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The potential for bio-CCS in Europe

Marginal abatement costs and transport logistics

Master's thesis in Sustainable Energy Systems

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DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT
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Abstract

Bio-energy carbon capture and storage (BECCS) has the potential to offset greenhouse gas emission (GHG) and can be an important part in meeting the Paris agreements goal of staying below a temperature increase of 1.5^{o}C. The aim of this work is to appreciate the potential for BECCS in Europe. This study compiles data on plants emitting biogenic CO_2 in the EU, Norway, Switzerland, and the UK using the European Pollutant Release and Transfer Register (E-PRTR) and estimate the costs of applying carbon capture and storage (CCS) technology to these plants.

The method focuses on the importance and cost of transporting biogenic carbon dioxide captured by CCS technology. By compairing transport scenarios, factors influencing transport costs are identified. Results from factors show that adding ports along European rivers does not significantly affect transport costs, whereas the use of clusters and their positioning greatly influences costs. The primary cost determinant is the distance from the plant to the storage site.

The total cost span starts aboutof BECCS ranges 110 €/tCO_2 and 586 out of the 605 plants in the study fall below 900 €/tCO_2. The transport cost was on average about 60 % of the total cost. The transport cost is mostly between 150 and 400 €/tCO_2 with long-term storage sites. The main share of transport cost is for transport between cluster to storage location, while only 14 % on average are the transport from plant to cluster.

Furthermore, the potential of BECCS as a negative emission technology (NET) is evaluated. The total potential of CO_2 emissions (including fossil and biogenic) for capture is about 270 Mt CO_2 in Europe. Given that 25-50 % of global greenhouse gas emissions need to be mitigated by NETs to meet the Paris Agreement targets [1], the study identifies Sweden and Finland as key countries with significant BECCS potential, covering a total of 47.5 and 30.5 % of the countries respective GHG emissions, mainly due to their pulp and paper industries.

Keywords: BECCS, MACC, CO2-capture, transportation, clusters, storage, costs, Europe, ports, sinks.

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Sanna Hidesjö, Gothenburg, June 2024

List of Acronyms

BECCS	Bioenergy carbon capture and storage
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon capture utilisation and storage
CDR	Carbon dioxide removal
CHP	Combined Heat and Power
DAC	Direct Air Capture
DH	District heating
EEA	European economic area
EFIP	European Federation of Inland Ports
GCCSI	Global CCS Institute
GHG	Greenhoese gas
Gt	Giga Tonne
IEA	International Energy Agency
MACC	Marginal Abatement Cost Curve
MEA	Monoetanolamine
MSW	Municipal Solid Waste
Mt	Mega Tonne
NETs	Negative Emission Technology
OPEX	Operational expenditures
PCC	Post Combustion Capture
PRTR	Pollutant Release and TRansfer Register
tCO2	Tonnes of CO2
TRL	Technological Readiness Level
WtE	Waste to Energy

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1 Introduction

1.1 Carbon capture technology and net negative emissions

In emitting Carbon dioxide (CO_2) to the atmosphere and increasing the amount already in circulation, the global temperature is rising. By the Paris agreement the goal of a temperature increase of maximum 1.5^{o}C compared to pre-industrial levels is the target, and a carbon budget corresponding to this target has been set [2]. This budget requires zero emissions by 2050, and more than likely net-negative emissions the second half of the century [2]. In part because the emission budget might be overshot, and in part because of emissios from hard-to-abate sectors [3].

Net-negative emissions equates to a scenario where carbon is actively being removed from the atmosphere. There are several possible ways of achieving this through negative emission technology (NETs), there among bio-energy carbon capture and storage (BECCS), afforestation, reforestation, enhanced weathering, ocean fertilisation, bio-char based carbon sequestration and direct air capture (DAC) [4]. Among these, carbon capture and storage (CCS) is a carbon dioxide removal (CDR) process that separates, compresses/liquidates, transports and stores CO_2 from gas streams [5].

Large scale CDR has been identified as a key component in climate change mitigation [6]. NETs are playing a critical role in both mitigating greenhouse gas emissions (GHG) and achieving the climate goals proposed by the Paris agreement [4]. There are several scenarios for reduction, but in focusing entirely on removal there is a projection of needing to remove about 4.9 GtCO_2 of total emissions annually by 2050 [7]. All scenarios reaching 1.5^{o}C by 2100 rely on large volumes of NETs, ranging from 25 to 50 % of current GHG emissions [1].

BECCS encompasses a strategic integration of several key processes;

- The utilization of biomass from arboreal and agricultural sources, which sequesters atmospheric CO_2 during photosynthesis.
- The thermochemical transformation of that biomass into thermal energy, electrical power, or secondary energy carriers such as gaseous or liquid bio-fuels, or alternatively, through biochemical pathways such as fermentation [1].
- The implementation of CO2 capture at point sources of biogenic CO2 emissions followed by the transportation and sequestration of CO_2 in geological formations. This hinges on the assumption that the biomass used as feedstock

> is cultivated in a manner that achieves near-zero or significantly reduced net carbon emissions. Specifically, a balance wherein the CO_2 captured by the growth of additional biomass approximately equals the CO_2 released during its subsequent conversion processes.

As biogenic materials consist of carbon absorbed from the atmosphere, combustion does not release new emissions into the carbon cycle (in comparison to burning fossil fuels, which adds CO_2 to the atmosphere). Thus, capturing and storing biogenic carbon equates to removing carbon from the atmosphere, BECCS are therefore a net-negative emission technology.

In the long term, the primary limiting factor of BECCS is not the actual technology but rather the supply of biomass [1]. Estimates of the global BECCS potential vary widely, ranging from 1 to 85 GtCO_2, with a median estimate of 12 GtCO_2 in modeling mitigation scenarios aimed at limiting warming to 2°C [8].

Implementing BECCS presents several challenges. One significant issue is the reduction in efficiency of the processes where CCS is applied; electrical efficiency decreases up to 14 % and costs increase [9]. Additionally, the storage and transport of CO_2 pose potential public safety risks. The feasibility of large-scale BECCS remains untested, with cost estimations varying widely. Furthermore, feedstock availability, system integration, and transport infrastructure are major points of contention that need to be addressed. These factors collectively influence the practicality and scalability of BECCS, underscoring the complexity of its implementation on a global scale.

The global potential of BECCS as a mitigation measure could also be restricted by the availability of geological storage of CO_2. Most sources do consider that BECCS have the potential to reach the long term target of the Paris Agreement [10]. Costs approximations for capture by BECCS varies but is appreciated between 20 to 175 \$/tCO_2 [10]. Compared to DACCS which has a higher projected capture cost up to 1000\$ per ton depending on source [11] and has a higher levelized cost of carbon than BECCS overall [12]. In comparison between the two, the results are highly sensitive to the price of biomass and amount of negative emissions.

Plants emitting biogenic CO_2 in Europe include pulp and paper mills, municipal solid waste (MSW) fired waste-to-energy plants (WtE), and biomass-fired combined heat and power plants (CHP) [13]. These plants do not compete with food production and land, and are often of a size where implementing CCS could be economically feasible [13].

1.2 Literature review

Previous works have extensively covered CCS implementation as well as general comparison between NETs. There are also several papers which have explored possible transportation options and need of infrastructure for captured CO_2.

Rosa et al [13] quantified the technical potential for biogenic CDR in the European union, while identifying sinks and clusters. They looked at seven prospective BECCS emitters in Europe, determining biogenic CO_2 content and CDR efficiencies for each plant configuration (Bio-power, incinerators, pulp and paper, wastewater, crop residues, food waste and manure). Rosa et al. concluded that BECCS is a large but constrained resource in Europe with about 200 Mtons of biogenic CO_2 that could be technically deployed for CDR in Europe. Assessing feasibility of net-zero emissions by domestic biogenic CO_2 sources, concluding that with a high emission reduction scenario, domestic BECCS are sufficient to meet the climate-neutrality target for Sweden, Finland and Estonia.

Carton et al. [6] argue that literature on NETs is largely hypothetical, focused on future scenarios and risks, which enriches debates on feasibility but lacks real-world examples despite the long-standing existence of CCS technology. The hypothetical nature of storage costs is attributed to a focus on research over practical standards and subsidies.

Buidinis et al. [5] investigated carbon budget estimations and cost of CCS, as well as source-to-sink matching, supply chain and building rate. As their investigation was done with fossil sources, the primary interest of this work lies in the transport route and reasoning around infrastructure for transport of CO_2.

For marginal abatement cost curves (MACCs) Johnsson et al.[2] have mapped the costs of installation and operation of post-combustion caption (PCC) with monoethanolamine (MEA) in all industrial plants with annual emissions of 500 ktCO_2 or more in Sweden. Considering differences in investment cost and potential of excess heat and steam demand.

Yue et al. [14] looked at decarbonisation opportunities using MACCs, providing ways of calculating emission reduction targets and comparing differing sustainable sources in achieving those targets. They determined that MACCs are highly dependent on model assumptions and that the bioenergy availability plays a critical role.

Turgut et al [15] investigated different transport strategies and cost calculations of CCS in Europe. The mapping of major transportation connections for differing sustainability scenarios (the EU ambition, the mid-way scenario and the worst case scenario) was done. The results were that they found contributions of the three industry sectors in emissions reductions are neither geographically nor sector-wise homogeneous across the pathways.

d'Amore et al [16] explored European wide supply-chain optimization. Mapping sources of CO_2 and mapping optimal transportation routes based on differing scenarios. They found that removing 50% of industrial CO_2 in each country costs 60.5 €/ton, increasing to 81.4 €/ton if onshore sinks are forbidden. They also noted that ships have a more important role in transportation in Southern Europe, if storage is restricted to offshore North Sea basis.

The European Commission issued a study that identified 100-120 CO_2 clusters and 100 storage sites across Europe [17]. The study looked at eight different scenarios in capture volume and storage and tried to determine the optimal transport network of CO_2 from investment cost perspectives up to 2050.

The Clean Air Taskforce [18] developed a tool for identifying long and short-term storage in Europe, based partially on the European Commissions report [17]. For ports, the European Federation of Inland Ports (EFIP) [19] identified possible industrial level ports along the rivers in Europe.

The largest research gap found throughout the reviewed works is the exclusion of all rivers as possible transportation routes for CO_2. There is also a need of performing the study on current emission trends from currently online plants. The transport studies mentioned are, excepting Rosa et al, performed on fossil sources. Transport methods are most commonly train and ship while truck and railway is seldom explored. Clustering has not been done on biomass plants and long-term sinks have not been analyzed from strictly a biomass perspective.

1.3 Aim

The overall aim of this work is to estimate the European potential for CDR through BECCS from capture of biogenic CO_2 from current point sources, including thermal heat and power plants and pulp and paper mills. The work estimates the cost of BECCS for all plants, including the cost of capture, transport and storage, resulting in marginal abatement cost curves. Transport scenarios are compared, focusing on the location of potential storage sites and transport nodes (ports and clusters). The work also identifies the countries in Europe with the greatest potential for NETs through BECCS and evaluating the importance of establishing CO_2 hubs/clusters that collect captured emissions from multiple smaller plants for cost-effectiveness in CO_2 transport.

The work maps the current plants emitting biogenic CO_2 in Europe, and plots the cost of application of CCS technologies to those plants, applying different transport scenarios for each plant, adding compression and liquefaction costs as well as storage cost.

The transport options explored are by pipeline, truck or ship. The effect of several different infrastructure decisions in transport is evaluated, mainly looking at the plant, clusters, port and sink location.

2 Background

2.1 BECCS supply chain

The CCS transport chain encompasses several parts, which are the capture, transport, and storage of CO_2. The transport segment specifically entails the conditioning, shipping, pipelines, trucks, and reconditioning of CO_2 before its final storage [20].

2.2 CO_2 sources and capture

Carbon capture can be done by several technologies, where pre-combustion capture, post-combustion capture, oxy-fuel and chemical looping combustion are the most prevalent options. The amine based PCC has the highest degree of technological readiness level (TRL) 8-9 [2] being in use since 1996 [21]. The MEA solvent PCC is often used as a reference process in other works dealing in biogenic capture, such as Rosa et al [13].

PCC works by capture of CO_2 from the flue gas after combustion in the equipment [22], see Figure 1. The flue gases emitted from the power plant undergo a cooling process and are subjected to treatments designed to mitigate the presence of particulates. Subsequently, the NOx and SOx used in the treatment, boosted by a fan to counteract the pressure drops inherent in the system, cross over to an absorber. Within the absorber, a lean amine solution engages in a counter-current interaction with the flue gases, effecting the absorption of CO_2. The now purified flue gases proceed unobstructed to the stack. Meanwhile, the CO_2-laden amine solution is conveyed to a stripper, where the amine is detached from the CO_2. At the apex of the stripper, the CO_2-rich solution undergoes condensation to remove the water, and the resultant gaseous CO_2 is directed onward for subsequent drying and compression [23].

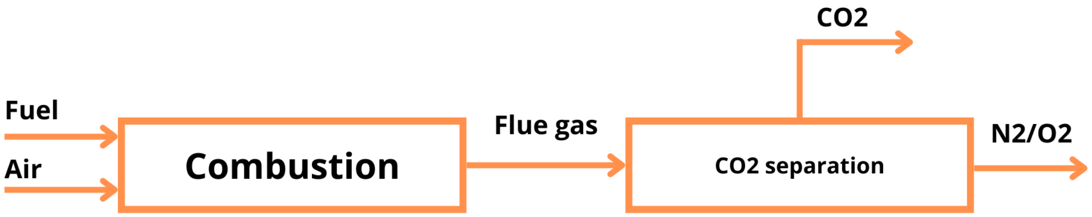


Figure 1: Line diagram of CO_2-capture plants with PCC

The process of PCC is most suitable at power plants where flue gas is most prevalent [24]. There lies a challenge in making PCC cost effective for lower concentration of CO_2 in the flue gas, which can be detrimental to the separation, capture system, and process and plant efficiency. In combined heat and power (CHP) plants the concentration of CO_2 is about 13 % per volume [25]. Pulp and paper, along with WtE-plants typically has a concentration of CO_2 in flue gas between 10 and 12 % [26].

Carbon capture rate can be close to 100 % with PCC, but there is a sharp increase in cost from capture about 90 % and higher [27]. The main advantage of PCC is that it can be integrated (retrofitted) into existing processes without altering the combustion process [9].

2.2.1 Pulp and Paper

Point sources of biogenic CO_2 emissions to which PCC could be applied include the pulp and paper sector, which is a major industrial user of bioenergy. In Europe the pulp and paper industry produces about 85 Mtons of paper and boards [28]. The industry is responsible for just under 2 % of all fossil and biogenic emissions from industry in 2022 [29], the sector uses bioenergy from biomass combustion and non-biogenic CO_2 from fossil fuel combustion and chemical processes. Biogenic CO_2 primarily originates from the combustion of spent pulping liquors and wood fuels in recovery and combustion units [30]. Non-biogenic CO_2 emissions arise from fossil fuel use in recovery systems, lime kilns, and the addition of carbonaceous chemicals in recovery processes [31]. The pulp production can be split into chemical and mechanical pulping, see Figure 2. What process is used often depends on whether paper or just pulp is being produced [32]. If paper is being recycled to new papermass that will affect the process, adding shredding before a different type of chemical solvents are applied [33]. GHG emissions in this sector stem from combustion in recovery units, the use of makeup chemicals, combustion in lime kilns, and the use of sorbents in acid gas control systems.

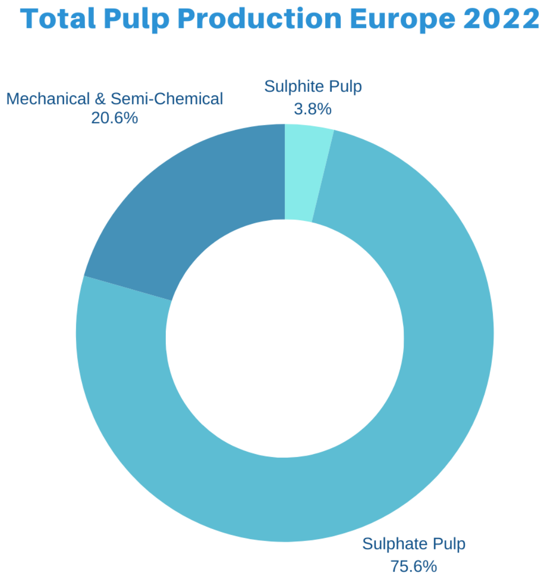


Figure 2: Ditribution of pulp production in Europe in 2022 According to CEPI [28]

The pulp and paper manufacturing sector is energy and raw materials intensive, with high capital costs and long investment cycles [28]. The use of bioenergy in the sector needs to increase with 45 to 50 % in 2030 in order for the sector to be on path towards the Paris agreement [29].

2.2.2 Thermal plants

Other plants using bioenergy include thermal plants, with the most common type being CHP, where generation of electricity and district heat are done simultaneously, utilizing waste heat from the electricity generation to increase overall process efficiency [34]. Common types of CHP plants include steam cycles, solid fuel boilers, gas turbines and engines, wood gasifiers, combined cycle power plants, and steam engines. They can both serve internal energy needs and export electricity.

CHP plants can utilize a variety of biomass resources for fuel, including direct combustion in dedicated plants or co-firing with coal, using up to 10 % biomass or more with bio-coal produced via torrefaction [34]. Co-firing is defined as simultaneous combustion of different fuels in the same boiler. It provides an alternative to emission reduction by replacing fossil fuel with biomass, but also as a result of the interaction of fuel reactants of different origin, such as biomass and coal [35]. Biomass can also be converted into biogas or BioSNG for use in gas engines and turbines. However, the use of liquid biofuels (e.g., biodiesel, ethanol) in CHP is less common due to their high production costs and energy-intensive production processes [27].

Another type of thermal plant is the WtE plant, where MSW is combusted to produce electricity. Advantages of WtE is the reduction of waste volume, the recovery of energy, the decrease of fossil fuel reliance, and the fact that the technology is providing a cheap or income-generating energy source [36].

2.3 Transport and storage

The process of transport begins at conditioning plants where captured CO_2 is purified and liquefied under specific pressures, which are critical for influencing the efficiency of the subsequent transport and storage phases [37]. After purification, the liquefied CO_2 is stored temporarily in cryogenic buffers both before and after it is transported [20]. The final transport stage, reconditioning, prepares the CO_2 for storage by reheating it and potentially expanding the capacity of the receiving facilities.

There is a growing interest and investment in CO_2 transport infrastructure to support large-scale CCS efforts. Pipelines are generally the most cost-effective method for CO_2 transport, especially for large quantities, though shipping can be competitive for long-distance [38].

Key geologic parameters affecting CO_2 storage feasibility and cost include permeability, thickness, depth, porosity, and lateral continuity. Favorable reservoirs for lower-cost storage are those that are permeable and thick [39]. The potential for European storage of CO_2 has been surmised by the Clean Air Task Force [40] which is based on a report by the danish ministry of climate, energy and utilities [18].

Pipeline are suitable for transporting larger volumes of CO_2. Large volume transport at low operating costs and minimal environmental impact during operation, though construction can have significant environmental effects [41].

Pipeline transport can be categorized into dense phase, gas phase, and supercritical phase, each with distinct operational and cost considerations [20]. Dense phase transport is less sensitive to temperature and pressure changes but requires specific conditions. Long-distance transport (over 400 km) typically involves dense phase CO_2, operating above its critical pressure. The dense phase is operationally stable and efficient. Offshore pipelines share similar cost components with onshore pipelines but tend to be more expensive due to the complexities of offshore construction.

Pipeline operations necessitate further pressure adjustments using pumps or compressors. Isolation valves are strategically installed for maintenance and safety, especially in densely populated areas. Metering stations are typically located at the pipeline's start or end, rather than along its length. Offshore pipelines, which do not use intermediate stations, must be designed to handle pressure drops acceptably over their length. Pipeline monitoring involves continuous measurement of flow, pressure, and temperature, with systems in place for corrosion protection and internal inspection.

Ship transport of CO_2 is primarily suited for medium to large volumes over medium to long distances, such as from large emitters to offshore or land-based storage sites [41]. Currently, only small ships (1000-2000 m^3) transport limited CO_2 volumes, exclusively in liquid form [41]. CO_2 liquefaction is necessary with less energy required if fed by high-pressure CO_2 from pipelines rather than directly from capture plants. Conditions for transporting liquid CO_2 vary, including low pressure (around 6-8 bar and approx. -50°C) for high density but requiring heavy insulation, medium pressure (15-18 bar and -25 to -30°C) which is common today, and high pressure (40-50 bar and +5 to +15°C) requiring less insulation but heavier tanks [42].

Designs for CO_2 carrier ships differ based on pressure and temperature, impacting the design of export terminals and liquefaction plants. Terminals need well-insulated storage tanks, possibly including a buffer for delays, and to be equipped for efficient ship loading/unloading [20].

Shipping emphasizes the economies of scale, where larger ships are more cost-efficient due to lower unit costs despite higher initial investments [20]. CO_2 shipping also enforces the importance of selecting the appropriate materials and designs for CO_2 storage tanks based on the CO_2's state—whether it's in a high-pressure ambient temperature, medium pressure, or low-temperature condition [43]. Each state demands specific materials, like forged carbon steel for high-pressure conditions and specialized low-temperature materials for low-temperature conditions.

Notably, low-pressure CO_2 transport ships cost less than half compared to medium pressure ones, largely due to less efficient cargo volume utilization with higher pressure tanks. For medium pressure, which is the industrial standard, data is uncertain for capacities above 12,000 t due to limited studies, and for high-pressure conditions, CAPEX data is highly uncertain. Refurbishing old gas carriers for CO_2 transport might reduce costs by over 60 % compared to new vessels. However, considering that the investment cost is only 14 % of the total CO_2 transport cost (including liquefaction), CAPEX savings from refurbishment are relatively minor in the overall cost context [41]. Full CO_2 ship transport chain CAPEX also includes CO_2 terminals for export and receiving, with estimated costs for terminals designed for CO_2 at 15 bara and -27°C.

Truck transport of CO_2 may be economical for short distances and small quantities but are not expected to be a major players in large-scale CCS deployment [39].

Road transport of CO_2 is typically done in liquid form under conditions similar to ship transport, at pressures of 15-18 bar and temperatures between -25 to -30°C [41]. This method is suitable for small to medium volumes of CO_2, ideal for transporting CO_2 from small point sources to utilization facilities or export terminals.

2.4 Clusters

BECCS facilities located near each other form what are known as source clusters, as shared CO_2 transport networks could significantly reduce costs through economies of scale. Geological storage locations are designated as sinks.

From an industrial perspective, clusters are defined as groups of businesses and organizations that gain competitive advantages through mutual cooperation, such as shared technologies, buyers, suppliers, or labor pools. The economic self-interest of each member enhances the competitiveness and viability of the cluster [44]. In CCS, such clustering not only leverages geographical advantages but also aligns with broader economic and environmental goals, making it a critical element for policy and strategic planning in CCS deployment.

Clustering, or the development of CCS hubs, plays an important role in making CCS economically feasible. By aggregating multiple CO_2 sources and storage sites into clusters, economies of scale can be achieved, significantly reducing costs and risks. This is achieved through shared infrastructure and efforts in planning, transportation, storage, and regulatory compliance, making the investment in CCS more attractive [45]. Examples of such clustering efforts include projects like Rotterdam CCUS Porthos hub [46] in the Netherlands that aims to collect all CO_2 from Rotterdam and transport to North sea storage sites. Another example is Net Zero Teeside in the UK which is a collection of plants from industry, power and hydrogen [47]. A final example is the CarbonNet project in Australia which aims for clusters in Victoria State to the Pelican storage Site in the Bass Strait [48] [45].

The application of clustering in CCS projects not only aids in overcoming the economic challenges posed by high initial costs and operational risks but also plays a pivotal role in aligning CCS initiatives with broader economic, environmental, and strategic objectives [44].

3 Methodology

The method of the work is illustrated in Figure 3. This method involves using the input data, biogenic plants, nodes, CO_2 emissions, coordinates, transport options and economic functions, to calculate the cost of carbon capture for each plant based on amount of CO_2 captured.

The method begins with the data collection, then the node routes for each plant, the transportation between plants, cluster, port and sinks, are determined. These locations are the possible points to go via on the journey from plant to sink. The lowest-cost transport route inbetween these nodes is the final route of transport for each plant. When the most cost-effective route is determined, then the costs, including compression and liquefaction, are added to the cost of carbon capture and storage. The output is volume of CO_2, cost in total from plant to sink, transport route and mode. The plants are then sorted by increasing total cost and the cumulative amount of CO_2 is calculated and visualized in a MACC.

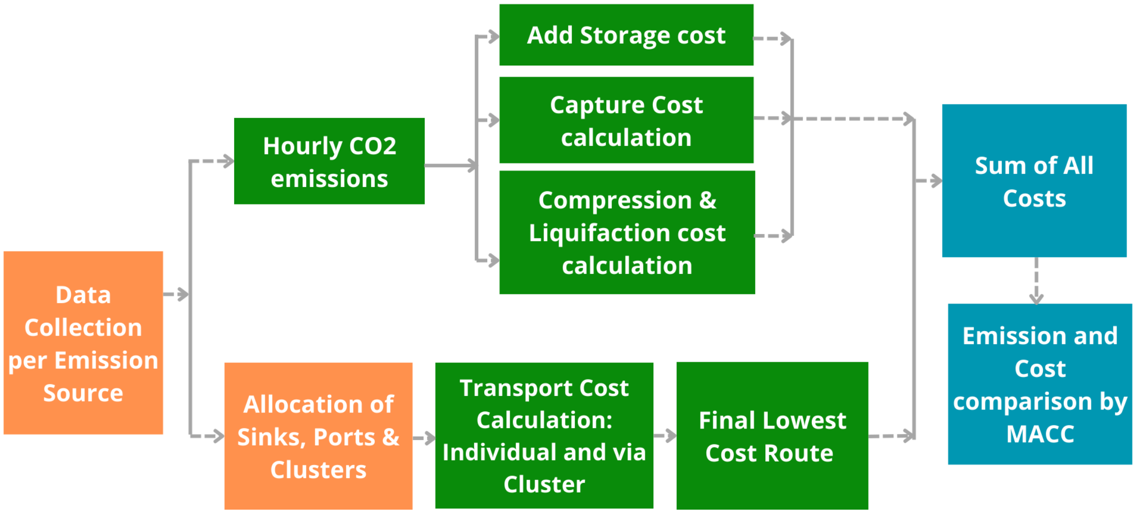


Figure 3: The methodology of producing a final cost comparison

3.1 Plant Database and biogenic emissions sources

The emission data for all countries is found in the European pollutant release and transfer register (E-PRTR) for 2022. The database is based on the EEA Industrial Reporting Database, which has been updated for 2022 [49]. In this work all countries in the European union are included, as well as Norway, Switzerland and the United Kingdom. Containing detailed data on energy input and emissions for large combustion plants, around 50,000 industrial facilities in the EU that contribute to air, water and soil pollution. In this work, the document 'F1_4Detailed releases at facility level with E-PRTR Sector and Annex | Activity detail into Air-xlsx' is used. To be included in this dataset plants must meet certain criteria. They need to fall under at least one of the 65 economic activities in Annex I to the regulation and exceed at least one of the E-PRTR capacity thresholds [50], for CO_2 the threshold is at 100 million kilograms per year [51]. Second, they need to release pollutants that exceed specific thresholds specified for air, water and land in Annex II to the regulation [50]. Finally, the plants must transfer waste off-site that exceed specific thresholds set out in Article 5 of the regulation [50]. The pollutant threshold for carbon dioxide is 0.1 Mt/yr according to the E-PRTR [51].

The thermal plants are classified as belonging to the 'Energy Sector' in the datasheet, and has the main activity label of 'Thermal power stations and other combustion installations' (1(c)). In total there are 162 plants with biogenic CO_2 emissions in this category, see Figure 4 for percentage comparison of spread between plant types.

The WtE energy plants are classified as 'Waste and wastewater management' and have the main activity label 'Installations for the incineration of non-hazardous waste in the scope of Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste' (5(a),5(b)). In total there are 308 plants in this category.

The pulp and paper plants are classified as 'Paper and wood production and processing' and have the main activity label 'Industrial plants for the production of pulp from timber or similar fibrous materials'(6(a),6(b)). There are 134 of these plants.

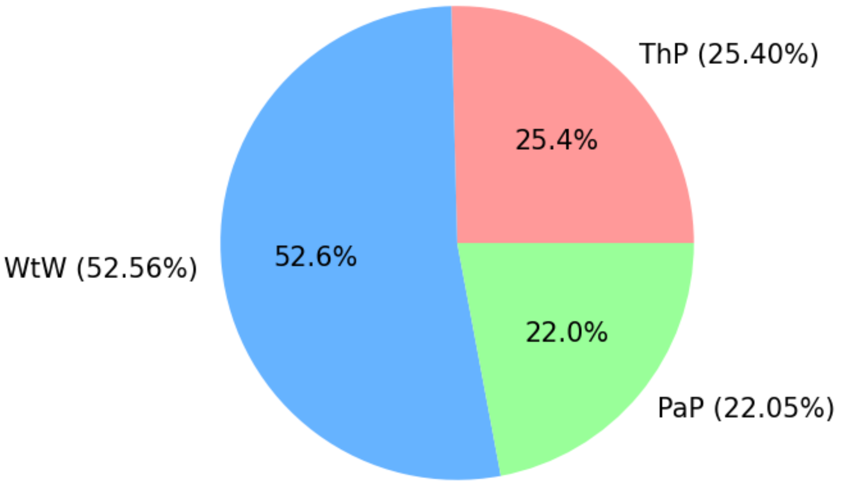


Figure 4: Distribution of plant types in percent, the amount of plants, not regarding size of emission

The CO_2 emission data is not complete for many of the plants. Although it is clear that some of the CO_2 emissions are from fossil and some are from biogenic sources, the division and exact numbers are missing, instead only the total amount of CO_2 emissions are provided by the E-PRTR. Assumption of WtE plants should be that there are about a 50-60 percentage rate of biogenic emissions of the total. For thermal co-firing plants, anywhere between 10 and 30 % will be biogenic. In the MACC modelling parts of this work, the total emissions (biogenic and fossil) have thus been included.

However, in estimating the potential for BECCS, the resulting graphs are modelled with the most conservative of potentials found above. For all thermal plants that co-fire, which are not 100 % biogenic, an assumption that 10 % of the CO_2 emissions are biogenic is made. For all waste plants the assumption of 50 % biogenic CO_2 emissions is made. This estimation of BECCS capabilities will reflect somewhat of the potential for the technology, whithout overly estimating the potential.

3.2 Capture cost

The same method for calculation as Gardarsdottir et al. 2018 [52], is implemented to calculate capture cost. In their own study, the method is assumed to be MEA PCC.

Flue gas flow and CO_2 concentration are considered in the evaluation. The CO_2-absorption process is divided into the absorber/stripper section and the compressor section. Oxygen and impurities in the flue gases, such as SOx and NOx, are not considered in the compressor. The stack and eventual units for treating or heating the flue gases prior to the stack are not included in the scope but assumed to be a part of the industrial facility. If the captured is to be transported by pipeline the CO_2 is compressed in a 4-stage compressor and consequently pumped to 110 bars for delivery to transport.

The cost estimates do not include piling, chemicals or any purchase of land, and do not cover any additional costs of secondary buildings. The possible heating utilities investments and costs relating are not included in the CAPEX. All utility costs are strictly considered as the costs associated with utility provided by external systems that generate an operating cost for the capture plant. The components in the absorber and stripper section are scaled against the flue gas volume flow for the appropriate flue gas CO_2 concentration, while the components in the compressor section are scaled against the flow of CO_2 captured. Equipment cost for CAPEX was estimated by Gardarsdottir using Aspen In-Plant modelling. All of the cost should be greater in 2024 compared to 2015 (cost data was taken from 2015 by Gardarsdottir) given rate of inflation during and after the Corona pandemic. The annual labor cost includes the annual salary of one plant engineer and six operators in 2018. The price of electricity is assumed to be in the upper range of the Platts-Pan-European Power Index 2016. The cost of steam is based on steam produced from a dedicated natural-gas CHP plant, as a part of the CO_2 capture facility 2015, while the cost of cooling water represents cooling with seawater. Even though a significant increase in costs are expected in the 2024 economy the original numbers are used, since the calculations are extremely thorough and the time required to redo them is not available in this work.

Load hours differs between plants based on the main activity, a mean value is implemented based on the EEA id for each plant type. For thermal plants the load hours are assumed as 7750 based on a paper by the European commission [53]. For WtE plants load hours are assumed as 8000 hours based on a paper by the Energy Information Administration (EIA) [54]. For pulp and paper mills load hours are assumed at 7481 hours based on a paper by the Confederation of European Paper Industries (CEPI) [54][55]. The CO_2 presence in the flue gas is assumed as 12 % for all plant types.

The initial step of calculations is to determine the amount of carbon that is captured per year. In eq. 1 it is calculated based on the CO_2 emission data per plant and multiplied with a boiler efficiency and the capture rate of tons per year. The flue gas flow per hour is then calculated by eq. 2 and the cost of the absorber and stripper part can be calculated by eq. 3. The cost of compression is calculated by eq. 4.

$$\text{CO}_2\text{ captured} = \text{Emissions} \cdot \eta_B \cdot \text{Capture rate} \qquad [t/yr] \tag{1}$$

$$\text{Flue gas flow} = \frac{2{,}000{,}000}{110} \cdot \frac{\text{CO}_2\text{captured}}{\eta_{RB}} \cdot \frac{1}{0.04} \qquad [m^3/\text{h}] \tag{2}$$

$$\text{Absorber+Stripper} = 4121.7 \cdot \text{Flue gas flow}^{0.6498} \qquad [M€] \tag{3}$$

$$\text{Compressor cost} = 7004.6 \cdot \text{CO}_2{}^{0.5243} \qquad [M€] \tag{4}$$

The specific CAPEX is calculated by dividing the sum of the costs of transformation, by the CO_2 emission captures in ton per year. The annuity factor in eq. 5, is based on the assumption of a 25 year lifespan of the plant, and is used when an annual CAPEX is calculated.

$$\text{Annuity factor} = \Sigma \frac{1}{(1+r)^n} \qquad [1/yr] \tag{5}$$

The Fixed cost is calculated by multiplying the annual CAPEX with maintenance cost and dividing by the annuity, adding the cost of labour and operators. The cost for capture is then the annual CAPEX, Fixed and Variable costs added together and divided by the amount of CO_2 captured to get the €/tCO_2, eq. 6.

$$\text{Total capture cost} = \frac{(\text{CAPEX} + \text{Fixed} + \text{Variable})}{CO_2 \text{ captured}} \qquad [€/t] \tag{6}$$

In calculating the cost of liquefaction, based on the Danish Energy Agency [42], an annuity factor based on a 50 year lifespan is calculated. The CAPEX of liquefaction is calculated by multiplying the investment cost with the CO_2 captured. OPEX by the sum of the electricity cost and the Fixed O&M multiplied by the amount of CO_2.

All initial inputs into the cost calculations are found in Table 2.

Parameter	Value	Unit
Capture Rate	90	%
CO_2 in flue gas concentration	12	%
Total electricity consumption compression and liquification	137	kWh/tCO_2
Investment in capture	1.33	M€/tCO_2/hr
Fixed O&M in capture	0.05	M€/tCO_2/hr
Lifetime plants	25	yrs
Annualized Maintenance Cost	4	% of investment cost
Operators	0.66	M€/a
Engineers/Labour	0.16	M€/a
MEA	2	M€/a
Cooling Water	3.2	€/tCO_2
Electricity cost	55	€/MWh
Cost of steam for capture	17	€/t

Table 2: Input Capture cost calculation

The cost of storage is unknown but to represent it in this work, it is assumed to be 50 €/tCO_2.

3.3 Transport network cost calculation

In determining a route to sink from each plant a decision logic following Figure 5 is followed. Where the first choice is to go from plant either straight to sink or port using a truck or pipeline, or to go to a cluster. In going to the cluster, all CO_2 emissions from plants to that cluster are combined and from the cluster a route going either to sink or port is chosen. If the route ever goes to port it will then go to the sink via ship or offshore pipeline.

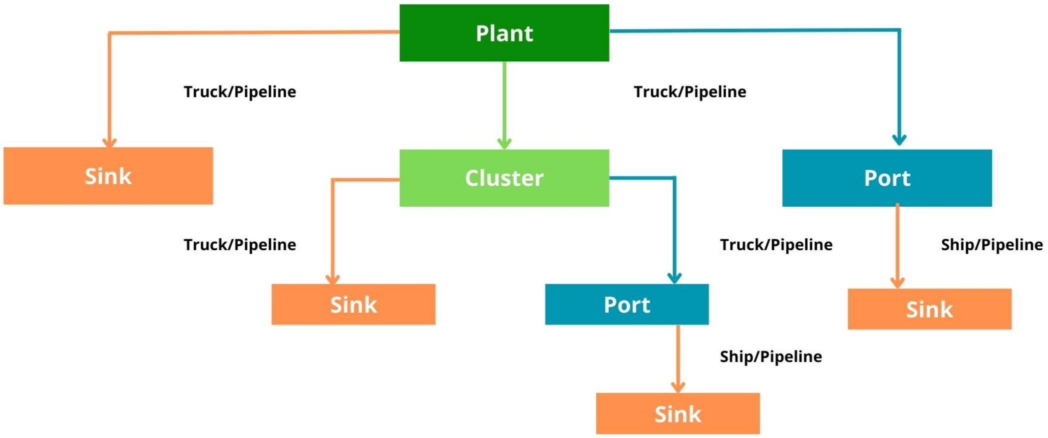


Figure 5: Decision logic for routes, the possible routes to take to go from a plant to a sink and by which transport method each route option could be taken

Upon determining the nearest node for each plant, optimal routes between plants and clusters are calculated, incorporating a 1.2 scaling factor to account for the curvature of actual travel paths versus direct linear routes. The algorithm assesses multiple transportation options, such as truck, pipeline, and ship, based on a series of logistical constraints such as minimum and maximum transport distances for each mode. This step involves cost calculation functions tailored to each mode, enabling a comparative analysis to identify the most cost-effective option for each segment of the route.

The output for the chosen transport mode and associated costs is determined for each cluster to compare the aggregate costs at the cluster level, where the combined CO_2 emissions from multiple plants are considered. This aggregation enables the exploitation of economies of scale, thereby reducing the per-ton cost of CO_2 transported. Summation of the entire route from plant to sink via cluster is then compared to the individual routes that could be taken from each plant. The evaluation extends to comparing the cost efficiencies between routes that utilize cluster aggregation versus those that do not, thus determining the most economical approach for each plant's CO_2 output.

The compression and liquefaction cost are summed up depending on route of transport. If there is a switch between pipeline and truck or ship there is a need for added cost of conditioning, which is added onto the initial preparation from the plant to pipeline or truck (compression pipeline, liquefaction for truck and ship).

3.3.1 Cluster and allocation calculation

This section includes analysis of the spatial distribution of bioenergy plants in relation to key infrastructure transportation nodes. First, cluster centers are identified by feeding in the plant position data from d'Amore et al. [56] for steel manufacturers, refineries, cement producers, and power plants with fossil origins, and adding the bioenergy plants provided from Rosa et al [13] and Chalmers power plant database. Using K-means clustering to decide on a set number of clusters and allocating each plant to a cluster. The number of clusters is decided by first feeding the data through a DB-scan clustering code which allocated outlier plants as noise and eliminated those clusters that are for a very small selection of plants, landing on a mean number of clusters at 30.

The assignment of the remaining infrastructure began with importing coordinate datasets for sinks (Clean air task force [40]), ports (Rosa et al. [13]), and cluster centers from the above results with coordinates for each location.

The purpose of the code is then to calculate the distance of each plant to the nearest node. This is achieved through the definition of a generic function that calculates the Euclidean distance between each plant and the entities of interest. The closest entity to each plant is determined. For sinks, additional information regarding their location (onshore/offshore) is appended. For visualisation of nodes in original scenario see Figure 6 and appendix 18 for other scenarios. Ports are depicted in blue (data from Rosa et al.), clusters indicated in purple, and the biogenic plants illustrated in green, with the size of dot indicating emission size (E-PRTR). Additionally, sinks represented in orange (Clean Energy Task Force) are depicted.

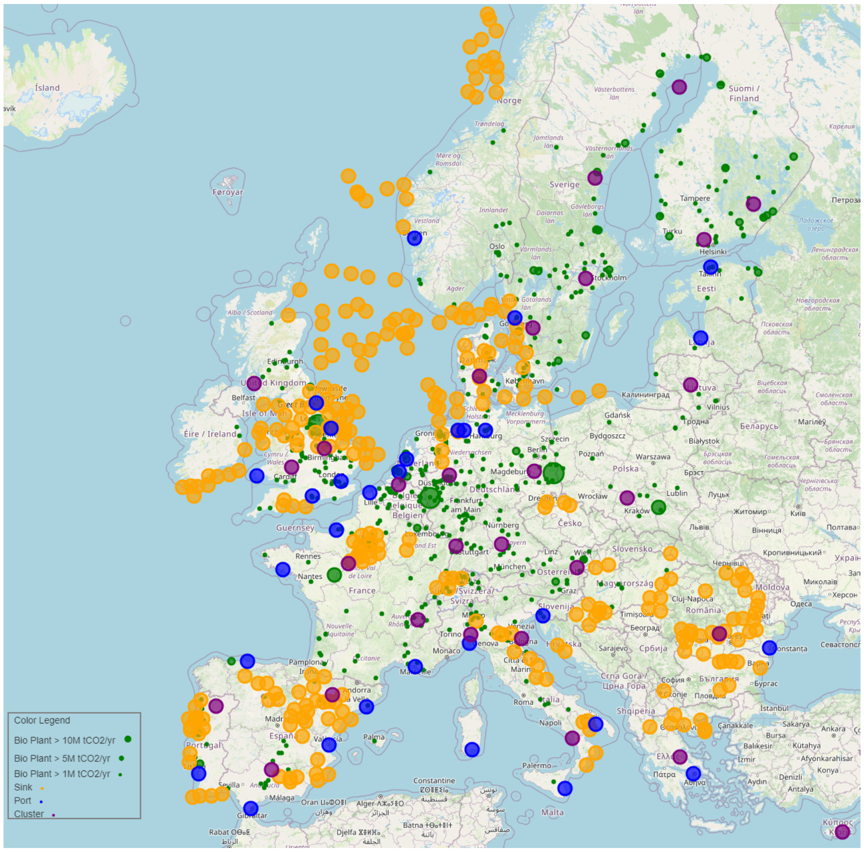


Figure 6: Visualisation of sinks, plants, ports and clusters based on the first dataset

3.3.2 Pipeline cost calculation

The calculation of pipeline cost hinges on several factors, including the pipeline's distance, its location (onshore or offshore), and the amount of CO_2 emissions it is designed to transport. The cost function that calculates the pipeline cost delineates into two main components:

CAPEX: This encompasses the upfront investment needed for the construction of the pipeline. It is determined by the pipeline's distance, the rate of CO_2 to be transported (converted from annual emissions to tons of CO_2 per hour), and a specific investment cost that varies depending on whether the pipeline is onshore or offshore. calculation are based on the investment costs of the Danish Energy Agencies report [41], see Table 3. To calculate the total CAPEX, a conversion of the annual emissions into a rate of tons of CO_2 per hour is done, which is multiplied by the unit cost and the pipeline distance. The CAPEX is annualized over the pipeline's technical lifetime to distribute the initial investment across its operational years.

OPEX: This includes the fixed operational and maintenance (O&M) costs, which are assumed to be constant per ton of CO_2 per hour per year, irrespective of the pipeline's location. The OPEX is calculated based on the pipeline distance and the amount of CO_2 captured. Variable O&M costs are considered negligible and are thus not included. The operational expenditure is obtained by multiplying the fixed O&M cost by the pipeline distance (converted to kilometers) and the CO_2 hourly rate.

The function will calculate the annual total cost of implementing and operating the pipeline, assuming that the pipeline operates continuously throughout the year at the given emissions rate.

Levelized Cost of CO_2 transport or any depreciation of CAPEX over time will not be considered directly. It is assumed that the pipeline operates at full capacity matching the emissions rate provided, without considering detailed capacity factors or efficiency losses.

$$\text{CAPEX}_{\text{pipeline}} = \text{Investment cost} \cdot CO_2 \text{ Captured} \cdot \text{Distance} \qquad [M€/yr] \tag{7}$$

$$\text{OPEX} = \text{Fixed O\&M cost} \cdot \text{Distance} \cdot CO_2 \text{ Captured} \qquad [M€/yr] \tag{8}$$

$$\text{Total Annual Cost} = \frac{\text{CAPEX}}{\text{Technical Lifetime}} + \text{OPEX} \qquad [M€/yr] \tag{9}$$

Description	Value	Unit
Technical lifetime	50	years
Construction time	1	years
Investment cost ON-shore dense phase	13	per 120 tCO_2/h [€/tCO_2/h/m]
Investment cos OFF-shore	33	per 120 tCO_2 [€/tCO_2/h/m]
Fixed O& M	20	[€/tCO_2/h/year/km]

Table 3: Pipeline costs [41]

3.3.3 Ship cost function

The specific transport cost associated with shipping CO_2 over a given distance is expressed in eq. 13. The calculation is designed to estimate the cost per ton of CO_2 transported using a ship, taking into account various operational CAPEX, and maintenance costs. The calculation is grounded in several constants and assumptions regarding the costs and operational parameters of the shipping process, see Table 4.

The ship and the CO_2 export terminal CAPEX are based on assumed values per ton of CO_2 capacity [41]. Fixed O&M costs are considered as a percentage of the total CAPEX. The cost of heavy fuel oil (HFO) per ton and the ship's daily energy demand are used to estimate the fuel expenses associated with the transportation process. The number of round trips per year are calculated based on the ship's capacity and the total annual volume of CO_2 to be transported. This estimation also considered the time required for loading, unloading, and round-trip travel. The total annual CAPEX costs for the ship and terminal are computed.

CAPEX: Studies indicate significant cost variation for ships based on CO_2 pressure conditions. For medium pressure, which is the industrial standard, CAPEX data is highly uncertain, see Table (4) for appreciations of costs based on The Danish Energy Agency[41]. Full CO_2 ship transport chain CAPEX also includes CO_2 terminals for export and receiving, with estimated costs for terminals designed for CO_2 at 15 bara and -27°C.

OPEX: Main OPEX components are ship fuel costs and ship operation and maintenance (O&M), with Fixed O&M typically estimated at 5% of CAPEX annually.

$$\text{CAPEX}_{\text{total}} = \text{CAPEX}_{\text{t}CO_2} \cdot \text{ship capacity} \qquad [M€] \tag{10}$$

$$\text{Fixed O\&M} = \text{CAPEX}_{\text{total}} \times \text{Fixed O\&M rate} \qquad [M€] \tag{11}$$

$$\text{Fuel cost} = \left(\frac{\text{Energy demand} \times \text{Fuel cost}}{1000} \right) \cdot 365 \cdot \text{Trips per year} \qquad [M€] \tag{12}$$

$$\text{Total annual cost} = \text{annual CAPEX} + \text{Fixed O\&M} + \text{Fuel cost} \qquad [M€] \tag{13}$$

Description	Value	Unit
Energy demand per day	90	kWh
Ship capacity	4000	tCO_2
Maximum Cycle time	24	hours
Technical lifetime	40	years
Construction time	2	years
Investment cost	9560	€/tCO_2
Fixed O& M	457	€/tCO_2/year
CAPEX Ship	1000	€/tCO_2
CAPEX Terminal	2500	€/tCO_2
Annual CAPEX rate	6	%
Fixed O& M rate	5	%
Fuel cost	270	€/MWh

Table 4: Ship cost data [41]

3.3.4 Truck cost function

The calculation of the truck cost takes two primary inputs: the distance of transportation in kilometers and the annual amount of CO_2 transported in tons. The function is designed to compute the annual cost of CO_2 transportation by truck based on these inputs, incorporating both fixed and variable cost components associated with CO_2 emissions.

Trucks are not an option for longer distances and a maximum distance of 500 km is selected where trucks are no longer an option.

$$\text{Total Cost} = \text{Fixed Cost} + (\text{Variable Cost} \cdot \text{Distance}) \qquad [\text{€}/tCO_2] \tag{14}$$

Description	Value	Unit
Energy demand	0.17	kWh/km/tCO_2
Technical lifetime	10	years
Construction time	0.5	years
Transport fixed cost	3.63	€/tCO_2
Variable cost per km	0.13	€/tCO_2/km

Table 5: Truck costs from Danish Energy Agency [42]

3.4 Scenarios

The original scenario is the base on which comparisons are made. It is with the clusters based on all of industry (not just bio-plants) as the scenario is meant to mimic the more real-world scenario of clustering. The ports are by ocean only, mimicking other works which all exclusively have ocean ports. The original scenarios use long-term sinks. The short-term sink scenario is more realistic the coming years, but as the work is looking at a scenario were all plants have installed CCS and is actively transporting and using the technology long-term sinks that seem more realistic.

There are several scenarios which are furthering the initial results and analysis. The first being the switch from the long-term sinks, to the short-term sinks. The process does not change from the one described above, but the allotment is simply done with the information of the short-term sinks instead of the original long term. In the short-term scenario, there are 10 sinks whereas in the long term there are 314.

In the added ports scenario ports along the larger rivers in the EU are added to the original port data as possible nodes, the new ports and their coordinates are from the EFIP. This scenario uses the same cost functions for the ship transportation as the original scenario, to reflect real-world cost a cost function for river-barges would have been preferable.

In trying to determine the importance of the cluster location to the transport cost, another cluster scenario is performed. These clusters are solely based on the biogenic plants that are contained in the work (from E-PRTR, excluding fossil sources as well as biogenic plants from Chalmers power plant database and Rosa et al). The same amount of clusters as in the first scenario is generated and all other data is the same as in the original scenario.

4 Results

In this chapter overall costs and calculation results for the scenarios are presented. MACCs are analyzed to identify trends and outliers. Additionally, MACCs are generated for each scenario to compare cost trends across different types of plants, and costs per country are examined, noting any discrepancies due to missing data.

4.1 Marginal abatement cost curves

In Figure 7 the MACCs for each scenario are plotted. The cost per ton of CO_2 captured, transported and stored is on the y-axis and the cumulative amount of CO_2 captured and stored on the x-axis. The amount of CO_2 is the total amount of emissions per plant, including the parts that are fossil in origin. The total potential is about 270 Mt of CO_2. The blue line is the original scenario with the long term sinks and ports only in the open sea. The red line is the added ports scenario, where ports are added along rivers in the EU. The green line is where short-term sinks are used instead of the long term ones. The yellow line is for the bio-cluster scenario.

Table 6 is the amounts of CO_2 included under a threshold cost, represented by the dashed line in Figure 7. The amount of plants included in every scenario is also included in the table. For example very few plants can capture, transport and store CO_2 under a limit of 150 €/tCO_2, for the bio-cluster scenario it would be 3 plants, with the cumulative emission of 25.2 MtCO_2.

For Figure 7 a cut-off at 900 €/tCO_2 is placed, more plants are included in the raw data but these are outliers with very large costs that make the plots less readable. In total 605 plants are included in the dataset and 586 are plotted. The plants excluded all have emission magnitudes on the smaller side or a long distance to travel and are thus above the threshold off 900 €/tCO_2. All scenarios have the same capture and storage cost for individual plants, the differences lie in transport and compression and liquefaction costs.

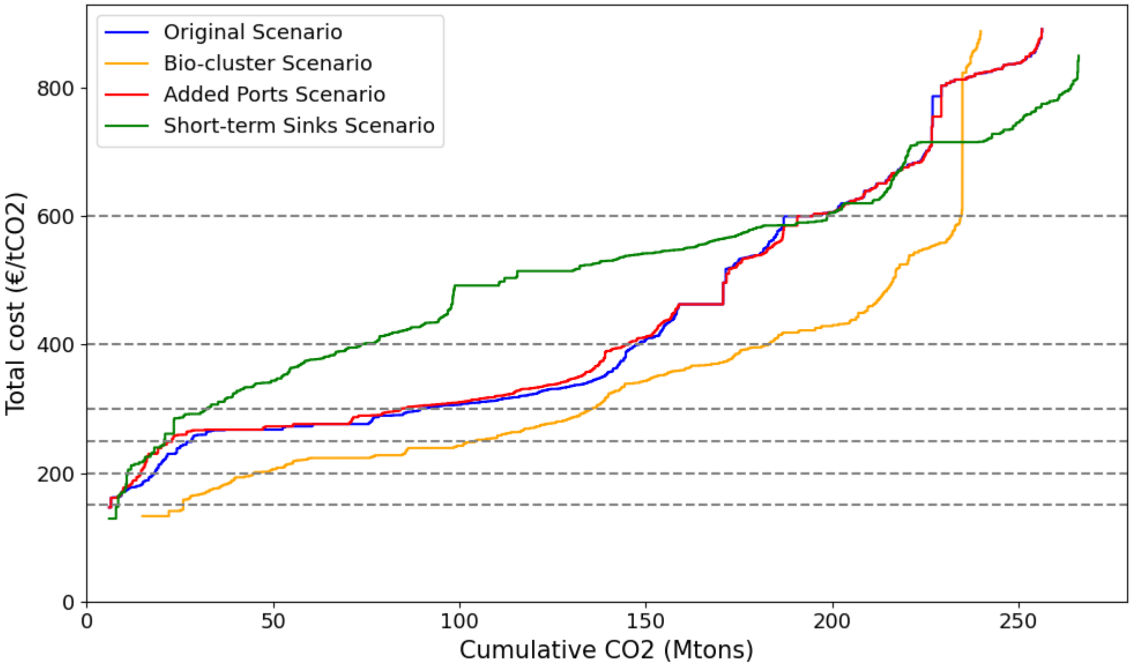


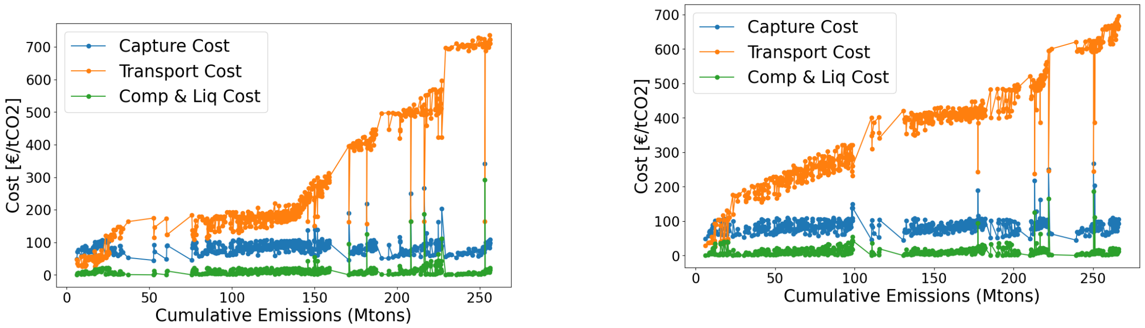
Figure 7: Total cost comparison of original scenario, added ports scenario, bio-cluster scenario and short-term sink scenario plotted against the cumulative emissions for the plants. The amount of CO_2 is the total amount of emissions per plant, including the parts that are fossil in origin

Threshold	**Original Scenario**		**Bio-clusters**		**Short-term Sinks**		**Added Ports**	
	MtCO_2	Plants	MtCO_2	Plants	MtCO_2	Plants	MtCO_2	Plants
150	6.1	1	25.2	3	7.9	2	6.1	1
200	18.1	30	44.9	55	10.8	8	14.4	21
250	27.0	72	104.2	137	20.4	33	21.8	52
300	89.5	125	135.5	241	31.8	45	84.2	105
400	147.2	340	182.2	378	73.4	260	144.4	323
600	190.5	440	234.5	519	198.5	449	190.7	441

Table 6: Amount of captured CO_2 below each cost threshold and the number of plants included of the dataset. The amount of CO_2 is the total amount of emissions per plant, including the parts that are fossil in origin

The bio-cluster scenario has a much larger amount of CO_2 included for each threshold, as well as number of plants, especially for 250 €/tCO_2. The short-term sink scenario is significantly smaller in emissions captured at the 300 €/tCO_2 cost level compared to the other three scenarios, this is because most plants are more expensive than 300€/tCO_2, see Appendix 27, so only 45 of the plants for the short-term scenario are included at this stage. As the cost increase the scenarios converge in both captured CO_2 and plants below the threshold cost. For the short-term sink scenario the line drawn at 600 €/tCO_2 shows that when more plants are included in this scenario it is somewhat more cost effective than the original and port scenario.

The original scenario MACC, plotted as the blue line in Figure 7, has an initial value furthest to the lower left, that represents a plant at 146 €/tCO_2. The overall explanation of cost increase can be found by referencing Figure 8, where cost of capture, transport and compression and liquefaction are compared. Until about 150 Mt the cost distribution in the figure is quite even, then the transport cost drastically increases. The increase in transport cost is attributed to distance from sink, meaning that the transport over longer distances increase the costs. Since the transport method is similar for all plants in the same scenarios, the distance and emission level are the aspects which will determine costs the most. Other higher costs are attributed to smaller amounts of CO_2 captured. As shown in Table 6 and Appendix 27, most plants in the original scenario are in the range of 300 €/tCO_2.



a) Cost distribution original scenario

b) Cost distribution short-term sinks scenario

Figure 8: Cost trend comparisons original and short-term sink secnario. The amount of CO_2 is the total amount of emissions per plant, including the parts that are fossil in origin

The total capture cost of the bio-cluster scenario starts at 132 €/tCO_2, as per Figure 7. It is the most cost-effective scenario until about 700 €/tCO_2. With the lowest incline starting at highest cumulative emission. The cost effectiveness compared to other scenarios is due to lower transport cost based on more ideal cluster positions for the specific plants involved. The overall trend is quite similar to the added ports and original scenarios. The bio-cluster scenario does cross over the other scenarios between 600 to 800 €/tCO_2. The trend is mainly because of six plants that drastically increase in cost, making the almost straight vertical line that can be observed in Figure 7. For these plants, the transport cost is between 100 and 400 €/tCO_2. Looking at the cost trend comparison for the bio-cluster scenario, pictured in appendix, the transport cost does not increase so drastically, compared to the other costs in the same way as the original cluster scenario, but the trend of transport costs increasing does start at approximately 150 Mt again. In the amount of plants in each cost range, illustrated in Appendix 26, plants are much more evenly distributed between 140 and 600 €/tCO_2.

The added ports scenario follows the original scenario closely in Figure 7, and in the cost distribution and plant distribution. The cost does increase above the blue line in the original MACC, and decrease below the blue line sometimes, but the same plants create plateaus in the same places. The small cost differences are due to the port chosen being more or less cost effective in comparison to the original scenario. In fact, only three clusters go via a port for both scenarios and the difference in route is then only applivable to the plants which are assigned to those clusters.

In the short-term sinks scenario, see appendix 21 for node placement, the distance increases to most sinks as there are a lot fewer to choose from. The curve starts at 128 €/tCO_2 and then increases with the original scenario until about 260 €/tCO_2 where it starts to delineate with a cost increase from 261 to 292 €/tCO_2, an increases much more drastic than the other scenarios. Looking at Figure 8 the transport cost for this scenario increases immediately and the difference is entirely due to the increased distance. The overall cost trend does dip below the others at approximately 600 €/tCO_2, because most plants are in this size, see Appendix 29 and Table 6.

The capture costs are consistent across all scenarios. Examination of data reveals that none of the facilities that are most cost effective in capture emerge as the most cost-effective overall. This observation is predominantly driven by the costs of transportation. The distribution of transport costs over total cost of capture and storage is illustrated in Figure 9, for the original scenario. The distribution with the highest peaks are between 60 and 80 % which shows that the transportation severely affect the outcome of the total cost and cost trends. There are also some outliers in the data, where transport costs are extremely high.

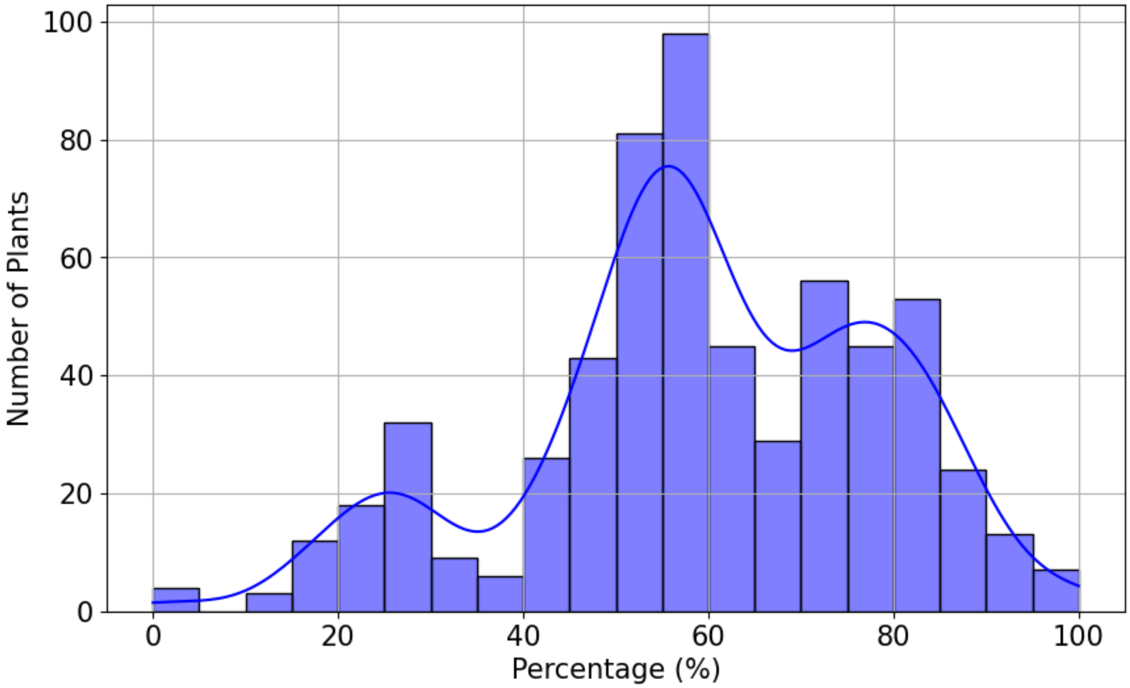


Figure 9: Distribution of percentage of total cost by transport, histogram with trendline

Going further into the cost of transportation, the cost from plant to cluster is at a mean about 14 % of the total cost of transport. The rest is the transport cost from cluster to plant. The main reason for the lower cost is that the distance from plant to cluster is quite small for most plants (almost every route is under 500 km and is taken by truck, see distribution in Appendix 30).

4.2 Cost of cluster-to-sink transportation

If the route goes via a cluster, then the captured CO_2 per plant is combined between plants and transported as one mass, applying the principle of economies of scale, as larger amounts of CO_2 transported can make the per tonne cost less. The option to go via a cluster in the route logic is taken by all plants in this work. The economies of scale does then seem to be most favorable.

In Figure 10 the transport modes from cluster to sink per scenario are illustrated. The original scenario and added ports scenario are identical both with the biggest share of going via a port to the sink, and only the original scenario is shown in the Figure 10. The short-term sink scenario has the biggest share per truck but is otherwise similar to the bio-cluster scenario.

Pipeline is the dominant transport method from cluster, this is mainly due to the economies of scale with the combined amount of CO_2 from each plant, pipelines become most cost effective. The original and added ports scenario have the same distribution. None of the transport is by truck to port and then ship, but there are two clusters in the original scenario which go with a pipeline to a port. The short-term sink and bio cluster scenario have some clusters that go to a sink with a truck. In the bio-cluster scenario this is due to the closeness of the cluster to a sink.

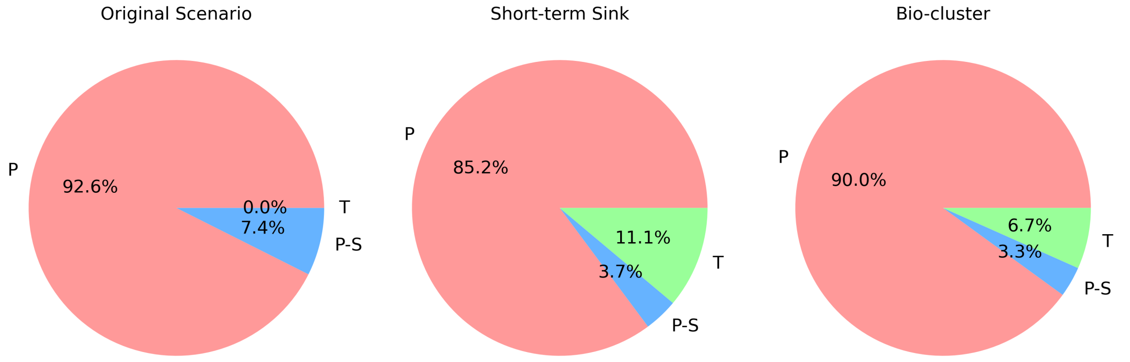


Figure 10: Distribution of transport modes per cluster per bio-cluster, original scenario and short-term sinks scenario. Transport modes are illustrated by letters, P that stands for pipeline, T for truck, P-S for pipeline then ship

Going more in depth into the cluster transportation calculations for each scenario, the original scenario has two clusters that go via a port and not directly to sink from cluster. Cluster 19 and 21 both go via pipeline to a port and from there go by ship. The cluster with most plants are number 30 with 45 plants that together have 21.5 GtCO_2/yr with a cost of 153 €/tCO_2. Other bigger clusters are number 13 with 55 plants, 35 MtCO_2 at 160 €/tCO_2 and cluster number 16 with 43 plants, 129 MtCO_2

at 97 €/tCO_2.

The ports scenario differs quite a bit from the original scenario when looking at specific clusters even though the transport method entirely matches, but in this scenario it is cluster 20, 22 and 26 that go via a port instead of directly to a sinks, they all go via pipeline and then ship. The lowest transport cost is still cluster 8, it costs 19 €/tCO_2 with 5 MtCO_2, and 22 plants included in this cluster. The highest costing cluster is number 4 that costs 691 €/tCO_2 and 11.9 MtCO_2, only 5 plants are included. The clusters with most plants assigned to them are cluster 13 that has 55 plants, 229 €/tCO_2 and 35.5 MtCO_2, cluster 16 that has 43 plants, 110 €/tCO_2 and 5.75 MtCO_2 and cluster 30 that has 45 plants, 153 €/tCO_2 and 9.8 MtCO_2.

The short-term sink scenario has cluster 8, 13 and 17 all go via a port to the sink, again all going with pipeline-ship. Cluster number 2 has cheapest transport cost of 14.8 €/tCO_2, with 24 plants an a combined emission of 12.7 MtCO_2. The most expensive cluster is number 1 with 605 €/tCO_2, 24 plants and 23.4 MtCO_2. The cluster with the most plants are cluster 13 that has 55 plants, 397 €/tCO_2 and 53.1 MtCO_2, cluster number 16 has 43 plants, 192 €/tCO_2 and 12.9 MtCO_2, and cluster number 30 that has 45 plants, 380 €/tCO_2 and 9.8 MtCO_2.

The bio-cluster scenario only has two clusters that go via a port to the sink, both by pipeline then ship. Cluster number 3 that cost 309 €/tCO_2 and has 25.4 MtCO_2 and cluster number 28 that costs 1052 €/tCO_2 and has 41.8 MtCO_2. The cheapest cluster is number 9 with 20.8 €/tCO_2, with 20 plants in total and 48.1 MtCO_2. The most expensive is cluster 10 1165 €/tCO_2 with 8 plants and 4.9 MtCO_2. The clusters with most plants allocated to them are cluster 3 that has 40 plants, cluster 13 has 47 plants, 147 €/tCO_2 and 19.4 MtCO_2 and cluster 15 that has 36 plants, 21.5 €/tCO_2 and 31.2 MtCO_2.

The cost from cluster to sink is illustrated in Figure 11. The original and added port scenario are very similar and the short-term scenario is only slightly more costly. The bio-cluster scenario a little bit less so. Thus, the transport to cluster is a quite large contributor to the transport cost differences between scenarios. The transport mode to cluster from each individual plant are very similar, the bio-cluster scenario does have fewer transport routes via trucks.

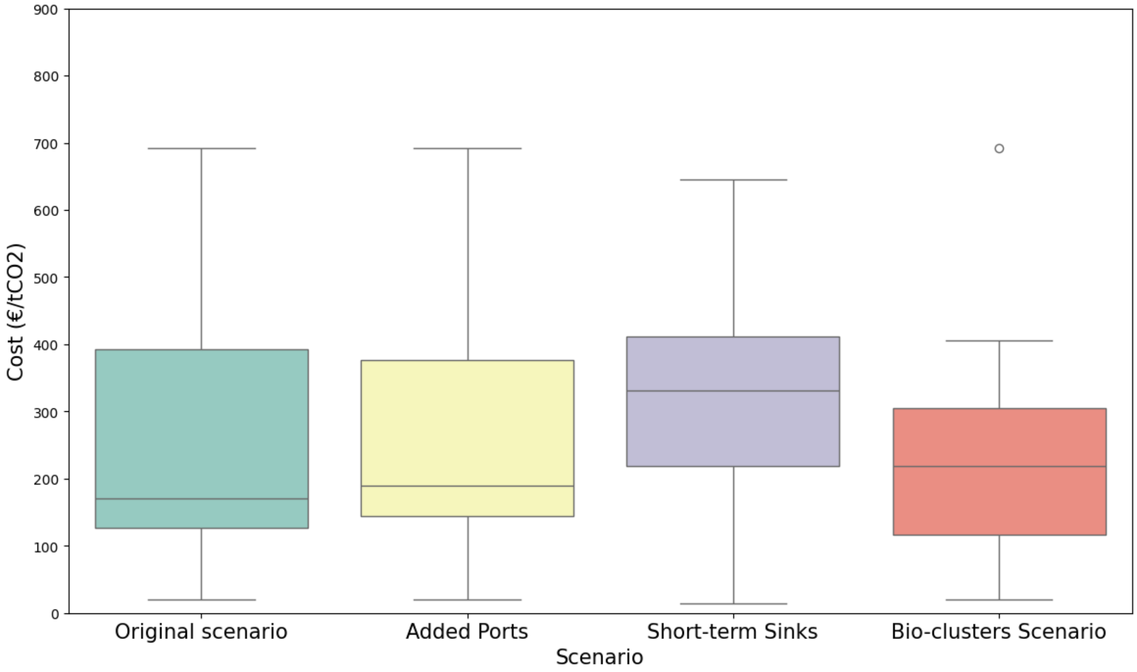


Figure 11: Box chart over cost of transportation per cluster per scenario

4.3 Country-specific MAC curves

When comparing specific nations in the original scenario in relation to one another, see Figure 12, some countries are excluded as they have very few plants and very few trends can be gleaned from them, there is also a cut-off at 900 €/tCO_2 that some countries exceed which is not plotted. In Figure 12 the overall emissions for the biogenic plants are plotted, including the fossil origin CO_2.

Much larger cumulative emissions in Germany are noted, this can mainly be contributed to a few very large thermal plants in similar cost range of about 250 to 350 €/tCO_2. Large individual plants are more easily identified in the horizontal lines in this curve, for example the UK thermal plant Drax is the line beginning at 5 Mt and ending at about 17 Mt, with the increase in cost from about 240 to 450 €/tCO_2.

Finland and Sweden have the most incline plotted, meaning their costs rise the highest the quickest, in the range that is plotted. They exhibit very similar trends with Sweden having a larger cumulative emission at the same cost. The trend similarities may be because of the similar plant portfolios with large biogenic emission sources between Sweden and Finland and similar distances to sinks. Norway and Denmark have high costs immediately with smaller CO_2 amounts, this is attributed to few biogenic plants overall.

In the short-term sinks scenario France had 22 out of the 30 most cost effective plants. This is almost entirely due to small transport costs, and it can be deduced that their proximity to one of the few sinks in this scenario is the cause of this. In the original scenario the span between countries in the top 30 plants is divided between Germany, the UK and France. These are the three countries that are most cost effective in the beginning according to the Figure 12. With Sweden crossing over France and Germany briefly.

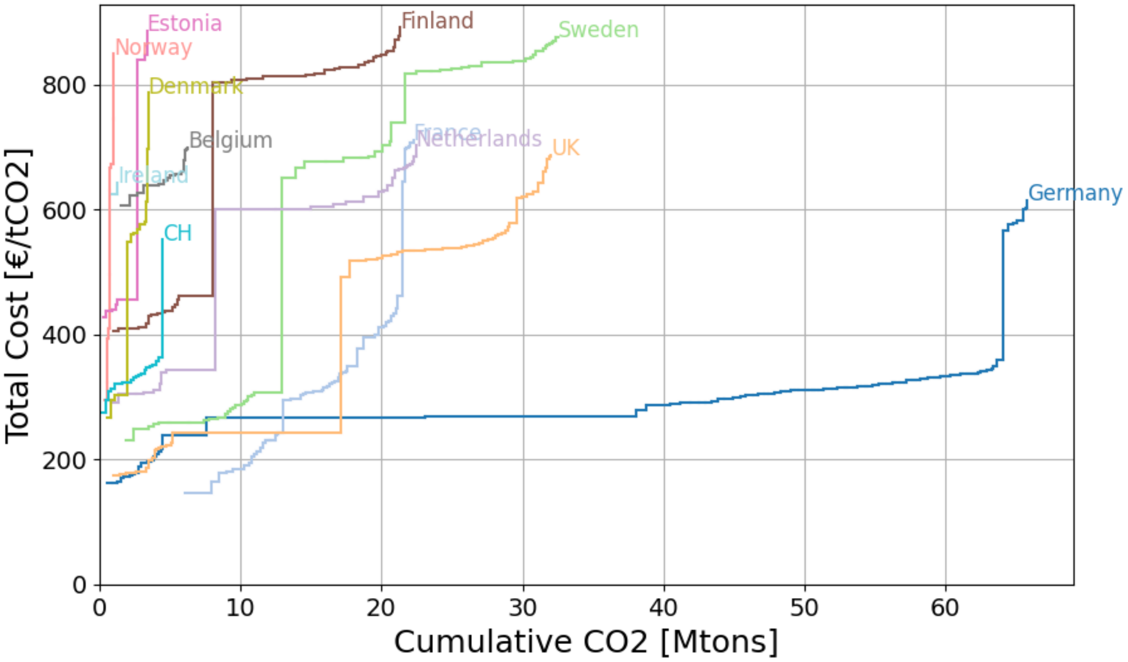


Figure 12: Country specific MACCS for countries with a total capture cost over 400 €/tCO_2. The amount of CO_2 is the total amount of emissions per plant, including the parts that are fossil in origin

4.4 Sector-specific MAC curves

Having split up the emission source to type of plant, significant changes can be more easily located in the trends plotted.

Referring to Figure 13, the different types of plants are plotted against each other in the original scenario. The pulp and paper and the waste plants have similar curve tendencies, but overall more emissions can be captured for a lower cost of the waste plants compared.

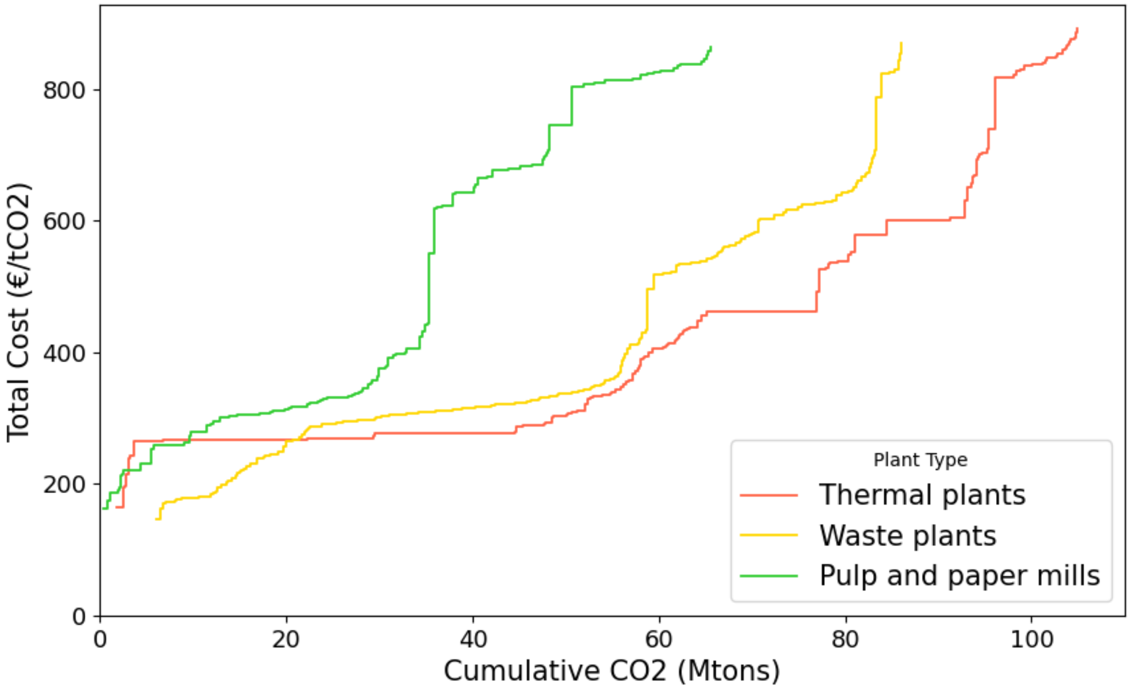


Figure 13: Total Cost of CO_2 Capture by Plant Type vs. Cumulative CO_2

Looking at Figure 14, that plots the amount of plants against the emission spread across differing plant sorts, the thermal plants specifically have many large plants that are not in the plot. However, most of the plants are in the smaller emission scale.

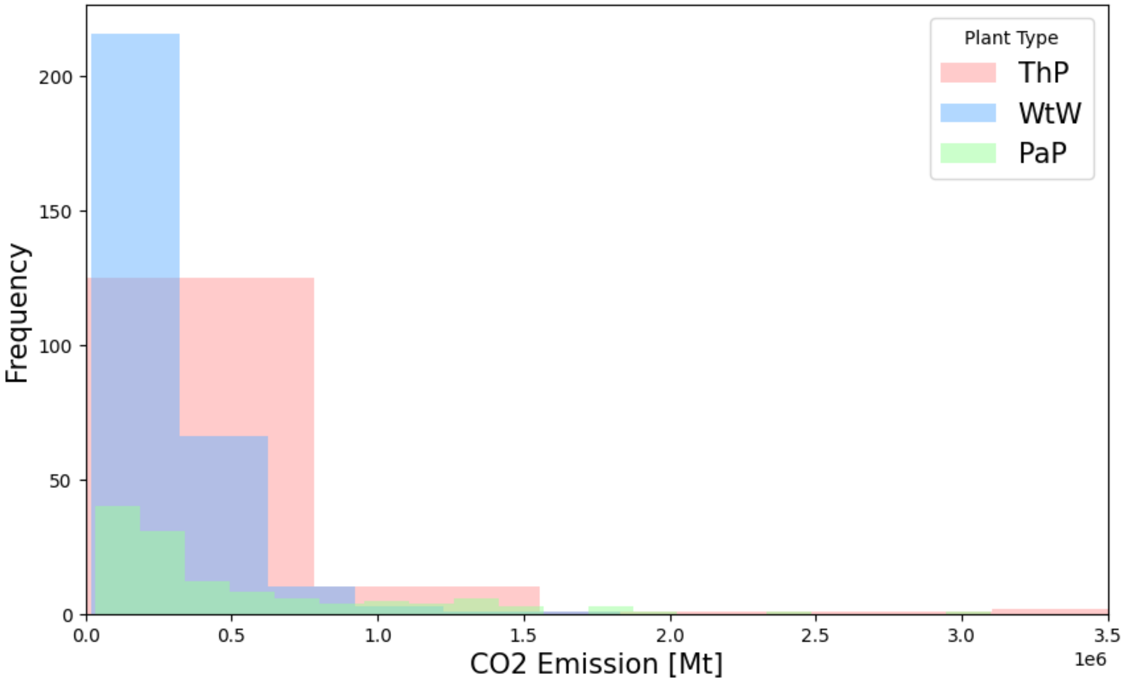


Figure 14: Histogram over emission per plant and plant type

It is important to reiterate that the CO_2 captured is not entirely biogenic, and that for the thermal plants the biogenic CO_2 is a fraction of the total (between 10 and 30 %). So, even though the thermal plants seem to be most cost effective according to Figure 13 the cumulative emissions would be much smaller if only the biogenic CO_2 was represented. This is true for the WtE plants but to a smaller extent (about 50 to 60 %). The pulp and paper mills are most likely quite true to form in showing biogenic CO_2 capture costs, even though some pulp mills do use fossil energy sources. The pulp and paper has most potential for BECCS in comparing plant types.

Most plants are waste plants, see Figure 4, for spread percentage wise. But most of those plants are on the smaller emission scale and very few are over 0.5 Mt. There are fewer pulp and paper plants overall, see distribution in Figure 14, the emissions for these plant are overall smaller, but there are a few bigger ones.

The appreciation of biogenic emissions is the most conservative scenario, where all thermal plants which are not known to be entirely biogenic are assumed to have a biogenic CO_2 constitution of 10 %. All waste plants are appreciated to have and biogenic CO_2 part of 50 %. In making these assumptions the biogenic emissions per country are illustrated in Figure 15.

Sweden here has the largest amount of biogenic emissions and thus has the highest potential for sequestration of biogenic CO_2 via BECCS. This is largely due to the amount of pulp and paper production. The UK, which is second in magnitude is so largely beacuse of the singular biogenic emissions of about 11.8 Mt from the Drax plant.

Germany's large industrial base, heavily reliant on thermal and waste plants, is by far the largest GHG emitter. Heavily due to the countries energy transition strategy, which includes phasing out nuclear power and temporarily increasing fossil fuel use. Despite high total emissions due to advanced and high-capacity plants, Germany does have high comparative biogenic emissions, the third in the Figure 15. Because of the assumptions made the countries with large emission sources from thermal plants which are not entirely biogenic, such as Germany, are placed lower in the magnitude scale then they would have been otherwise. If the assumptions were on the higher end, with 30 % of emissions being biogenic for thermal plants, then Germany would most likely have the projected highest potential for BECCS.

For France, no one source is entirely the cause of the quite high biogenic emissions, rather, the biogenic emissions originate from many smaller plants.The Netherlands have a lot of thermal plants which generate substantial fossil CO_2 emissions. Consequently, these nations, as well as Germany, must capture significant volumes of fossil CO_2 to achieve biogenic CDR through BECCS. This approach can substantially mitigate CO_2 emissions, however, it also entails the drawback of potentially necessitating the transport of vast amounts of CO_2, while not achieving proportionately large volumes of biogenic CDR.

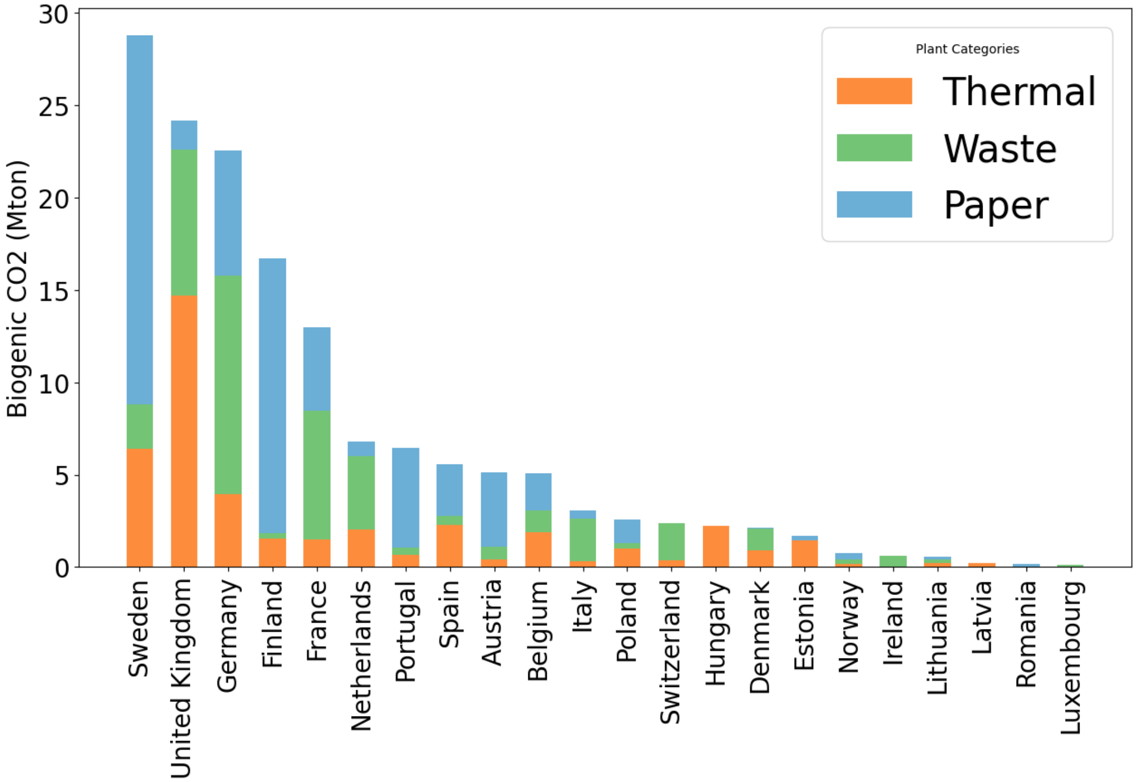


Figure 15: Total CO_2 emissions by country and thermal, WtE and pulp mills

There are some discrepancies in the data when comparing to the appreciation made by Rosa et al [13]. Mainly some countries are quite below what was appreciated by them, for example Finland is short of 25 Mt biogenic CO_2 and Estonia is not close to 10 Mt. The discrepancies in emission data may be attributable to the filters applied to the E-PRTR data (the three rules applied by the agency itself, the activity labels and activity codes picked out in this work). But the main contributor is the simplifications made to appreciate the biogenic emissions for plants where the emissions are not 100 % biogenic from the start.

The cumulative national emissions of GHG are depicted in Figure 16, as reported by [57], with the green part of each bar being the possibility of coverage of those emissions by capture and storage of the biomass emissions calculated in this work. Notably, the nations with the highest emissions do not necessarily align with those demonstrating the greatest capacity for carbon capture. For instance, Sweden is identified as a country where GHG emissions are considerably lower than others, but a large part of those emissions can potentially be offset by BECCS. From the countries covered in this work Sweden and Finland have significant capability in this area, reaching above the 25 % coverage of GHG by CDRs proposed by Möllersten et al (Sweden 47.5 % and Finland 30.5 %). [1] . This result coincides with the one produced by Rosa et al [13].

In the next order of magnitude is Portugal and Estonia that cover 10.8 % and 12 % each. After these countries the potential coverage of GHG emissions by BECCS per country is a lot smaller in magnitude (1-2 %). These other European countries do not have the potential for domestic BECCS to cover a large enough portion of the CDR quotas. They would thus need to resort to other CDR technologies, or outsource net-negativity points to other countries. For Sweden, Finland and Estonia the reason for the greater potential for BECCS is the pulp and paper production, these nations are the leading producers in Europe. For Estonia it is the combination of thermal co-firing plants and quite small GHG emissions to begin with.

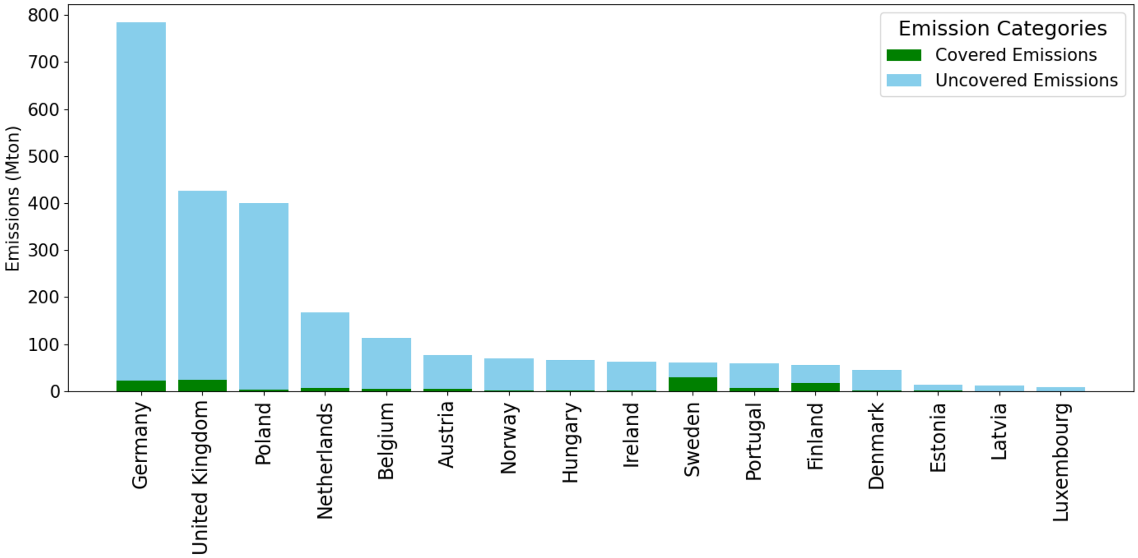


Figure 16: GHG emissions 2022 with potential coverage

5 Discussion

This chapter explores the implications of the findings presented in the results section, examining the economic and technical viability of BECCS.

5.1 Costs complications and estimations

Even though no major technological barriers exist for the implementation of CCS, there will be no real world implementation of CCS technology before it becomes economically feasible.

As implementing post-combustion CCS will decrease, the electrical efficiency of a power plant by up to 14 % [9], demand large amounts of energy to drive the capture process (electricity production cost would increase between 30-70% [9]) and space, the prospect of CCS will need to be the better option economically over emitting CO_2 and paying a CO_2 tax/price.

There will be no market for BECCS until the market potential and standards for carbon trading are more certain [5], [31]. The European Union has thus far given insufficient incentives for large scale implementation [58]. BECCS are not included in Article 7 of the ESR or in the ETS [59], and are thus not included in the legal framework established for fossil fuel based CCS. Since BECCS requires large-scale units, policies must be constructed to deal with them specifically, described by among others by Zetterberg et al [58].

Unforeseen costs could also be added to those already projected. The possibility of royalty payments for CO_2 storage, similar to those for oil and gas extraction, could impact storage costs, especially in contexts with a carbon price or storage tax credit [60]. CO_2 storage costs typically decrease as the scale of a storage projected increases. Since 2017, investment plans for several potential CCS hubs have been announced in the United States, China, and Europe, indicating a growing focus on developing shared CO_2 infrastructure.

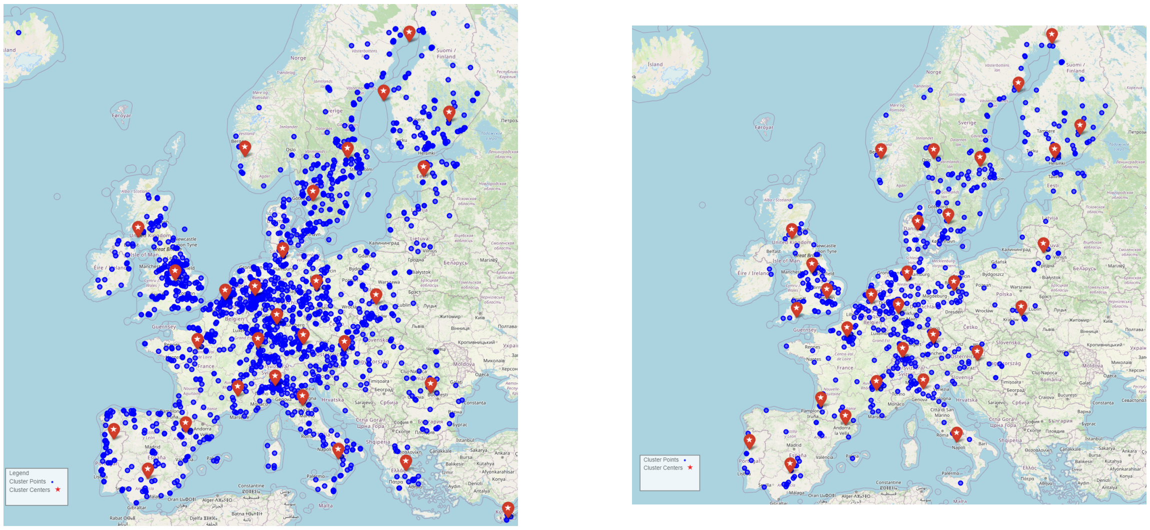
Inspecting Figure 9, the transport cost is at a mean about 60 % of the total cost. The compression/liquefaction mean cost is about 6 % of the total cost. The technology in use for transport as well as the geographical considerations which heavily influence the specific cost of transport are then responsible for two thirds of the costs. The infrastructure for pipelines, and other transportation methods could make a huge dent in the cost if re-purposing of natural gas pipelines could be done.

5.2 Other cluster scenario

In the original scenario, 30 clusters are generated across Europe, with central Europe having a higher density of plants per cluster. Outlier plants affect the clustering by moving clusters closer to themselves. In the bio-cluster scenario, clusters are derived from bio-plants used in the study, making them representative of the exact bio-plants used, but not necessarily of the broader industry. This scenario excludes fossil fuel-based industries, potentially limiting its real-world relevance.

Comparing the two scenarios, the original has more concentrated clusters in central Europe and more outliers, while the bio-cluster scenario has more evenly distributed clusters, particularly in Sweden and Finland. In the bio-cluster scenario, all clusters have allocated plants, unlike the original where some clusters are sparsely populated or redundant. Costs and emissions are more evenly spread in the bio-cluster scenario, and trucks are used effectively for transport within 500 km. In contrast, the original scenario does not find truck transport cost-effective.

In Figure 17, the bio-cluster scenario is plotted next to the original one. The cluster scenario with bio-clusters gives a markedly more cost effective result, see Figure 7, that is to be excepted, as the clusters are optimally placed to these specific plants. But these clusters will not be optimal to the overall industry, as all types of plants should be included to make an overall best infrastructure for industry as a whole. Even though the bio-clusters are more cost effective, as they are specifically designed for these plants, they should not be used as a marker, and the original cluster scenario is a better indicator on where clusters may be located in Europe.



a) 30 clusters generated from over a thousand plants (biogenic and fossil)

b) Clusters based on bio plants included in the study

Figure 17: Comparison of cluster distribution across Europe for differing scenarios

5.3 Problematics with BECCS based on other works

As previously delved into by Yue et al [14], the more scenarios delved into, the more ”flip-flop” and MACC uncertainty is established. There are however several scenarios that would be of interest for further cost analysis. More in depth analysis of port scenarios, where river barges were used for the cost comparison, instead of cost calculations with regular ships. In the scenario added to the results portion of the report, the EFIP ports were added, but the same cost model for ships operating in the ocean was applied, rather than one more appropriate for the specific conditions of transport via the more shallow European rivers. Other scenarios with more insight into the cost dynamics would be the comparison of the cost of implementing BECCS to offset fossil CO_2 to investing in totally renewable energy sources, to reduce fossil CO_2 produced overall. Large-scale deployment of BECCS will present socio-political and economic challenges, and it will be essential to avoid adverse effects on other sustainable development goals. Reliance on NETs in climate stabilization scenarios might detract from immediate, deep mitigation efforts by other renewable sources.

As biomass is not allowed to contend with food production there is limited space for increasing the amount in circulation. If the 2020 bioenergy crop yields are to go by, then that amount will not suffice for achieving net-negative emissions by BECCS. According to Hanssen et al. [7], improving agricultural yields globally is crucial if BECCS are to be made an important part of NETs intended to stay the global temperature increase. One way to achieve a higher yield could be investment into more efficient agriculture. If yields intensity improves, land used for conventional farming could be repurposed for biomass.

5.4 Uncertainty in method and data

There are several ways in which results could be enhanced in there level of detail, and ways to build upon the method and resulting outcomes to build a more comprehensive base for analysis.
It is important to note that several simplifications have been made in the course of this work. If a further analysis is to be made it would be advisable to problematize some of these aspects further.

The load hours calculated in Chapter 3.1 are very generic for each plant type. By changing the expectations of operating hours all cost aspects, excepting storage, are affected. Changing the operation hours for just one plant, to see if the difference was great in magnitude, the fact was that the cost only changed between 3 to 10 €/tCO_2, between 6500 and 8000 hours. This was only the findings for one specific plant however and could be different if done for all.

The fact that storage costs are universally represented by a value (50 €/tCO_2) is also an aspect that can be improved, even though it is very hard to know or foretell any type of cost of storage as of today. The existence of several chimneys at a site could also be accounted for in the capture cost estimation.

In transport costs more pipeline aspects could be taken into account, as well as leveling and pumping stations. The lack of a commercial market for CO_2 transport by ship adds considerable uncertainty to cost estimates. Most studies base their findings on Liquefied petroleum gas and similar gas carriers, which might not fully encapsulate the nuances of CO_2 transport.

6 Conclusion

Of the plants included in the dataset 586 out of 605 have a theoretical cost in the same cost spectra, where implementation of BECCS seems cost feasible. The high costs for those excluded are mostly due to small emissions (leading to high capture costs) or locations very far from any cluster or sink, making for high transport costs. The total CO_2 emission potential, including both fossil and biogenic origins, for Europe is about 270 Mt of CO_2

The total cost span is between 110 and 900 €/tCO_2. The transport cost is on average about 60 % of the total cost, it is mostly between 150 and 400 €/tCO_2, and only 14 % on average are the transport from plant to cluster. Transport costs are highly dependent on distance and transport modes. Looking at the bio-cluster scenario the result indicated that the cluster positions are very important for overall cost of transport. Analyzing the overall cost data trends the fact is also that the cost of transport is in this work identified as one of the most important factors for overall cost of implementing CCS, on average about 60 % of the total cost. In contrast to the bio-cluster scenario the indication of the added ports scenario is that port location is not of great import for transport cost. Mainly because few routes actually go via a port, only two clusters in the original scenario, it is seldom the most cost effective option. There is often extra distance added to the route by going via a port, and when the mode of transport most likely to be most cost effective is pipeline, to go straight to sink is best, unless the distance is very long to the closest sink.

For a route going from a plant to a cluster the most cost effective transport option will most likely be a truck. From a cluster to sink, pipeline is instead the most cost effective. Every plant in this study go via a cluster, which is highly indicative of the fact that added together emissions for economies of scale is of importance.

As in previous works, the potential for net negativity trough BECCS was within the bounds for Sweden and Finland, the appreciation is that 25 to 50 % of GHG need to be covered for there to be a chance at the 1.5 degree target. The countries with most potential after that were then Portugal and Estonia. Sweden, Finland and Portugal produce large amounts of pulp and paper, which is the main reason for their potential. Access to biomass, types of industry etc, in each country make BECCS suitable for some, and is less effective for others. In reaching net-negativity globally BECCS can be one of the solutions, but can not be the only negative emission technology in action.

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8 Appendix

A Illustration of nodes for different scenarios

Bellow are visualizations of ports, in blue. Clusters, in purlpe. Plants, in green with different sizes illustration emission scale. And orange, sinks.

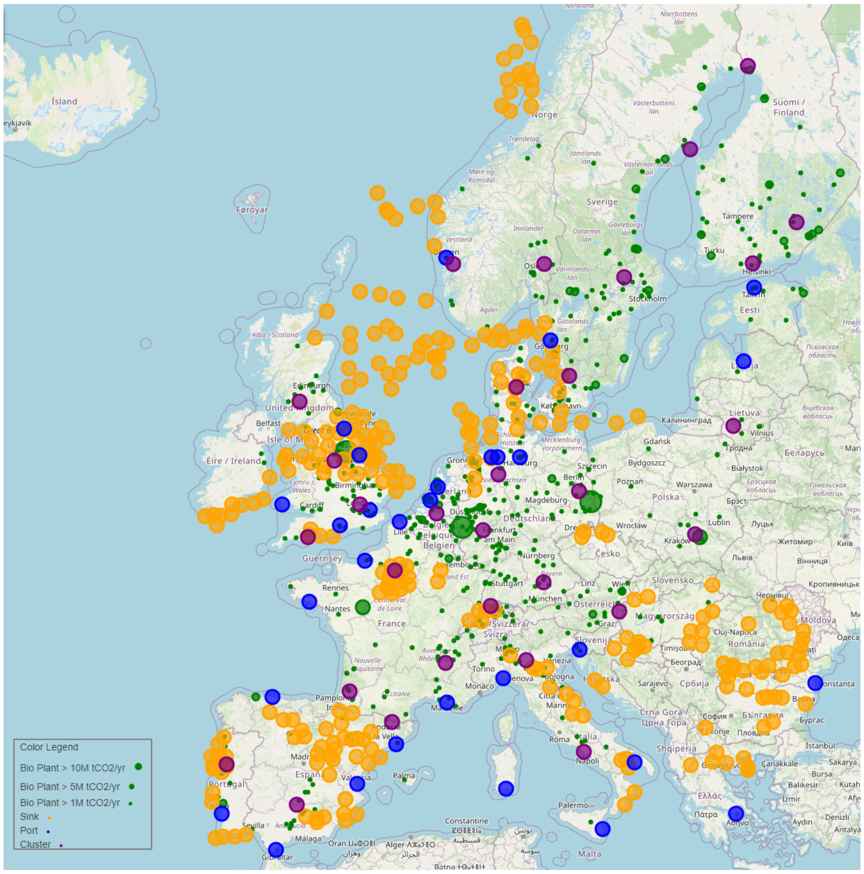

Figure 18: Nodes for biocluster scenario

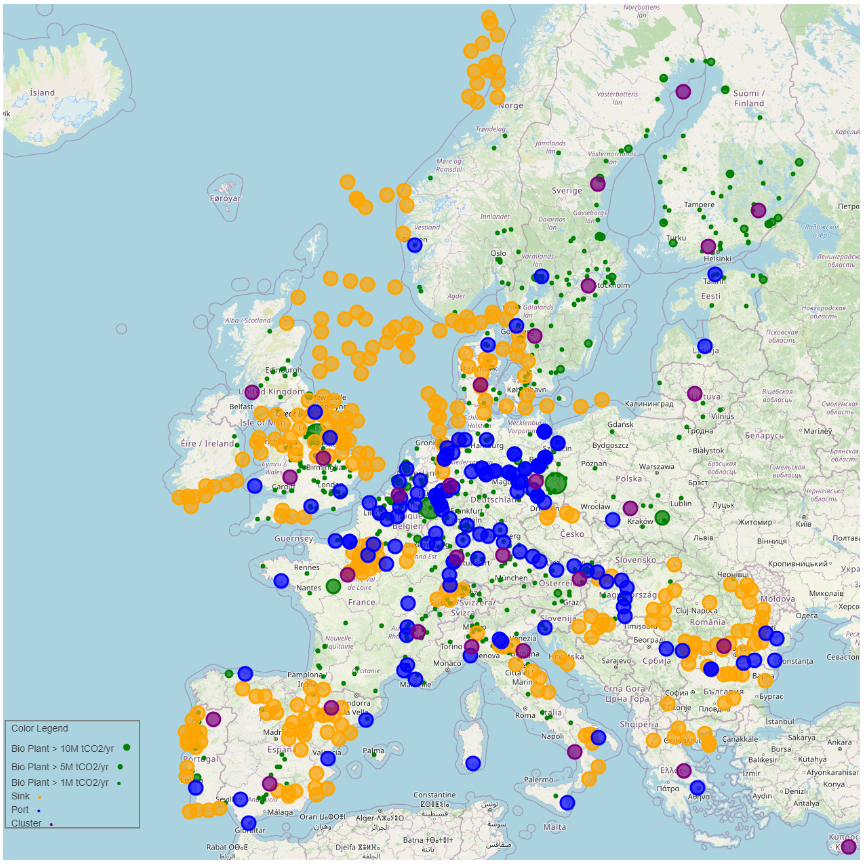

Figure 19: Nodes for added ports scenario

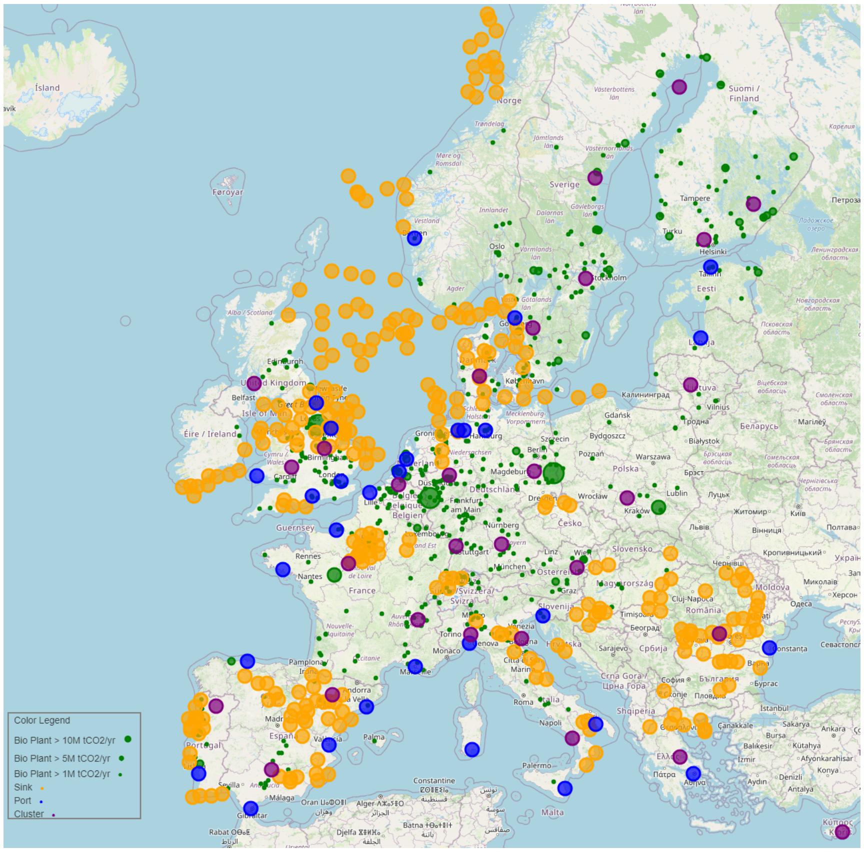

Figure 20: Nodes for original scenario

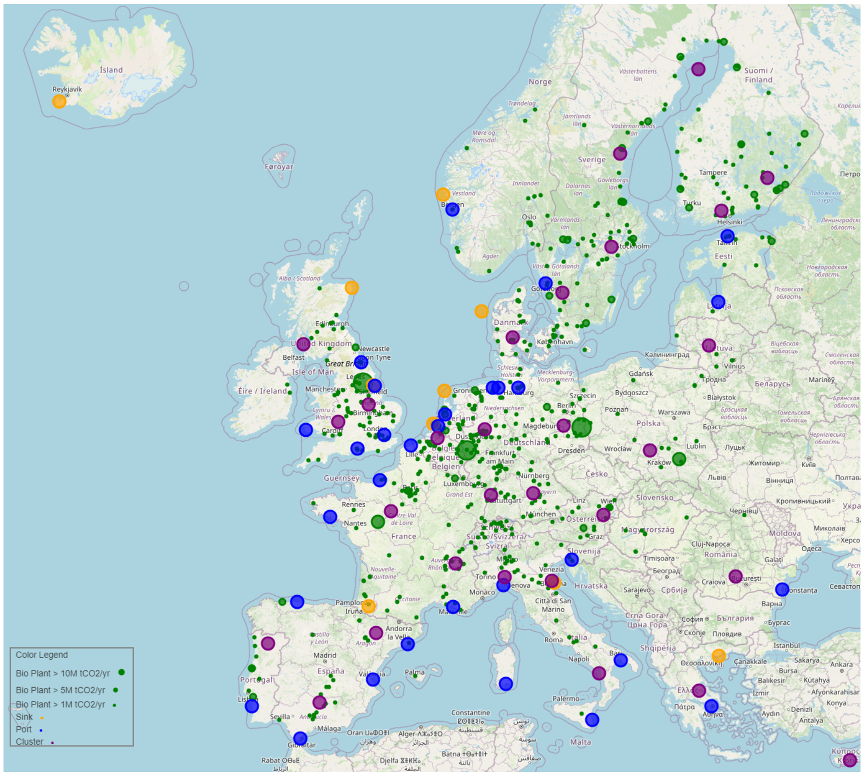

Figure 21: Nodes for short-term sinks scenario

B Codes for calculation of routes

The code for calculating and visualizing the sink, port and cluster for each plant.

```python
import pandas as pd
import numpy as np
from scipy.spatial.distance import cdist
import matplotlib.pyplot as plt
import seaborn as sns

sns.set()
import folium
from folium.plugins import MarkerCluster

# Load data
bio_plants = pd.read_excel("EEA_plants (1).xlsx")
sinks = pd.read_excel("new_sink.xlsx")
clusters = pd.read_excel("ClusterC_bio.xlsx")
ports = pd.read_excel("ports.xlsx")

# Data preparation for bio_plants
bio_plants = bio_plants.rename(
    columns={
        bio_plants.columns[0]: "plant_name",
        bio_plants.columns[2]: "longitude",
        bio_plants.columns[3]: "latitude",
        bio_plants.columns[4]: "emissions [tCO2/yr]",
    }
)
bio_plants["ID"] = "BioPlant_" + (bio_plants.index + 1).astype(str)

# Data preparation for sinks
sinks = sinks.rename(
    columns={sinks.columns[1]: "latitude", sinks.columns[2]: "longitude"}
).dropna(subset=["latitude", "longitude"])
sinks["ID"] = "Sink_" + (sinks.index + 1).astype(str)

# Data preparation for ports
ports = ports.rename(
    columns={ports.columns[4]: "latitude", ports.columns[5]: "longitude"}
).dropna(subset=["latitude", "longitude"])
ports["ID"] = "Port_" + (ports.index + 1).astype(str)

# Data preparation for clusters
clusters = clusters.rename(
    columns={clusters.columns[0]: "latitude", clusters.columns[1]: "longitude"}
).dropna(subset=["latitude", "longitude"])
clusters["ID"] = "Cluster_" + (clusters.index + 1).astype(str)

# Function to find the closest entity
def find_closest_entity(bio_plant_coords, entity_coords):
    distances = cdist(bio_plant_coords, entity_coords, metric="euclidean")
    return np.argmin(distances, axis=1)


# Append information about the closest entities
def append_closest_entity_info(df, entity_df, entity_coords, entity_type):
    closest_indices = find_closest_entity(
        df[["latitude", "longitude"]].values, entity_coords
    )
    df[f"closest_{entity_type}_id"] = entity_df.iloc[closest_indices].index
    df[f"closest_{entity_type}_name"] = entity_df["ID"].iloc[closest_indices].values
    df[f"closest_{entity_type}_latitude"] = entity_df.iloc[closest_indices][
        "latitude"
    ].values
    df[f"closest_{entity_type}_longitude"] = entity_df.iloc[closest_indices][
        "longitude"
    ].values
    if entity_type == "sink":
        df[f"closest_{entity_type}_location"] = (
            entity_df.iloc[closest_indices].get("Location", np.nan).values
        )


# Append closest sink, port, and cluster information to bio_plants
append_closest_entity_info(
    bio_plants, ports, ports[["latitude", "longitude"]].values, "port"
)
append_closest_entity_info(
    bio_plants, clusters, clusters[["latitude", "longitude"]].values, "cluster"
)
append_closest_entity_info(
    bio_plants, sinks, sinks[["latitude", "longitude"]].values, "sink"
)

# Function to add entities to map
def add_entities_to_map(f_map, entities_df, entity_icon, entity_color, popup_info):
    for idx, row in entities_df.iterrows():
        folium.Marker(
```

```
            location=[row["latitude"], row["longitude"]],
            popup=f"{popup_info}: {row['ID']}",
            icon=folium.Icon(color=entity_color, icon=entity_icon),
        ).add_to(f_map)


# Initialize the map
m = folium.Map(
    location=[bio_plants["latitude"].mean(), bio_plants["longitude"].mean()],
    zoom_start=5,
)

# Add entities to the map
add_entities_to_map(m, bio_plants, "leaf", "green", "Bio Plant")
add_entities_to_map(m, sinks, "star", "blue", "Sink")
add_entities_to_map(m, ports, "anchor", "red", "Port")
add_entities_to_map(m, clusters, "cloud", "purple", "Cluster")

# Save the map
m.save("bio_plants_map.html")
print("Map has been created and saved as 'bio_plants_map_biocluster.html'.")

# Visualize allocations
plt.figure(figsize=(12, 8))
plt.scatter(
    bio_plants["latitude"],
    bio_plants["longitude"],
    c="orange",
    label="Bio Plants",
    alpha=0.5,
)
plt.scatter(
    sinks["latitude"],
    sinks["longitude"],
    c="blue",
    marker="*",
    label="Sinks",
    alpha=0.8,
)
plt.scatter(
    ports["latitude"], ports["longitude"], c="red", marker="*", label="Ports", alpha=0.8
)
plt.scatter(
    clusters["latitude"],
    clusters["longitude"],
    c="green",
    marker="*",
    label="Clusters",
    alpha=0.8,
)
plt.xlabel("Latitude")
plt.ylabel("Longitude")
plt.legend()
plt.title("Bio Plants Allocation to Closest Sink, Port, and Cluster")
plt.show()

# Saving the combined result
output_file = "Final_All_biocluster.xlsx"
bio_plants.to_excel(output_file, index=False)
print(
    f"Excel file '{output_file}' has been created with bio plants and their nearest sink, cluster, and port, including em
)
```

```
import folium
from branca.element import Template, MacroElement
import numpy as np
import pandas as pd

bio_plants = pd.read_excel('EEA_plants.xlsx')
sinks = pd.read_excel('new_sink.xlsx')
clusters = pd.read_excel('ClusterC_bio.xlsx')
ports = pd.read_excel('ports.xlsx')

# Data preparation for bio_plants
bio_plants = bio_plants.rename(columns={
    bio_plants.columns[0]: 'plant_name',
    bio_plants.columns[2]: 'longitude',
    bio_plants.columns[3]: 'latitude',
    bio_plants.columns[4]: 'emissions [tCO2/yr]'
}).dropna(subset=['latitude', 'longitude'])
bio_plants['ID'] = 'BioPlant_' + (bio_plants.index + 1).astype(str)

# Data preparation for sinks
sinks = sinks.rename(columns={
    sinks.columns[1]: 'latitude',
    sinks.columns[2]: 'longitude'
}).dropna(subset=['latitude', 'longitude'])
sinks['ID'] = 'Sink_' + (sinks.index + 1).astype(str)

# Data preparation for ports
ports = ports.rename(columns={
    ports.columns[4]: 'latitude',
    ports.columns[5]: 'longitude'
}).dropna(subset=['latitude', 'longitude'])
ports['ID'] = 'Port_' + (ports.index + 1).astype(str)

# Data preparation for clusters
clusters = clusters.rename(columns={
    clusters.columns[0]: 'latitude',
    clusters.columns[1]: 'longitude'
}).dropna(subset=['latitude', 'longitude'])
clusters['ID'] = 'Cluster_' + (clusters.index + 1).astype(str)

# Function to set radius based on emissions or standard size for non-bio plants
def get_radius(emissions=None):
    if emissions is not None:
        if emissions > 10000000:  # more than 10 million
            return 15
        elif emissions > 5000000:  # more than 5 million
            return 10
        elif emissions > 1000000:  # more than 1 million
            return 5
        else:
            return 2  # for any emissions less than 1 million
    return 10  # standard size for sinks, ports, and clusters

# Initialize the map
m = folium.Map(location=[bio_plants['latitude'].mean(), bio_plants['longitude'].mean()], zoom_start=5)

# Modified function to add entities to map
def add_entities_to_map(f_map, entities_df, entity_color, popup_info, is_plant=False):
    for idx, row in entities_df.iterrows():
        radius = get_radius(row['emissions [tCO2/yr]']) if is_plant else get_radius()
        folium.CircleMarker(
            location=[row['latitude'], row['longitude']],
            radius=radius,
            color=entity_color,
            fill=True,
            fill_color=entity_color,
            fill_opacity=0.7,
            popup=f"{popup_info}: {row['ID']}"
        ).add_to(f_map)

# Add entities to the map
add_entities_to_map(m, bio_plants, 'green', 'Bio Plant', is_plant=True)
add_entities_to_map(m, sinks, 'orange', 'Sink')
add_entities_to_map(m, ports, 'blue', 'Port')
add_entities_to_map(m, clusters, 'purple', 'Cluster')

# Adding the legend with updated content and colors
template = """
{% macro html(this, kwargs) %}
<div style="position: fixed;
            bottom: 50px; left: 50px; width: 200px; height: 160px;
            border:2px solid grey; z-index:9999; font-size:14px;
            ">&nbsp; Color Legend <br>
    &nbsp; Bio Plant > 10M tCO2/yr &nbsp; <i style="color:green; font-size:24px;">●</i><br>
    &nbsp; Bio Plant > 5M tCO2/yr &nbsp; <i style="color:green; font-size:18px;">●</i><br>
```

```
    &nbsp; Bio Plant > 1M tCO2/yr &nbsp; <i style="color:green; font-size:12px;">●</i><br>
    &nbsp; Sink &nbsp; <i style="color:orange; font-size:10px;">●</i><br>
    &nbsp; Port &nbsp; <i style="color:blue; font-size:10px;">●</i><br>
    &nbsp; Cluster &nbsp; <i style="color:purple; font-size:10px;">●</i>
</div>
{% endmacro %}
"""

macro = MacroElement()
macro._template = Template(template)
m.get_root().add_child(macro)

# Save the map
m.save('bio_plants.html')
print("Map has been created and saved as 'bio_plants_map.html'.")
```

The code for calculating the transport route from plant to cluster. With costs for each. These results were them put into an excel, calculating the cost for each cluster to sink. The final route was then calculated, comparing each route option for each plant.

```python
# Pipeline cost function

# input of distance, on/offshore and emission amount
def calculate_pipeline_cost(distance, on_offshore, emissions_mtco2_year):

    # Which variables to use based on on/off shore
    if on_offshore == "ON":
        investment_cost_eur_per_tco2h_per_m = 13  # For onshore, dense phase, 120 t CO2/h
        fixed_om_eur_per_tco2h_per_year_km = 20
        technical_lifetime_years = 50
    elif on_offshore == "OFF":
        investment_cost_eur_per_tco2h_per_m = 33  # For offshore, single line, 120 t CO2/h
        fixed_om_eur_per_tco2h_per_year_km = 20  # Assuming the same O&M costs for simplicity
        technical_lifetime_years = 50
    else:
        return "Error: shoremust be either ON or Off."


    emissions_tco2_hour = emissions_mtco2_year #/ (365.25 * 24)

    # Calculate CAPEX
    capex = investment_cost_eur_per_tco2h_per_m*1000 * emissions_tco2_hour * distance

    # Calculate annual OPEX: fixed O&M cost * pipeline distance (km) * emissions rate (tCO2/h)
    opex = fixed_om_eur_per_tco2h_per_year_km * (distance / 1000) * emissions_tco2_hour

    # Annualize the CAPEX over the technical lifetime
    annualized_capex = capex / technical_lifetime_years

    # Total annual cost: Including both amortized CAPEX and OPEX
    total_annual_cost = annualized_capex + opex

    return total_annual_cost
```

```python
#Truck

# Input distance and emission amount
def calculate_co2_truck_transport_cost(distance_km, annual_co2_ton):

    # Constants
    FIXED_COST_PER_TON_CO2 = 3.8  # EUR/t CO2
    VARIABLE_COST_PER_KM_PER_TON_CO2 = 0.14  # EUR/t CO2/km

    # Calculate costs
    variable_cost_per_ton = distance_km * VARIABLE_COST_PER_KM_PER_TON_CO2
    total_cost_per_ton = FIXED_COST_PER_TON_CO2 + variable_cost_per_ton

    # Calculate the annual cost based on the volume of CO2 transported
    annual_cost = total_cost_per_ton * annual_co2_ton

    return annual_cost
```

```
# Ship

def calculate_co2_ship_transport_cost(annual_co2_tons):
    # Constants and assumptions
    CAPEX_ship_per_t_CO2 = 10000  # EUR/t CO2, assumption based on data sheet values for a 4000 t CO2 ship
    CAPEX_terminal_per_t_CO2 = 2500  # EUR/t CO2, assumption for 5000 t CO2 export terminal
    annual_CAPEX_rate = 0.06  # 6% annual CAPEX, assuming 40 years lifetime for ship and 25 for terminal
    fixed_OM_rate = 0.05  # Fixed O&M is 5% of CAPEX
    fuel_cost_MWh = 270  # EUR/ton HFO, from data sheet
    energy_demand_MWh_per_day = 90  # 4000 t CO2 ship energy demand, assuming daily operation
    ship_capacity_t_CO2 = 4000  # Ship capacity in tons of CO2
    annual_transport_volume_t_CO2 = annual_co2_tons  # Annual CO2 transport volume, input parameter


    try:
        annual_transport_volume = annual_transport_volume_t_CO2
    except ValueError:
        annual_transport_volume = 0


    cycle_time_hours = 24  # Assuming loading/unloading and round trip takes a full day (simplified)
    if annual_transport_volume > 0:
        trips_per_year = annual_transport_volume / (ship_capacity_t_CO2 * 365 / cycle_time_hours)
    else:
        trips_per_year = 0

    # CAPEX calculations
    CAPEX_ship_total = CAPEX_ship_per_t_CO2 * ship_capacity_t_CO2
    CAPEX_terminal_total = CAPEX_terminal_per_t_CO2 * ship_capacity_t_CO2  # Assuming a 4000 t CO2 capacity for the expor
    annual_CAPEX_ship = CAPEX_ship_total * annual_CAPEX_rate
    annual_CAPEX_terminal = CAPEX_terminal_total * annual_CAPEX_rate / (40 / 25)
    annual_CAPEX_total = annual_CAPEX_ship + annual_CAPEX_terminal

    # O&M calculations
    fixed_OM_total_annual = (CAPEX_ship_total + CAPEX_terminal_total) * fixed_OM_rate

    # Fuel cost calculation
    fuel_cost_annual = (energy_demand_MWh_per_day * fuel_cost_MWh / 1000) * 365 * trips_per_year

    # Total annual cost
    total_annual_cost = annual_CAPEX_total + fixed_OM_total_annual + fuel_cost_annual

    # Specific transport cost (EUR/t CO2)
    if annual_transport_volume > 0:
        specific_transport_cost = total_annual_cost / (annual_transport_volume)
    else:
        specific_transport_cost = float('inf')  # Return infinity if there's no volume to avoid division by zero

    return specific_transport_cost
```

```
import pandas as pd
import numpy as np

# Read Excel file
nodes = pd.read_excel('Final_All_biocluster.xlsx')

# Constants
RADIUS_OF_EARTH = 6371  # kilometers
SCALE_FACTOR = 1.2  # non-straight path adjustment
TRUCK_MAX_DISTANCE = 500  # kilometers

# Haversine function to calculate distance in km
def haversine(lat1, lon1, lat2, lon2):
    lat1, lon1, lat2, lon2 = map(np.radians, [lat1, lon1, lat2, lon2])
    dlat = lat2 - lat1
    dlon = lon2 - lon1
    a = np.sin(dlat/2)**2 + np.cos(lat1) * np.cos(lat2) * np.sin(dlon/2)**2
    return 2 * RADIUS_OF_EARTH * np.arcsin(np.sqrt(a)) * SCALE_FACTOR


def decide_transport_and_costs(row):
    distance_to_cluster = haversine(row['latitude'], row['longitude'], row['closest_cluster_latitude'], row['closest_clus

    if distance_to_cluster <= TRUCK_MAX_DISTANCE:
        cost_to_cluster = calculate_co2_truck_transport_cost(row['emissions [tCO2/yr]'], distance_to_cluster)
        route_to_cluster = 'Truck'
    else:
        cost_to_cluster = calculate_pipeline_cost(distance_to_cluster, row['closest_sink_location'],row['emissions [tCO2/
        route_to_cluster = 'Pipeline'

    return pd.Series([distance_to_cluster, route_to_cluster, cost_to_cluster], index=['distance_to_cluster', 'route_to_cl

# Apply the transport decision function to each row
nodes[['distance_to_cluster', 'route_to_cluster', 'cost_to_cluster']] = nodes.apply(decide_transport_and_costs, axis=1)

# Output DataFrame
output_df = nodes[['plant_name', 'emissions [tCO2/yr]', 'closest_cluster_id', 'route_to_cluster', 'cost_to_cluster', 'dis

# Print detailed DataFrame
print("Detailed Routes Information:")
print(output_df)

# Function to write DataFrame to Excel
def write_routes_to_excel(df, filename="Route_to_cluster_biocluster.xlsx"):
    # Write DataFrame to Excel file
    df.to_excel(filename, index=False)
    print(f"Routes have been written to {filename}.")

# Call the function with the DataFrame of routes
write_routes_to_excel(output_df)
```

```
import pandas as pd
import numpy as np
# Constants
RADIUS_OF_EARTH = 6371  # kilometers
SCALE_FACTOR = 1.2  # Account for non-straight paths
TRUCK_MAX_DISTANCE = 500  # Max distance for truck transport in km

# Read Excel files
nodes = pd.read_excel('Final_All_sinks.xlsx')
plant_to_cluster = pd.read_excel('plant_to_cluster_sinks (2).xlsx')

# Haversine function to calculate distance in km
def haversine(lat1, lon1, lat2, lon2):
    lat1, lon1, lat2, lon2 = map(np.radians, [lat1, lon1, lat2, lon2])
    dlat = lat2 - lat1
    dlon = lon2 - lon1
    a = np.sin(dlat / 2) ** 2 + np.cos(lat1) * np.cos(lat2) * np.sin(dlon / 2) ** 2
    return 2 * RADIUS_OF_EARTH * np.arcsin(np.sqrt(a)) * SCALE_FACTOR


def decide_transport_and_costs(row):
    # Use plant_to_cluster for cluster routing
    cluster_cost = plant_to_cluster.loc[plant_to_cluster['plant_name'] == row['plant_name'], 'Go by cluster cost'].min()
    transport_to_cluster = plant_to_cluster.loc[plant_to_cluster['plant_name'] == row['plant_name'], 'Transport mode'].il

    # Direct and combined routing calculations
    distance_to_sink = haversine(row['latitude'], row['longitude'], row['closest_sink_latitude'], row['closest_sink_longi
    cost_to_sink = calculate_pipeline_cost(distance_to_sink, "ON", row['emissions [tCO2/yr]'])

    distance_to_port = haversine(row['latitude'], row['longitude'], row['closest_port_latitude'], row['closest_port_longi
    distance_port_to_sink = haversine(row['closest_port_latitude'], row['closest_port_longitude'], row['closest_sink_lati
    cost_to_port_to_sink = calculate_co2_ship_transport_cost(row['emissions [tCO2/yr]']) + calculate_pipeline_cost(distan

    # Compare costs and select the cheapest route
    costs = [cost_to_sink, cost_to_port_to_sink, cluster_cost]
    routes = ["Plant to Sink", "Plant to Port to Sink", "Plant to Cluster"]
    transport_modes = ["P", "S-P", transport_to_cluster]
    min_cost_index = np.argmin(costs)

    return pd.Series([
        routes[min_cost_index], costs[min_cost_index],
        distance_to_sink, costs[min_cost_index] / row['emissions [tCO2/yr]'], transport_modes[min_cost_index]
    ], index=['route', 'cost', 'distance_to_sink', 'per_ton_cost', 'transport_mode'])
# Apply the function to each row in the DataFrame
nodes[['route', 'cost', 'distance_to_sink', 'distance_to_port', 'distance_port_to_sink']] = nodes.apply(decide_transport_

# Output DataFrame
output_df = nodes[['plant_name', 'emissions [tCO2/yr]', 'route', 'cost', 'distance_to_sink', 'distance_to_port', 'distanc
print("Detailed Routes Information:")
print(output_df)

# Function to write DataFrame to Excel
def write_routes_to_excel(df, filename="Route_decisions_sinks.xlsx"):
    df.to_excel(filename, index=False)
    print(f"Routes have been written to {filename}.")

# Call the function to write results
write_routes_to_excel(output_df)
```

C Cost illustration per scenario

The total cost of the BECCS process split into the different segments for each, with the transport cost being illustrated in orange. The different scenarios have different trends, where the transport cost affects the total slightly differently.

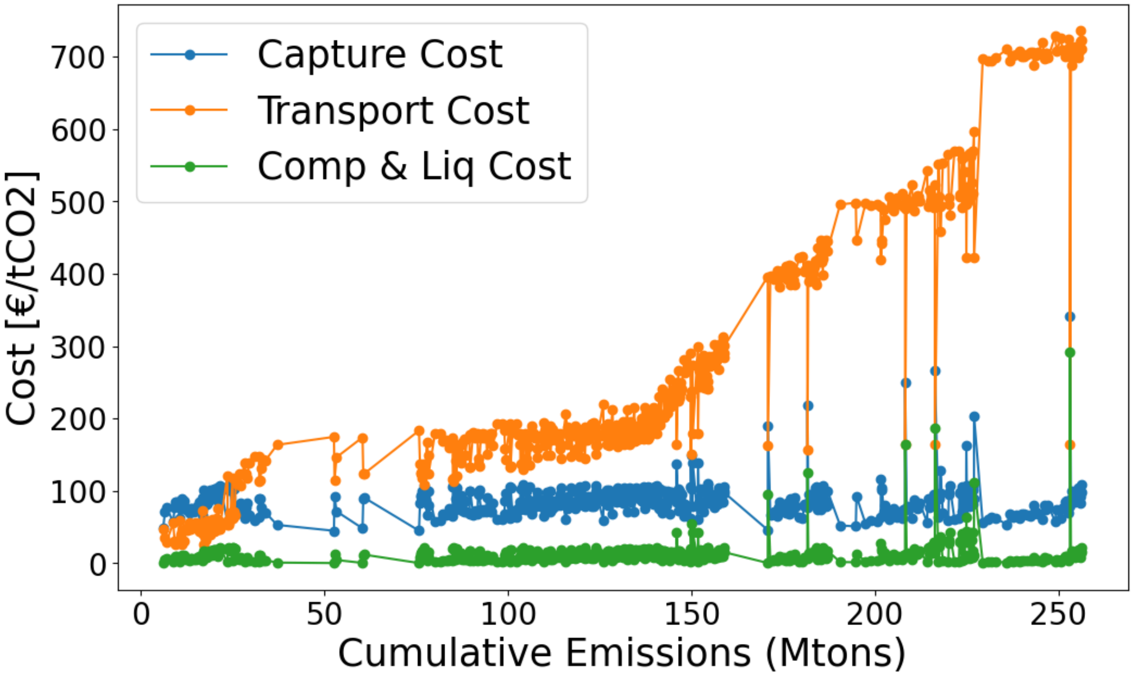

Figure 22: Cost trend original scenario

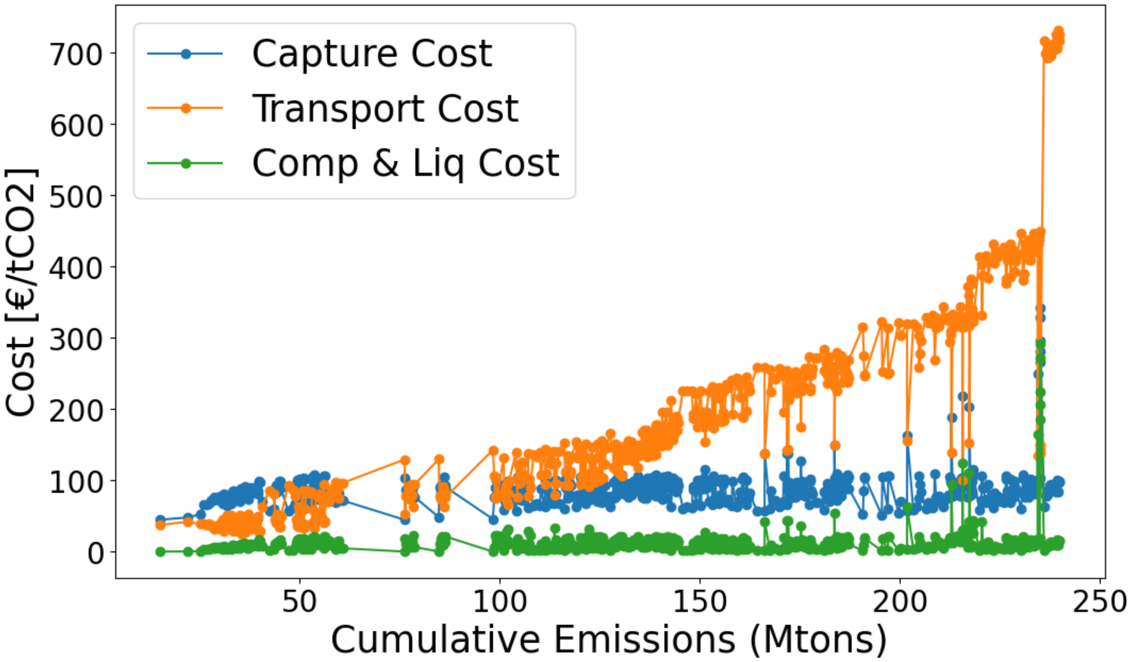

Figure 23: Cost trend biocluster scenario

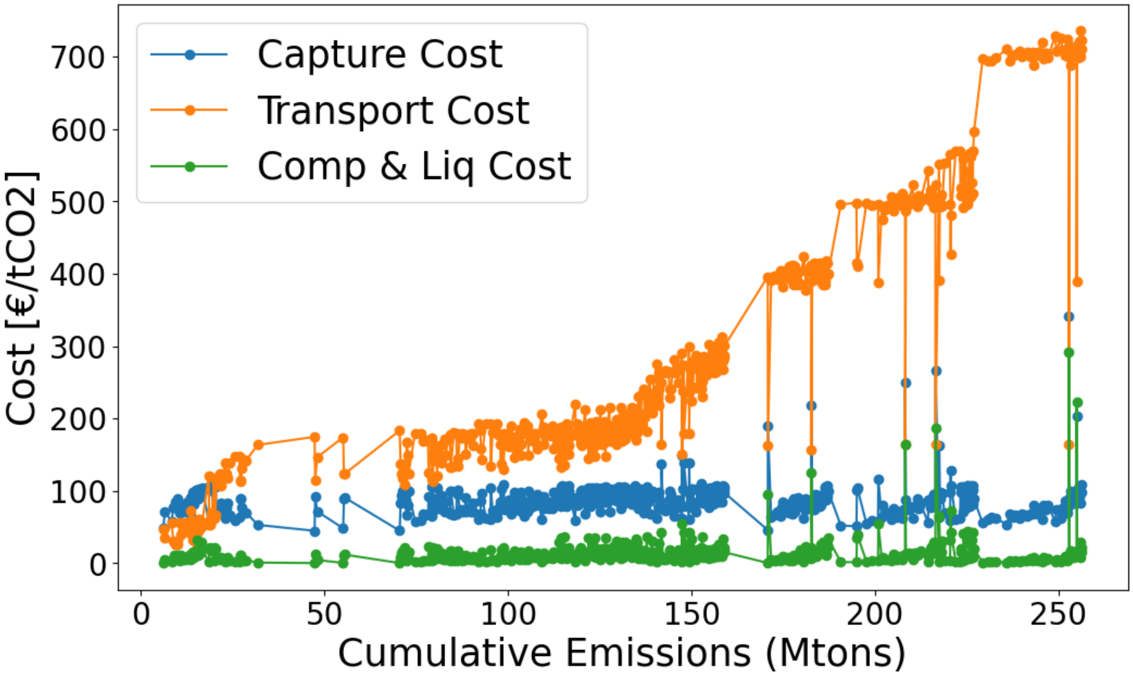

Figure 24: Cost trends added ports scenario

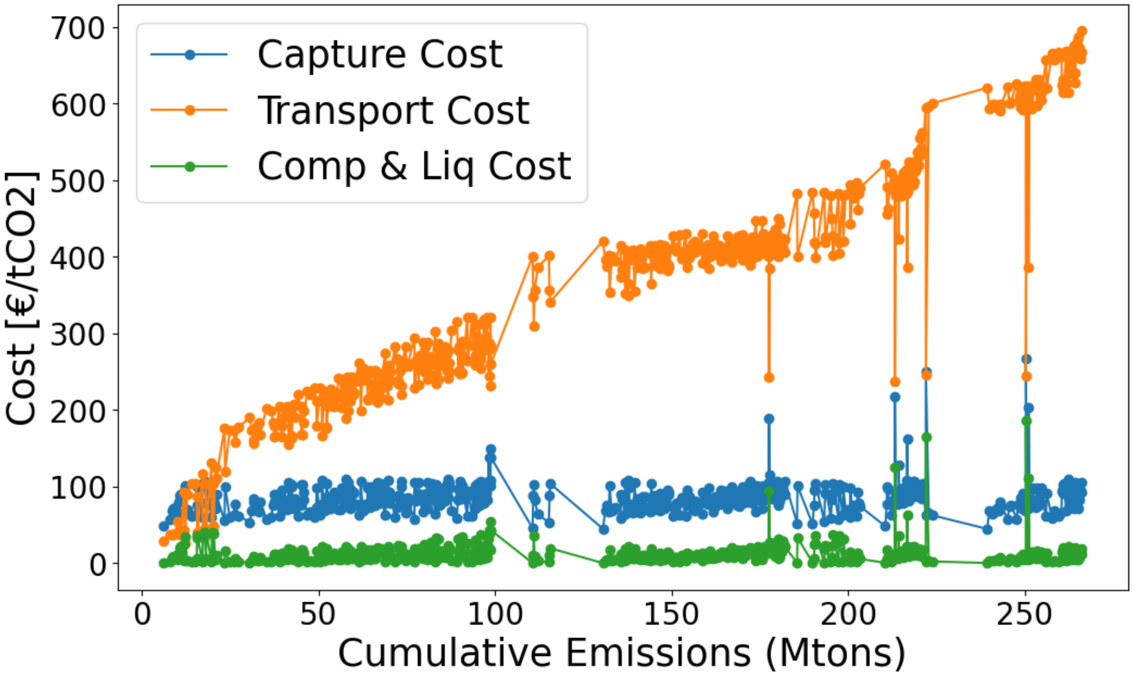

Figure 25: Cost trends short-term sinks scenario

D Plant distribution in cost ranges

Figures below illustrate where most amounts of plant were in the total cost ranges. For example in the biocluster scenario a little under 5 % of plants had a cost of 370 €/tCO_2.

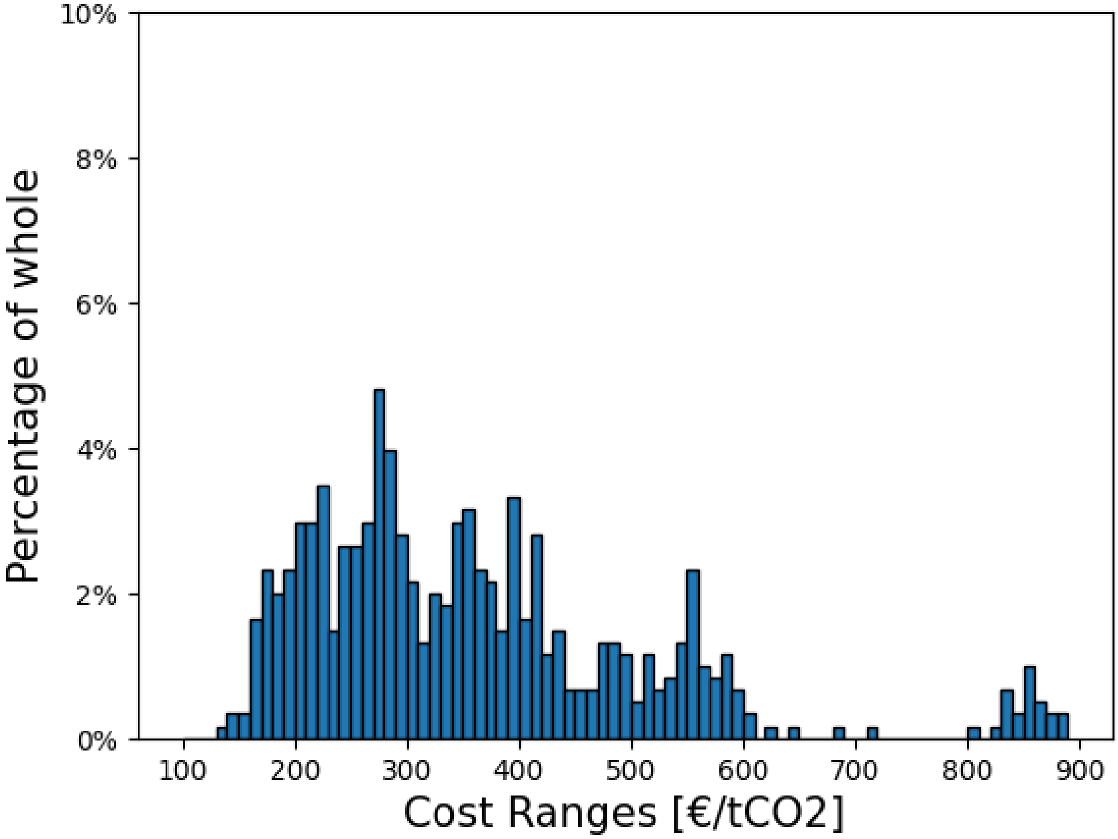

Figure 26: Percentage of plants biocluster scenario

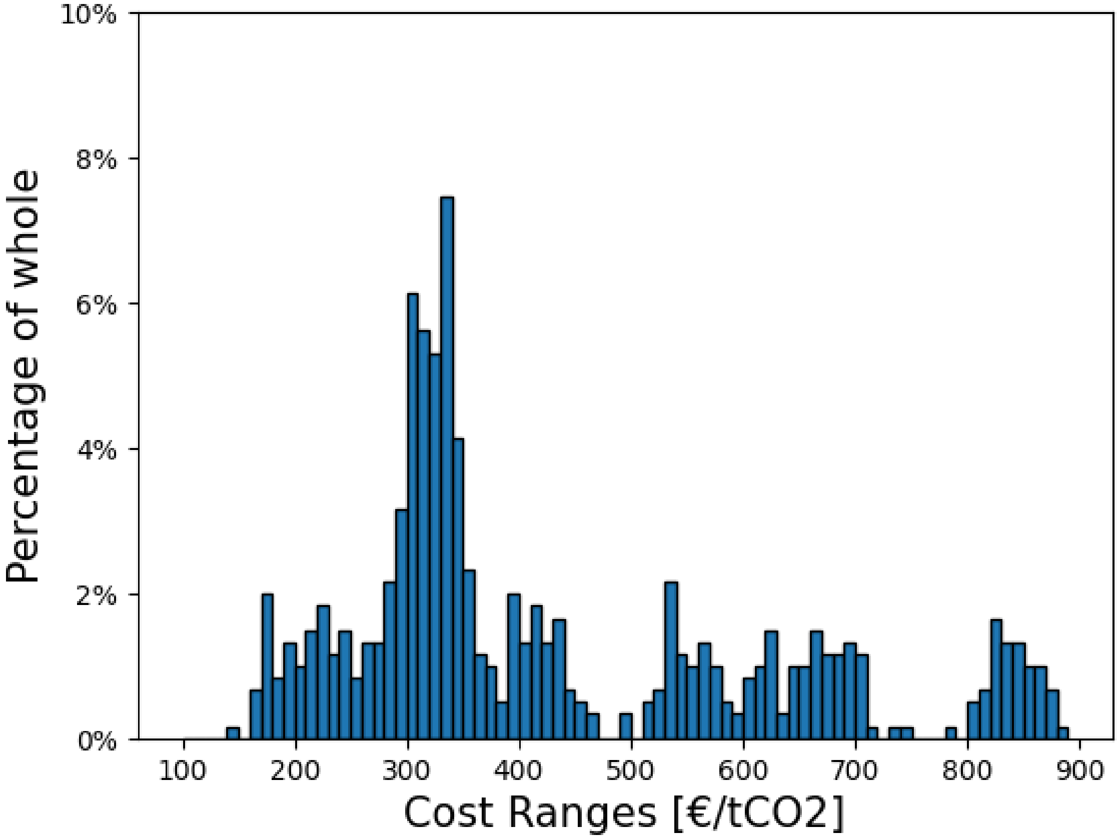

Figure 27: Percentage of plants original scenario

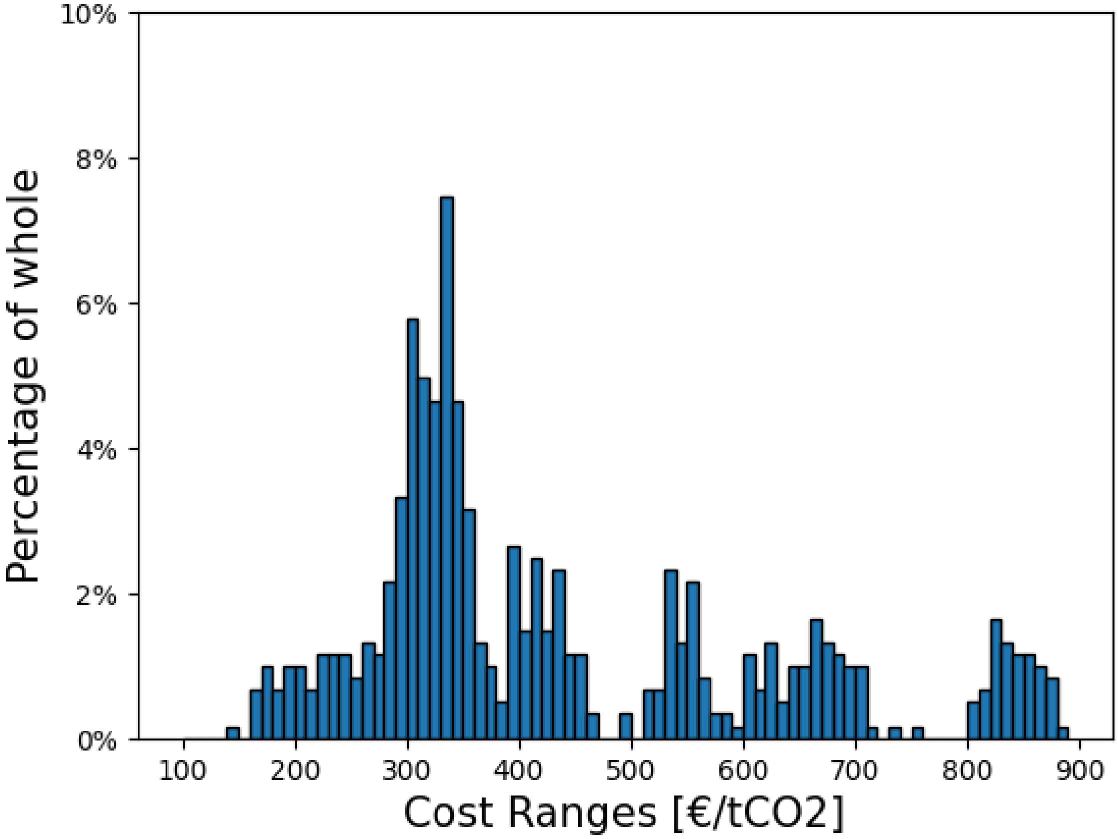

Figure 28: Percentage of plants ports scenario

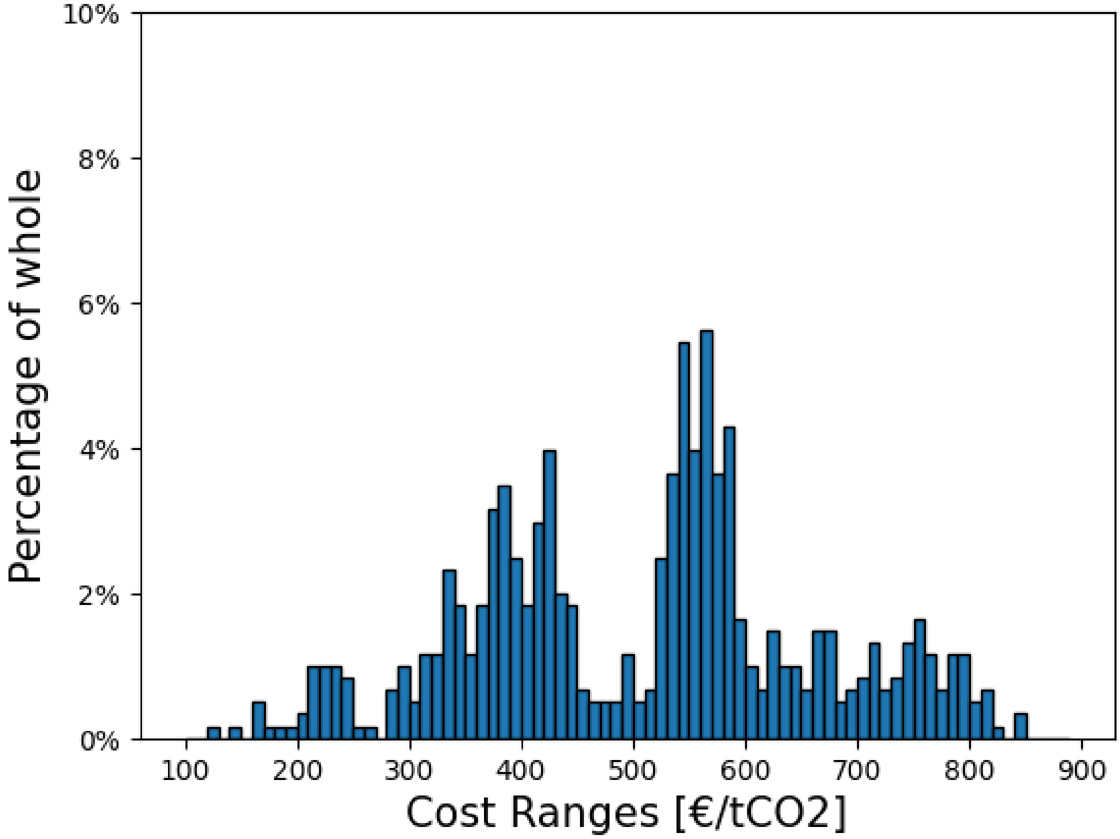

Figure 29: Percentage of plants short-term sinks scenario

E Transport routes from plant to cluster per scenario

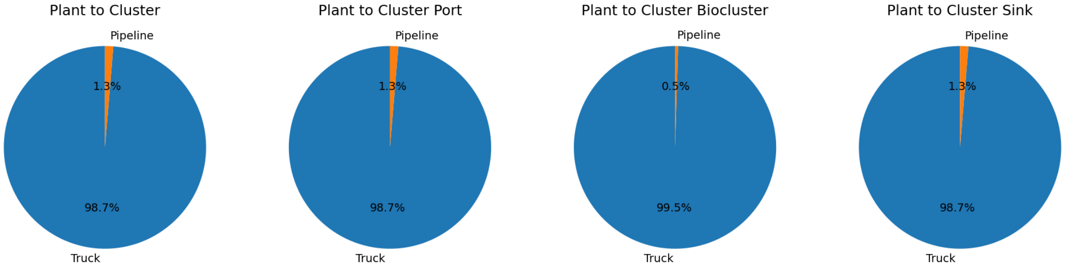

Figure 30: Transport routes to cluster from plant for each scenario