraid to go a little bit further infield if there is better storage available, right? And it could mean that, again, if you look at talking in terms of clusters, that you start off at one that is further away, but then the one that is closer that you've considered originally could be part of that cluster as the next site.

P: Yeah, so it's like a sequence you can follow.

K: Yeah. Yeah, so obviously you do have to think of distance because you have to think of terms of transport costs. And that'll all be factored in but then obviously other things will be factored in, in terms of costs when you are actually looking at the storage site itself as well. So it is kind of weighing all those options up yeah. Figuring out what's going to be the best for the scenario that you are in. Yeah. So it's, it's considerable, it's important, but it doesn't have to be the main factor.

P: Right. And so in this model as well, the black lines between them are pipelines. So they represent the construction decision of building a pipeline because, for my research, that will be economical in the long term. But of course if you see at first glance, it's quite a drastic building decision to build all of these pipelines, especially considering some of the long distance ones. I want to ask you: is it a good idea to build such a pipeline structure between the emitters and the storage cluster? Like the one you see in the image below with the pipelines going into the storage. With this supply chain you don’t have to load it into a ship or, and then store it, it just goes directly through the pipeline. Would you say it's feasible to create such a structure in the mid to long term?

K: It's very expensive. So obviously that has to be considered. I can't off the top of my head remember the costs that I've heard about how much it costs per kilometer to actually install. One of the other considerations is the utilization of existing pipelines that are already there, right? From, obviously from the oil and gas industry. Other things you have to think about when constructing a pipeline is what pathway you will be allowed to take, because obviously you have to consider what's already there. So it may be that you need to actually route it in a different direction to what you think, because you might have to follow an existing infrastructure, such as an existing pipeline network or whatever. And you may have to avoid certain areas for some reason. So for example, wind farms or there may be protected areas which we've got a lot of around the coastlines of the UK. It may not be that that would stop your construction of a pipeline, but there'd be lots of considerations and lots of things that you would have to adhere to in terms of planning and licensing.

P: I understand. And are there the ones that I've constructed here near the coast of the UK, you said that there's a lot of protected areas?

K: Well, for these pipelines it's not going to be a showstopper, it just probably means additional work in terms of the environmental impact assessments and things like that. Basically it would take longer to get through the planning side of things and getting it licensed probably.

P: Right. And that would not be optimal considering the fact that, well, I have a shorter time horizon on this one (2030).

K: Yeah, but that's fine because you can't really look into it for each one here. I mean, if you're interested in these areas, I can point you to where you can find GIS shape files of the areas I'm talking about. *Talks about protected area and pipeline data

P: So just one more question. It's about the economics side. I did a sensitivity analysis and then looked at the cost differences. For sensitivity, I excluded the onshore sites in the eastern one, where the storages are mostly onshore. Because, but they have a lot of public resistance against them, is what I find. For the NW one, it doesn't really affect it because most of it is offshore anyway. But for the SE one, the cost obviously goes up quite drastically because sites are mostly onshore. I did a similar sensitivity whereby I excluded saline aquifers and only considered depleted oil gas fields, because literature states that it's cheaper. I found that total costs increased as well because if you just include those ones, you miss out on a lot of other storages that are close by. And there's just quite a lot of SAs in the northwest as well that are just closer as well to the emitters. The question I want to ask you is, do you think it's valid to say that you should select a nearby saline aquifer over, say, a depleted oil and gas field even though in general they are cheaper? Could the extra distance cost savings make up for extra costs at the site?

K: So, I guess it depends on how much CO_2 you wanted to store and how much available space you've got in the storage sites you're looking at. Quite often you will have a lot larger storage in the saline aquifer than you might have in a depleted oil and gas field. So I guess what I'm saying is there isn't really a simple answer. It's going to be site specific. In some areas you may go for the saline aquifer because there may be certain characteristics about saline or aquifer that are more attractive than the oil and gas field. Take for example the case of the Norwegian North Sea field. area They were extracting hydrocarbons from a field and it was very high in CO_2 (the content of the actual oil). And so because they were going to be taxed if they released the CO_2, that they were wanting to separate off from what they've extracted. If they vented it to the atmosphere; they were going to be charged extra taxes by the government for that. So they discovered there was a saline aquifer deeper than the hydrocarbon field that they could store in straight from the platform where they separated the CO_2 from. And it worked out that it was actually an amazing way to store it because, although it was a sandstone, it was quite a loose sandstone and its porosity and permeability was amazing. So it was really easy to inject CO_2 into because the CO_2 flowed incredibly easily through the sandstone without causing any issues in terms of over pressuring and things like that, even though it was a saline aquifer. So there was porous fluids in there already. So what I'm saying is you might find that you've got an amazing aquifer somewhere like that that may be more attractive than a hydrocarbon field.

P: Alright I expected that answer as well, so it's perfectly fine. And what I make of that as well is that you also should consider, there's also like a distinction between combined fields. That is, the ones that are depleted oil and gas fuels with saline aquifers integrated within them. Or vice versa.

K: Yeah, actually, I mean, in the North Sea there's lots of these stacked aquifers that can, you know, could provide some amazing storage for a long time and obviously you're going to use just one platform to actually reach them from.

P: Exactly. It's quite attractive when you look at it like that.

*Closing remarks