An Integrated Analysis of Carbon Capture and Storage Strategies for Power and Industry in Europe

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Abstract

Industry is responsible for one-quarter of the global CO_2 emissions. In this study, four different climate pathways are analyzed with a cost minimizing multihorizon stochastic optimization model, in order to analyze possible realizations of carbon capture and storage (CCS) in the power sector and main industrial sectors in Europe. In particular, we aim to achieve a deeper understanding of the distribution of capture by country and key sector (power, steel, cement and refinery), as well as the associated transport and storage infrastructure for CCS. Results point to the synergy effect of sharing common CCS infrastructres among power and major industrial sectors. The contribution of CCS is mainly found in three industrial sectors, particularly steel, cement and refineries) but also in the power sector to a lesser extent. It is worth noting that retrofitting of CCS in the power sector was not considered in this study.The geographical location for capture and storage, as well as timing and capacity needs are presented for different socio-economic pathways and corresponding emission targets. It has been shown that contributions of the three industry sectors in emissions reductions are neither geographically nor sector-wise homogeneous across the pathways.

Keywords: carbon capture and storage, industry, decarbonization, power sector, stochastic optimization

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1. Introduction

Carbon Capture and Storage (CCS) is expected to be one of the key technologies to decarbonize the economy and is considered essential in order to reduce industrial CO_2 emissions [1][2][3]. Since power and industry together generate almost half of the total CO_2 emissions, they are also the predominant sources of captured CO_2 in 2 degree scenarios (2DS). Among the industrial emission sources, the top CO_2 emitters are cement, steel and refineries. While emissions from these industries related to energy generation could be reduced through fuel switching, their process emissions cannot be avoided without either CO_2 capture or drastically changing the industrial process. For instance, in cement production, 60% of the total emissions comes from the clinker production. In crude steel production, the basic oxygen process and blast furnaces are significant CO_2 emitters. CCS is unavoidable to achieve carbon-neutrality in most of these sectors. A rigorous literature review covering CCS in steel, cement, and refinery industries can be found in Leeson et al. [4]. There are also strong technical reviews covering different aspects of CCS deployment [5] [6].

As the third largest emitter of greenhouse gas emissions globally, after China and the United States, Europe has the ambition to be in the driving seat when reducing emissions. In this paper, we use a combined power sector and industrial model of Europe to explore possible synergies between these sectors in terms of CCS infrastructure. The model is a long-term capacity expansion model with the capability to balance hourly load and supply under short-term uncertainty for power markets. The results related to CCS indicate investments needed to capture, transport and store CO_2 as well as the timing and volume of these investments for each country. The results are guided by different climate targets associated with consistent socio-economic pathways, further also called climate scenarios.

Integrated Assessment Models (IAM) have been at the heart of the Intergovernmental Panel on Climate Change's (IPCC) analyses of pathways, where the objective is to keep average global warming below 1.5 or 2 degrees Celsius [2]. However, many databases built upon the Shared Socioeconomic Pathways (SSPs) scenarios do not present details about industrial CCS on a regional level. Several relevant European studies exist: Vangkilde-Pedersen et al. [3] model European capacity for geological storage of CO_2 in deep saline aquifers, oil and gas structures, and coal beds in an extension of GESTCO and CASTOR EU. The CEPS model by Mendelevitch [7] and InfraCCS by Morbee et al. [8] are two deterministic optimization models analyzing CO_2 transport infrastructure. Knoope et al. [9] use a stochastic model to study the fluctuations in CO_2 price, the tariff received per ton of CO_2 transported, while modeling in different scenarios the willingness and timing of sources to join the CO_2 transport network. Middleton et al.[10] have a similar approach where they focus on uncertain injection rates and uncertain CO_2-storage capacities. In addition, there are several other regional modelling efforts such as MARKAL-NL-UU, and SimCCS [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. In [25], a CCS supply chain at the tactical level is modeled deterministically by considering spatial information of possible emitters in order to meet some bulk amount of emission reduction targets.

Our approach differs from the above in respect that it uses a multihorizon [26] stochastic power market model with both investment and operation decisions as well as CCS infrastructure details. Also in this study industrial emissions are exogenous parameters that are based on SSPs which have been developed by The Global Integrated Assessment Modelling (IAM) Community. The study of how development of CCS for power and industry in Europe until 2055 will evolve from a cost minimizing perspective is provided. An important part of the study assesses if using common infrastructure with industry affects the interplay between CCS and renewables in new power sector investments. The objective of the analysis is to provide projections of capacity and timing of investment decisions for CCS infrastructure.

Next, we provide modelling assumptions in Section 2. An overview of the model as well as details for the CCS-modelling follow in Section 3. Then, results and discussion are presented in Section 4 and we summarize and give a perspective about future work in Section 5.

2. Inputs and Modelling Assumptions

Our modeling takes the European power market model, EMPIRE [27] as a starting point. It has a long-term horizon towards 2055. The geographical resolution is limited to a node per country in EU-27 minus Cyprus and Montenegro plus Bosnia Hercegovina, Great Britain, North Macedonia, Serbia, Switzerland, and Norway. The model is a two-stage muiltihorizon stochastic model, with hourly resolution at the operational scale and 5-year-long investment steps. To the best of our knowledge, this study presents the first results based on a stochastic optimisation model for the European power sector and industry with this level of detail on CO_2 transport and storage. The model includes short-term uncertainty in load as well as intermittent power generation from renewable and hydro inflows for the power sector. Industrial emission amounts [28] and CCS-transport and -storage [29] are merged with these existing components of the EMPIRE model.

2.1. Climate Scenarios

In order to analyze pathways for emission reductions using sector models like EMPIRE, long-term demand trajectories for power, the emission projections for industrial sectors, global commodity prices, CO_2 -budgets, and technology costs need to come from economy-wide and often global models like IAMs. The output from the EMPIRE model is technology investments for power generation technologies, transmission capacities and CO_2 transport pipelines as well as operational detail for representative hours representing variability and uncertainty. Deterministic scenario analysis or pathway studies are often used as a tool to explore and evaluate the extensive long-term uncertainties associated with possible long-term developments [30]. With input from such long-term pathways, more detailed sector models can provide strategies for technology choice and infrastructure investments at country level, considering the short-term uncertainty and effects on operations.

The Climate Modelling Intercomparison Project 6 (CMIP6) is one of the most recent endorsed model intercomparison projects (MIPs) and has chosen nine among the total available scenarios produced by IAMS. In order to provide historically consistent and spatially more detailed emission datasets for other scientists, scenario results are aligned with the model results with a common historical dataset processed through the application of common rules across all models as previously done by [31]. Among the SSPs which have been developed by the Global IAM Community [2] we use: SSP1, a green-growth paradigm [32] , SSP4, a development that results in both geographical and social inequalities [33] and SSP5, a development path that is dominated by high energy demand supplied by extensive fossil-fuel use [34]. Narratives for the main SSP scenarios are supplied in Appendix C together with their associated radiative forcing levels. The three selected marker scenarios represent different climate target levels which are measured by 1.9, 3.4 and 8.5 Wm^{-2} radiative forcing levels respectively.

In addition, we include a long-term scenario representing the European Parliament's vision for Europe to become the first climate-neutral region. The EU 's communication document [35] underlines this ambition and presents eight different scenarios. The emission levels of the 8^{th} scenario, here denoted as 'EU Ambition' scenario, is used in this study. In this scenario, the total emissions forced to be less than 3.34 GtCO_2 in 2050-2055 from the power sector and 2.26 GtCO_2 for industry. The upper bound of emission for SSP1, SSP4, and SSP5 as well as an EU ambition scenario for power and industrial sector are presented in Appendix tables (C.15, C.16).

2.2. Power sector data

In EMPIRE, operations of all power generation technologies are aggregated per technology per country; and investment, operation cost, maintenance cost and fuel costs of each technology are represented by installed capacity (MW) and cost (Euro/MWh). The input data used by EMPIRE has been collected from multiple sources. Hourly load time series for all countries in the model come from the ENTSO-E data portal [36]. Also, net transfer capacities for cross-border exchange are based on ENTSO-E data. Investment costs and generation technology specifications are provided exclusively from members of ZEP market economics group II [37] and they are consolidated with updated values from [38],[35]. Installed capacity data for initial generator technologies are collected, and consolidated, from several sources including ENTSO-E [36], EURELECTRIC [39], EUR'Observer, NREAP and the following ISO and market operator's websites: National Grid, Red Electrica, Terna, EEX. Normalized production profiles for wind and solar generation for every country have been provided by the same data material as was used by the EU-funded project SUSPLAN [38]. The main cost components and lifetime assumptions of each power technology can be found in Appendix A.

2.3. Power sector and industrial emissions

The emissions from the power sector are partly shaped by the supply and load balance as described by the operational constraints of the model. Power sector emissions are calculated within the model as a result of the hourly operational generation:

$$\begin{aligned} PowerEmission = CarbonContentofFuel(tCO_2/GJ)* \\ [1 - CCSRemovalFraction]* \\ heatrate(GJ/MWhe)* \\ HourlyOperationalGeneration(MWhe) \end{aligned} \tag{1}$$

The carbon content[1] of each fuel type can be found in Appendix (Table B.14). A fixed heat rate level of 3.6 (GJth/MWhe) is used in order to

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[1] (https://www.eia.gov/tools/faqs/faq.php?id=73&t=11)

calculate the emissions from power.

The industry emissions for cement, steel and refineries are projected by interpolating to 2055 with a 25% increase from 2016 [40]. This interpolation rate is based on a steady acceleration rate assumption for manufacturing in the EU. The starting emission levels and the resultant emission projections for these three sectors are supplied in Appendix (B.11,B.12,B.13). The capture amounts are shaped in order to bring this raw production based CO_2 emission levels to the trajectories of each climate scenario. Sensitivity analysis has been performed for this growth rate. The location and timing results for capture do not change significantly when the growth rate for industrial emission (with no-policy) varies between 1.6% and 5.7% increase per period (which correspond to 10% and 40% increase in industrial emission respectively at the end of the horizon compared with 2020).

One challenge when modeling industrial decarbonization is to identify consistent long-term trajectories describing how CO_2 is reduced in industry sectors utilizing four main mechanisms: improvements in i) material efficiency, ii) fuel and feedstock switching, iii) energy efficiency and iv) CCS. The demand for CCS in the industry sectors cannot be directly extracted from the four pathways providing model input in our study and needs to be estimated.

In order to approximate the trajectory for the industrial emission reduction amount in each climate policy scenario, the numbers for the no-policy scenario (B.11,B.12,B.13) are used together with climate policy based emission trajectories (C.16). Based on the projections of IEA (2019) [41] 73% of industrial emission reductions are assumed to come from other technologies such as material efficiency, fuel and feedstock switching, energy efficiency and using best available technology (BAT); while CCS is estimated to contribute with the remaining 27% of the reduction. The total industrial emission reduction in our pathways are estimated as the difference between emission projections with no policy (B.11,B.12,B.13) and the industrial emission targets in the pathways. For these we use the above estimate that 27% of this reduction come from CCS to provide the industrial CCS amount as input for EMPIRE.

2.4. Parameters for CCS Components

All the parameter values for carbon capture technologies can be found in Table 1.

Table 1: Capture Parameters

Capture efficiency (Power Facility)[42]- %	90
Capture efficiency (Industrial Plant)- %	80
Industrial capture cost (Cement)[43] - euro/tCO_2	80
Industrial capture cost (Steel)[2] - euro/tCO_2	43.7
Industrial capture cost (Refinery)[3] - euro/tCO_2	161

Available storage locations and capacities are important model inputs which shape the results. In this study, only four countries are allowed to store CO_2 offshore due to the strong opposition to onshore CO_2 storage in Europe [44]. The storing countries and corresponding storage capacities used in this study are provided in Table 2 [4].

Table 2: CO_2 Storage Capacities for Countries. Source Global CCS Institute (the GCCS)

Country	**StorageCap (GtCO_2)**
Norway	55
GreatBrit.	78
Netherlands	4
Denmark	0.3

Developing CCS hubs can support new investment opportunities. Investing in shared CO_2 transport and storage infrastructure can reduce unit costs through economies of scale as well as attracting investment in CO_2 capture for existing and new industrial facilities. For this reason, a pipeline network developed over time that connects neighboring countries is proposed as a plausible way to transport CO_2 onshore. For offshore CO_2 transport, two solutions are possible, namely offshore pipelines and transport by ship. While offshore pipelines would be the most cost-efficient option for large capacity and moderate distances, ship transport will be more cost-effective for long distances and may be preferred in early deployment phases due to its lower investment and higher flexibility [45], [46]. In our model, the transport

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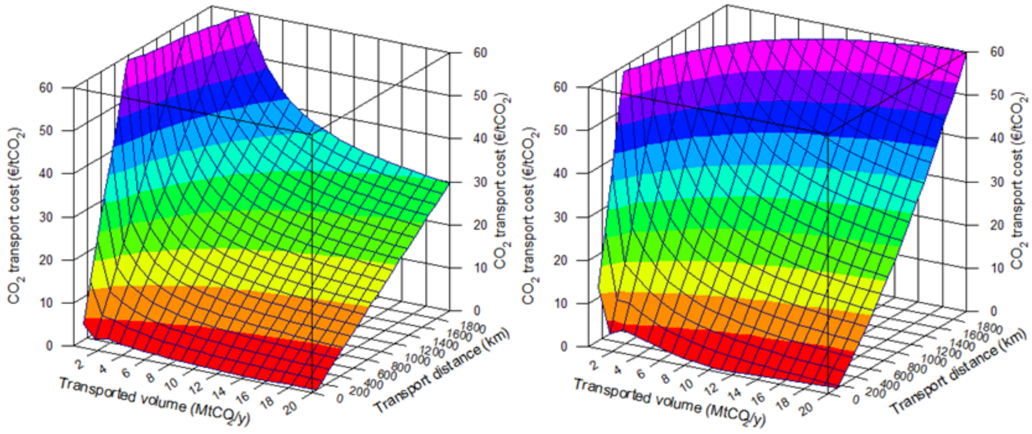
[4] https://www.globalccsinstitute.com/

distance to connect neighboring countries is calculated using the location of their capital cities. For countries which have candidate ports to transport CO_2, the locations of these ports are also considered as shown in Figure 1. For these cases, the port-to-port distances, the distances between the capitals and the ports, and the distances between ports and CO_2 storage locations are also included in the total estimated transport distances. Transport cost for within-country storage is neglected. Unit storage cost level of 14.3 euro/tCO_2 is used for the starting period [47]. This value is scaled with other financial discount rates as well as technology learning coefficients in the latter periods.

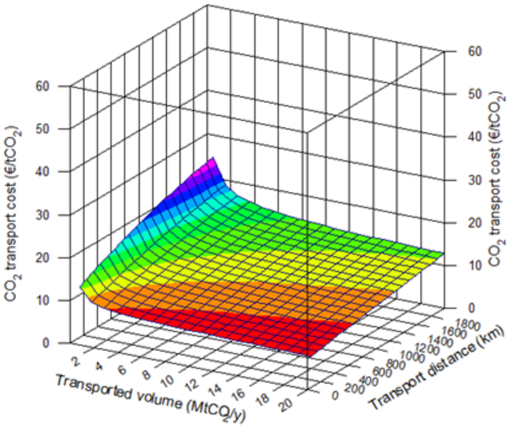
Figure 1: Possible CO_2 import/export ports for Europe

For a given means of transport, the cost is mainly affected by installed capacity and distance. In order to maintain the linear nature of the model, a predefined representative capacity for pipeline candidates is assumed within each period: for 2020-2025 1 Mtpa; for 2025-2030 5 Mtpa; for 2030-2035 10 Mtpa; for 2035-2055 20 Mtpa. In practice, this implies that if a pipeline capacity of 10 Mtpa is required between France and Germany in the period 2020-2025, the model assumes that 10 pipelines each with a capacity of 1 Mtpa can be built within this period. This is intended to mimic the deployment of a transport network over time. The CO_2 transport cost data used in the optimization model were generated based on the iCCS tool developed by SINTEF Energy Research for integrated techno-economic modeling of CCS [48], [6]. For each possible transport route considered in the model, the iCCS tool was used to generate transport unit cost (Euro/(tCO_2/y) for CAPEX or Euro/tCO_2 for OPEX) for the considered set of representative transport capacities and suitable transport means (onshore pipeline, offshore pipeline, shipping)/citeroussanaly2021pressure. It is worth noting that the pipeline capital cost model established by Knoope et al. [49] is used for the underlying cost assumptions in the iCCS pipeline estimates. An illustration of the transport unit cost as a function of the transport capacity and distance is presented in Figure 1 (a)-(c) for the different transport means considered.



(a) onshore pipeline transport

(b) offshore pipeline transport



(c) ship-based transport between harbours

Figure 2: Illustration of transport unit cost as a function of the transport capacity and distance for: (a) onshore pipeline transport (b) offshore pipeline transport (c) ship-based transport between harbour.

3. The EMPIRE model and the new CCS module

In this section, we first present a brief overview of the EMPIRE power market model, then we give the structure of the model´s objective function when only power markets are included. Next, we present the new CCS module for industry and infrastructure developed for this paper.

3.1. The EMPIRE power market model

EMPIRE[27] is a two-stage multihorizon [26] stochastic optimization model which is built for the analysis of European power markets beyond 2050. The model includes two time-scales for decisions, referred to as respectively long-term (strategic) and short-term (operational). In the current analysis, only short-term uncertainty is included, while decisions are both for the long term (investments in generation technologies and infrastructure) and operations (balancing demand and supply on hourly basis by dispatching generation). Strategic capacity investments are assumed to be available starting from the same time-period as the decision is made.

Operational uncertainties include renewable energy generation, load and hydro inflows. The operational uncertainty of renewable energy production is reflected in the wind and solar generation profiles, and seasonal availability of water stored in reservoirs for hydroelectric production. For every five-year investment step, stochastic inputs for three short-term trajectories (short-term scenarios) are represented with a reduced set of operational hours rather than computing the system dispatch over a full year of 8760 hours. The set of hours is subdivided into seasons, where there are four regular seasons and two extreme load seasons. Here 48 sequential hours are used to represent the regular seasons while 24-hour sequences are used to incorporate the volatility of extreme seasons within a long-term investment period.

In this paper, we have extended EMPIRE with industrial CO_2 capture, and more detailed modeling of CCS transport and storage infrastructure. The basic EMPIRE model only includes CCS on power generation. Details for this additional CCS model are presented below after we give an introduction to the objective function of EMPIRE. All the nomenclature regarding sets, parameters and decision variables can be found at the end.

3.2. Objective function and constraints of the CCS related components

The objective function of EMPIRE (2) discounts all costs at an annual rate of r, and the investment periods are given as five-year blocks. The factor

$\vartheta = \sum_{j=0}^{4}(1+r)^{-j}$ scales annual operational costs to the five year investment periods.

The first three terms of (2) represents costs of capacity investment, transmission and storage respectively . The last two terms relate to operational costs of generation and costs of load shedding. The terms for operational costs are scaled with the scenario probability π_ω and the seasonal scaling factor α_s, where α_s makes sure that the seasonal costs are scaled up to the length of each season. Here, π_ω is the weight attributed to each operational stochastic scenario, short-term uncertainty in load as well as intermittent power generation from renewable and hydro in inflows. In this study three distinct operational parameter sets are used to represent the volatility. Each of them assumed to have equal probability since the starting values of each time series used for the three different scenario are drawn from real data by assuming each data point is uniformly distributed.

$$\begin{aligned}\min z = &\sum_{i\in\mathcal{I}}(1+r)^{-5(i-1)}\times \\ &\Big[\sum_{n\in\mathcal{N}}\sum_{g\in\mathcal{G}_n} c^{\text{gen}}_{g,i}x^{\text{gen}}_{n,g,i} + \sum_{l\in\mathcal{L}} c^{\text{tran}}_{l,i}x^{\text{tran}}_{l,i} + \sum_{n\in\mathcal{N}}\sum_{b\in\mathcal{B}_n}\left(c^{\text{storPW}}_{b,i}x^{\text{storPW}}_{n,b,i} + c^{\text{storEN}}_{b,i}x^{\text{storEN}}_{n,b,i}\right)+ \\ &\vartheta\sum_{\omega\in\Omega}\pi_\omega\sum_{s\in\mathcal{S}}\alpha_s\sum_{h\in\mathcal{H}_s}\sum_{n\in\mathcal{N}}\Big(\sum_{g\in\mathcal{G}_n} q^{\text{gen}}_{g,i}y^{\text{gen}}_{n,g,h,i,\omega} + q^{\text{ll}}_{n,i}y^{\text{ll}}_{n,h,i,\omega}\Big)\Big] \end{aligned} \tag{2}$$

3.3. Components of the CCS module

Here, we give the details of the new module for CCS-transport and -storage infrastructure and CCS in industry.

3.4. CCS related equations

3.4.1. Emission definitions

- Power emission definition $\forall n \in \mathcal{N}, i \in \mathcal{I}, \omega \in \Omega$

$$\begin{aligned} &powEmiss_{n,i,w} = \\ &\sum_{g\in GCCS,h\in\mathcal{H}} (1-E^{CCS})\cdot Heatrate/E^{gen}_g \cdot FuelCont_g \cdot y^{\text{gen}}_{n,g,h,i,\omega} + \\ &\sum_{g\in ERG,h\in\mathcal{H}} E^{CCS}\cdot Heatrate/E^{gen}_g \cdot FuelCont_g \cdot y^{\text{gen}}_{n,g,h,i,\omega} \end{aligned} \tag{3}$$

- Industry emission definition [5] $\forall pt \in PT, n \in \mathcal{N}, i \in \mathcal{I}, \omega \in \Omega$

$$indEmiss_{pt,n,i,w} = PP_{pt,n,i} \cdot (1 - p_{n,pt,i,w}) \tag{4}$$

- Capture from power $\forall n \in \mathcal{N}, i \in \mathcal{I}, \omega \in \Omega$

$$\begin{aligned} &powCapt_{n,i,w} = \\ &\sum_{g \in GCCS, h \in \mathcal{H}} (E^{CCS}) \cdot Heatrate/E^{gen}_{g} \cdot FuelCont_{g} \cdot y^{\text{gen}}_{n,g,h,i,\omega} \end{aligned} \tag{5}$$

- Capture from industry $\forall pt \in PT, n \in \mathcal{N}, i \in \mathcal{I}, \omega \in \Omega$

$$indCapt_{pt,n,i,w} = PP_{pt,n,i} \cdot (p_{n,pt,i,w}) \tag{6}$$

3.4.2. Objective function

The following expression is added to the original objective function of EMPIRE (2). Note that the investment and operational capture cost of power is included in the EMPIRE cost components for each relevant power technology separately:

$$\begin{aligned} &\sum_{i \in \mathcal{I}, \omega \in \Omega} [\sum_{pt \in PT, n \in \mathcal{N}} Cui_{pt} \cdot indCapt_{pt,n,i,w} + \\ &\sum_{(n1,n2) \in CLA} Co_{n1,n2} \cdot f_{(n1,n2),i,w} + \\ &\sum_{(n1,n2) \in CLA} Cf_{n1,n2} \cdot tpCO2inv_{(n1,n2,i)} + \\ &\sum_{(n) \in NS} CfNS_{n} \cdot tpNSCO2inv_{(n,i)} + \\ &\sum_{(n) \in N} Cui \cdot storCO2_{n,i,w} \end{aligned} \tag{7}$$

The costs added in this expression are related to total capture, transport, and storage of CO_2 respectively. The expression for transport contains the investment decision per period for capacity between countries (i.e. $tpCO2inv_{(n1,n2,i)}$) and capacities for the North Sea transport (i.e. $tpNSCO2inv_{(n,i)}$) as well as operational cost for the unit flow of these.

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[5] Here the emission amount, i.e. $PP_{pt,n,i}$ corresponds to both process and energy generation emissions taking place within the fence of industrial sites

3.4.3. Constraints

Balance constraints: The sum of capture from power generation and industrial capture as well as inflow from connected countries should be equal to the sum of total outflow and stored CO_2 for a country in each period for all scenarios.

$$\begin{aligned}&\sum_{pt\in PT} indCapt_{pt,n,i,w} + powCapt_{n,i,w} + \\ &\sum_{(n1,n)\in CLA} f_{(n1,n),i,w} = \\ &\sum_{(n,n2)\in CLA} f_{(n,n2),i,w} + storCO2_{n,i,w} \qquad \forall n \in \mathcal{N}, i \in \mathcal{I}, \omega \in \Omega\end{aligned} \tag{8}$$

Capacity constraint: The total CO_2 storage in a country, n, should be less than its CO_2 storage capacity.

$$\begin{aligned}&\sum_{i\in\mathcal{I}} storCO2_{n,i,w} \leq StorCap_n^{CO2} \\ &n \in \mathcal{N}, \omega \in \Omega\end{aligned} \tag{9}$$

Cumulative capacity investments: The following equation sets the relation between CO_2 transport investments per period,i.e. $tpCO2inv_{(n1,n2,i)}$ and the cumulative investment variable $tpCO2inst_{(n1,n2,i)}$.

$$\sum_{i\in\mathcal{I},st.i<ii} tpCO2inv_{(n1,n2,i)} \leq tpCO2inst_{(n1,n2,ii)} \qquad \forall (n1,n2) \in CLA, ii \in \mathcal{I} \tag{10}$$

Flow capacities: The following constraint ensures that CO_2 flow per period cannot exceed installed capacity.

$$f_{(n1,n2),i,w} \leq tpCO2inst_{(n1,n2,i)} \qquad \forall (n1,n2) \in CLA, i \in \mathcal{I}, \omega \in \Omega \tag{11}$$

Similar relationships exists between the variables which represent the CO_2 transport investment around the North Sea, $tpNSCO2inv_{(n,i)}$,$tpNSCO2inst_{(n,i)}$ and storage:

$$\sum_{i \in \mathcal{I}, st.i<ii} tpNSCO2inv_{(n,i)} \leq tpNSCO2inst_{(n,ii)} \qquad \forall n \in NS, ii \in \mathcal{I} \tag{12}$$

$$storCO2_{n,i,w} \leq tpNSCO2inst_{(n,i)} \qquad \forall n \in N, i \in \mathcal{I}, \omega \in \Omega \tag{13}$$

Emission bound: The next constraint ensures emissions are not exceeding the upper bound for emissions based on the climate scenarios presented earlier.There are separate bounds for power and industrial emissions separately (Table C.16 and Table C.15).

$$\begin{aligned} &\sum_{n \in \mathcal{N}} pow(ind)Emiss_{n,i,w} \leq EmissionBoundPow(ind)_i \\ &\forall i \in \mathcal{I}, \omega \in \Omega \end{aligned} \tag{14}$$

The bounds for industrial emissions are scaled down from the values in Table C.16 to account for the share that will come from CCS as discussed in the previous section.

4. Results and Discussions

In order to analyze pathways for emission reductions using sector models like EMPIRE, long-term demand trajectories for power, the emission projections for industrial sectors, global commodity prices, CO_2 -budgets, and technology costs need to come from economy-wide and often global models like IAMs. The output from the EMPIRE model is technology investments for power generation technologies, transmission capacities, and CO_2 transport pipelines as well as operational detail for representative hours representing variability and uncertainty. With input from long-term pathways, more detailed sector models, like EMPIRE, provide strategies for technology choice and infrastructure investments at the country level, considering the short-term uncertainty and effects on operations.

4.1. Analyses of climate scenarios

As mentioned above, three different Shared Socio-economic Pathways (SSPs) are used as consistent socio-economic assumptions that represent development along distinct storylines [31], namely SSP1, SSP4, and SSP5. In addition, we include a long-term scenario representing a European ambition scenario where the total emissions are forced to be less than 3.34 GtCO_2 in 2050-2055 from the power sector and 2.26 GtCO_2 for industry.

For industry, we take the total projected emission reduction as input; and calculated the portion that CCS will be responsible for as described in Section 2.3. In the power sector, emissions emerge endogenously as the result of formulas presented before in Eq (1). Investments in CCS infrastructure for power, cement, refinery, and steel are similarly endogenous variables. The model decides the timing and which country and industry (cement, steel, refinery) to invest in, under the constraint that the total amount of CCS for industry matches the endogenously given demand for industrial CCS. For the power sector, CCS is considered as an alternative to renewable technologies and the investments are driven by target emission levels of the power sector for each scenario. CCS in power is therefore only linked to CCS in industry through the joint infrastructure for transport and storage.

Here we present the results of the analyses for SSP1, SSP4, and SSP5 as well as an EU ambition scenario for power and the industrial sector. Figure 3 presents an overview of emissions (on the positive y-axis) and reductions(on the negative y-axis) for the different pathways. Please note that CCS includes the captured, transported, and stored CO_2 from both power and industry, while we use ´other´ to summarize the rest of the emission reduction technologies in industry. Also, remaining emissions in power and industry are shown.

The EU ambition and the green-growth scenario, i.e. SSP1 (1.9 Wm^{-2}), have similar emission targets. There is a slight difference in terms of the speed of the emission reduction between these pathways; that is, EU ambition uses an upper bound on total carbon emissions of 2 GtCO_2 for the industry and power sectors combined between 2020-25 whereas SSP1 meets that bound around 2030-35. Hence the EU ambition scenario is slightly more ambitious than SSP1. These two scenarios are further referred to as ‘sustainability scenarios. For SSP4 (3.4 Wm^{-2}), which can be called a ‘mid-way scenario’, an emissions level below 2 GtCO_2 is reached only after 2040. SSP5 (8.5 Wm^{-2}), can be considered a ‘worst-case scenario’, where the minimum level of emission is between 2020-25 and total emissions increase constantly towards the end of the horizon.

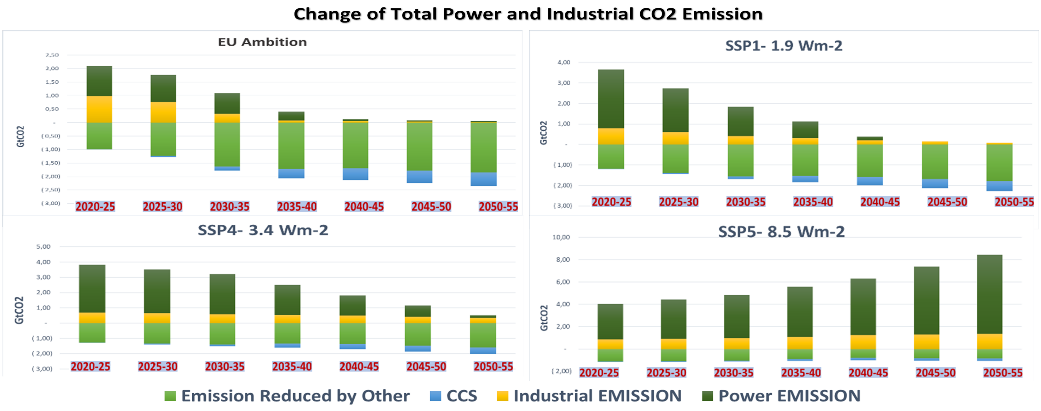

Figure 3: Net emission (positive vertical axis) and reduction regimes (negative vertical axis) of different climate scenarios, i.e. EU Ambition, SSP1 (1.9 Wm^{-2}) , SSP4 (3.4 Wm^{-2}), and SSP5 (8.5 Wm^{-2})

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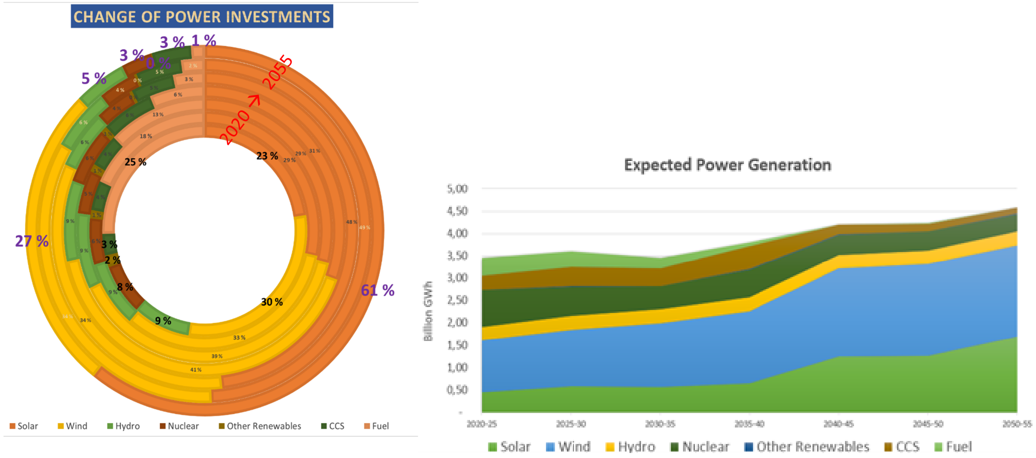
4.2. The power sector towards 2055

The main outputs of the EMPIRE model are summarized in Figure 4. In all scenarios, CCS is observed taking part among the green technologies, however its role as a new investment technology comes after some of the renewables in the power sector until 2055. All the pathways lead to an almost identical power mix with a high penetration and use of renewable resources. Among these, wind and solar together cover more than 70% of total generation followed by hydro resources with 7%. Then CCS and nuclear technologies are projected to act equally with 3-4% share for each within the total power generation pie. Solar dominates by the end of the horizon in terms of installed capacity with 61%, and it is followed by wind and hydro, with 27% and 5% respectively. Fuel and other renewable types exhibit diminishing behaviour along the horizon. On the cost side the highest entry does not change among the pathways: investments in renewable energy resources is estimated to cover at least 50% of all costs in all of the climate scenarios.

Among all cost components total cost for CCS technologies' ranges between 16-2%, with the highest investment in EU Ambition and the lowest in the worst-case scenario.

CCS costs in the model represent total expenses for industrial capture and investment and generation cost for any CCS power source as well as transport and storage. Total for new investment and corresponding power generation



(a) Power investments by 2055 (b) Distribution of expected power generation mix.

Figure 4: (a)Power Capacity Investments; (b)Expected Power Generation

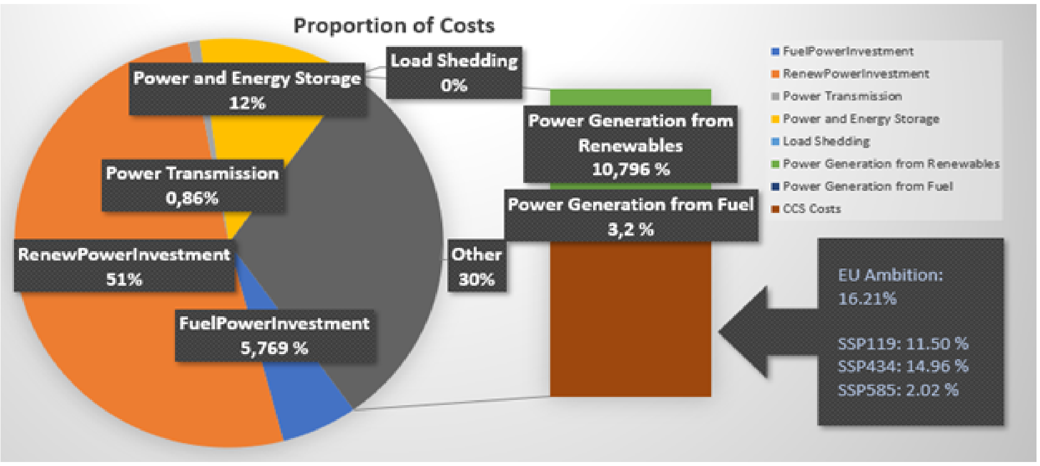


Figure 5: Total System Cost Breakdown

cost for power technologies with CCS are approximately 227 billion and 306 billion Euros respectively for SSP1-1.9 Wm^{-2} and EU Ambition (Figure 5). The mid-way scenario, i.e. SSP4-3.4 Wm^{-2} projects around 227 billion Euros as well, while the worst-case scenario foresees only around 13 billion Euros. Then the next largest CCS cost component is CO_2 transport which is estimated to reach 59 billion Euros for EU Ambition, 22.47 billion Euros for the mid-way and only 3.77 billion Euros for the worst-case scenario. It is followed by the cost for storage which varies between 24 and 3.2 billion Euros for sustainability scenarios and the worst-case scenario respectively. Finally, the cost for industrial CO_2 capture varies between 11.6-5.5 billion Euros. A fixed level of 3% yearly cost reduction is assumed for all CCS-related costs across all scenarios to account for technology learning.

4.3. Industrial Capture towards 2055

All the pathways in the study take an increasing need for total capture from industry over time as input. The set of maps in Figure 6 depict the output of the model regarding details of how industrial CCS can be realized in the four pathways. One of the main conclusions is the dominance of capture in the steel sector, then followed by cement and refineries. This ranking is intuitive considering the unit capture cost of each sector. Capture from the steel and cement industry exhibits rather consistent behavior across the sustainability and the mid-way scenarios. Germany, Norway, the UK, Belgium are the common countries capturing from steel sector for all scenarios. For the cement sector, the list changes: Denmark, Netherlands and Norway appears as the member of core group. Capture from refineries occur only for sustainability and mid-way scenarios. Netherlands and Norway seem to be the common countries of this list for the relevant pathways. In Figure 7, we compare ´EU ambition´ with the mid-way and worst-case scenarios. In terms of timing, the steel sector appears as the front-runner in all scenarios starting in the 2020-2025 period. For all the scenarios, the UK takes the lead. Starting date for all participant countries fluctuate among pathways. In the sustainability pathways the UK captures most from the steel, while in less optimistic scenarios Germany leads this sector. As an eye-catching difference from other sectors, Poland, Czech Republic, Luxembourg, Ireland and France contribute with relatively small amounts. When the worst-case scenario is considered, country mix for capturing countries is limited to Germany, Norway, the UK and Belgium.

Capture from the cement sector starts after 2025. Country mix for capturing from cement sector is also stable between the sustainability and the mid-way scenarios except for Ireland. Ireland seems to be contributing to EU Ambition with small amounts. For the worst-case scenario the duration and the capturing countries are rather narrow. For refineries, sustainability scenarios envisage the time interval between 2035 and 2040, while in the mid-way scenario CCS occurs between 2045 and 2050. For the sustainability scenarios, Germany leads in both the steel and cement sectors with total capture of more than 700 MtCO_2 from steel for both of the sustainability scenarios. In the worst-case scenario they continue capturing from steel with around 400 MtCO_2. In the lower end of the capturing countries, we find Finland, Poland and Ireland. For the mid-way scenario, the interval for steel is comparable, also ranging between 60 and 660 MtCO_2 for the capturing countries. For cement, the capture reduces to 8 MtCO_2 for Norway in the lower end and 165 MtCO_2 for Germany in the higher end. The change is drastic when moving to the worst-case scenario with nearly halved values for the steel sector, now between 85 and 410 MtCO_2, and cement sector between 10 and 100 MtCO_2. The range of capture amount from refineries varies between 6 and 70 MtCO_2 for the ´EU Ambition´ scenario, between 3 and 25 MtCO_2 for SSP1, and between 3 and 40 MtCO_2 for the mid-way scenario. In the worst-case scenario, there is no capture from refineries.

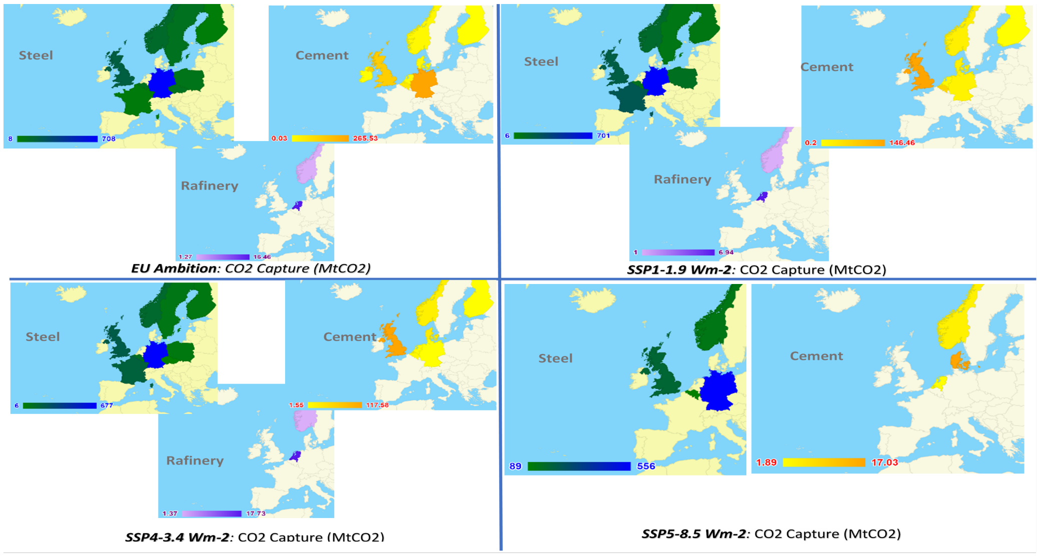


Figure 6: Total CO_2 Capture from each sector for all scenarios by 2055

The countries are represented in bubble charts in Figure 8, where industrial emission and capture are depicted on the vertical and horizontal axis respectively. The color scale aims to give an idea about the CO_2 storage of countries. If the ratio of capture to industrial emission amount is interpreted as a measure for the fulfillment of sustainability objectives, the countries close to the chart‘s right bottom corner perform better. Conversely, countries which lie around the left top corner are the ones which perform poorly with high emission and low capture. From this perspective the UK is differ-

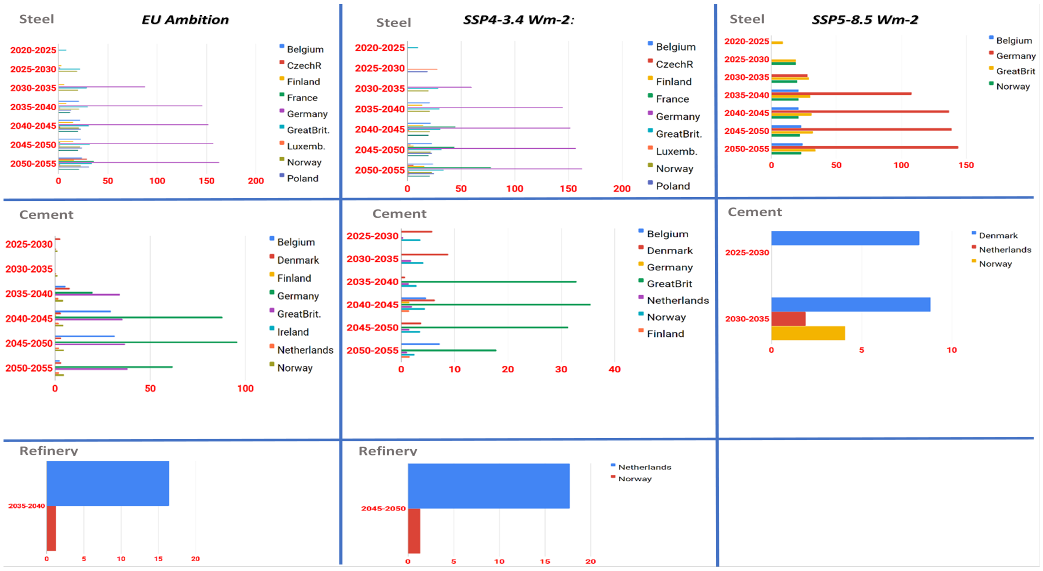
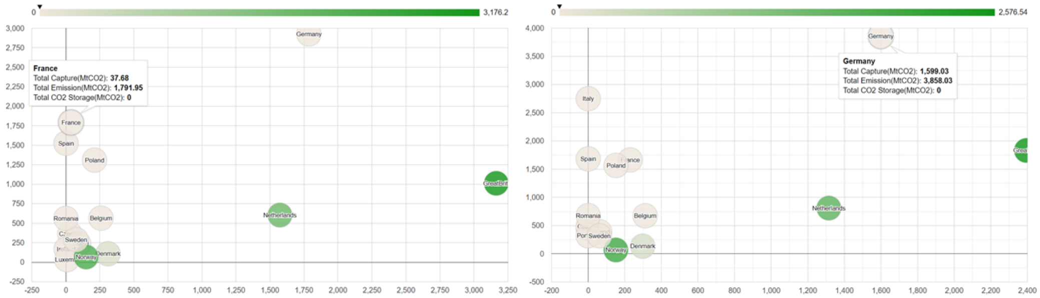


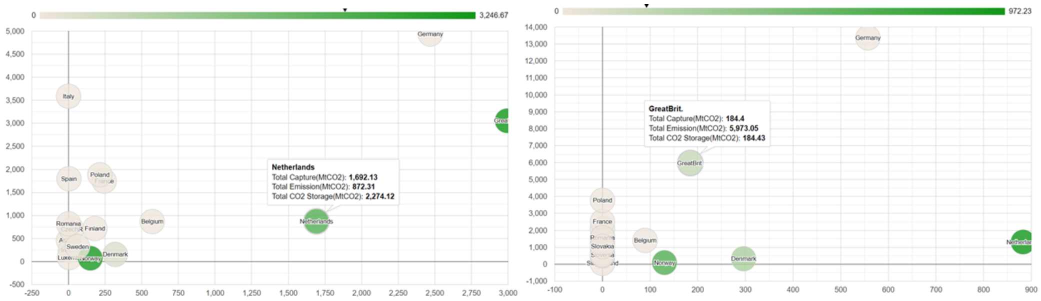
Figure 7: Timeline of CO_2 Capture from key sectors for one ‘sustainability’ scenario (EU Ambition), the ’mid-way’ scenario (SSP4-3.4 Wm^{-2}) and the ’worst-case’ scenario (SSP5-8.5 Wm^{-2})

entiated clearly from the rest by occupying the lower right side in all of the scenarios, by leading the capture (horizontal axis) in all but the worst-case scenario and staying at a moderate height for the net emission. The UK also leads storing together with Norway with dark green color. The Netherlands follows with capturing and storing although it emits similar amounts to Austria and Sweden. Netherlands has also another significant role as the most sustainable country in the worst case scenario. Similarly, Belgium is distinct from the capture perspective, in addition to emitting low, neck to neck with Romania, Czech Republic and Portugal. Top five net emitters stay same across scenarios as Germany, France, Italy, Spain, Poland, and the UK with different permutations. Note that there are countries which have industrial emission projections approximately between 500-150 MtCO_2 such as Austria, Bulgaria, Croatia, Hungary, and countries that have net emission levels under 50 MtCO_2 such as Switzerland, Luxemburg, Slovenia, Latvia, Estonia, Serbia, Bosnia, Makedonia which are modelled but not included in the bubble chart.



(a) EU Ambition

(b) SSP1-1.9 Wm^{-2}



(c) SSP4-3.4 Wm^{-2}

(d) SSP5-8.5 Wm^{-2}

Figure 8: Industrial emission (vertical axis) versus CO_2 capture from industry (horizontal axis) by country (in $MtCO_2$), together with CO_2 storage. Color intensifies as the amount of CO_2 storage increases.

4.4. Synergy Between Power and Industrial Sectors

The regional distribution of CO_2 capture from the power sector is shown in Figure 10. The starting date for this capture is projected between 2025 and 2030 for most of the scenarios. In order to achieve EU Ambition it should start until 2025. One of the main goals of this study is to reveal any synergies between the power and industry sectors. The storyline behind Figure **??** is framed by the question of 'how total CCS costs would change if the system starts with capturing only from power and then includes industrial sectors of interest, i.e. sharing the same infrastructure'. Furthermore, the question of 'how much total capture changes under this circumstance' accompanies. Resultant percentages for all the climate scenarios show us that with relatively less increase in total CCS cost, higher ratios of capture is attained through using the same infrastructure for both power and industry. For instance, by including industry to the infrastructure that was capturing only from power sector, total CCS costs would increase 6% in 'EU Ambition' pathway. After this investment the total capture from both power and industrial sectors will be 19% more than the amount that only power sector was capturing.

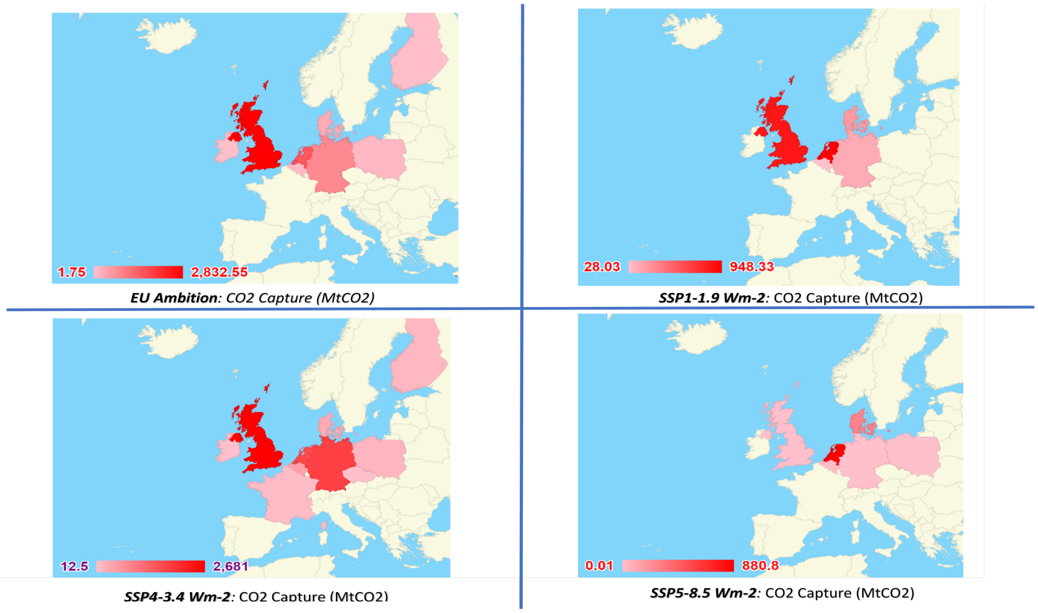


Figure 9: CO_2 capture from power sector for each climate scenario.

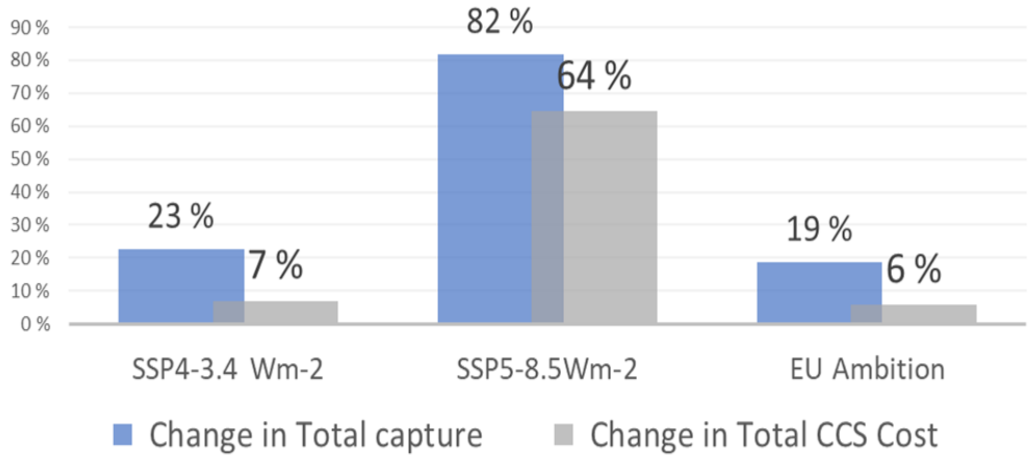


Figure 10: Relative changes when a CCS infrastructure capturing from only power sector includes industrial CCS.

4.5. Where to Store

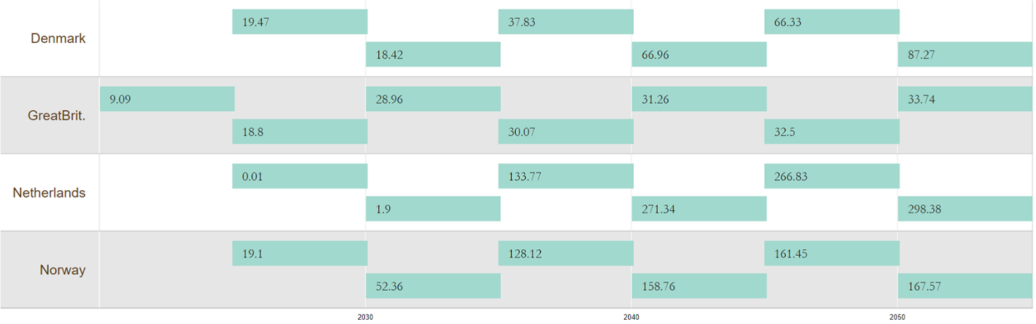
The captured volumes from all sectors must be stored, and the model thus optimizes the storage investments at pre-selected offshore storage locations. Due to the controversies of onshore storage from legal and social acceptance aspects, only four countries (Denmark, the Netherlands, Norway, and the UK) are assumed to be able to store until 2055, all of which have offshore storing capability. Individual storage investments of each country are represented by colors as the third dimension on the bubble chart. As expected, given the storage locations, the countries involved in CCS are distributed around the North Sea. The optimal capturing countries are the ones close to storing locations since it helps reducing the transportation costs. The amount of storage for each country per period is shown in Figure 11. One of the two generic conclusions for all scenarios regarding CO_2 storage The UK is the leading country by starting storing by 2020 with captures from steel and power. The UK is stated as the most capturing country above. It stores all its capture and this makes the UK also the most storing country in most of the scenarios. Then it is followed by Norway, Denmark and the Netherlands which start storing between 2025-2030 for all scenarios. The worst-case scenario acts differently also in terms of the ranking of most storing. Denmark and the UK store mostly their own captured CO_2 except for the scenarios where Poland and Ireland capture. The Netherlands and Norway are CO_2

storage providers for other European countries. This means, they store more than their own captured CO_2. The total amount of CO_2 stored in the UK ranges between 184-3246 MtCO_2. Norway's storage amount varies between 688-3113 MtCO_2, while total storage of the Netherlands is observed between 972-2274 MtCO_2, and finally Denmark stores consistently 290 MtCO_2.

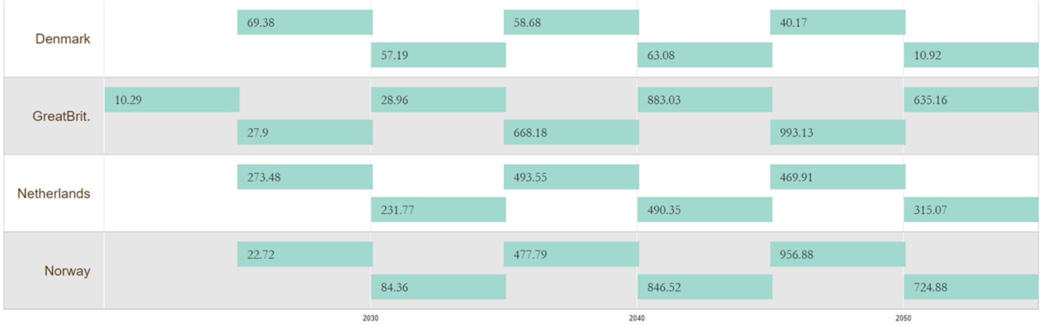
4.6. How to Transport

Investments in a limited number of transport corridors allow for capturing ability outside the major storing countries. Figure 12 provides an overall idea about the directions and weights of these connections for a representative sustainability and mid-way scenario. In particular, Germany exports to Norway, and Belgium exports to the Netherlands for all scenarios. Furthermore, a Finland-Norway connection is also observed in the sustainability scenarios with a capacity of around 13 MtCO_2 per 5 year period. The UK and Denmark generally do not import, i.e. they store only what they capture. Exceptions occur when Ireland captures and ships to the UK, and Poland captures and ships some portion to Denmark. On the other hand Poland also captures in order to achieve EU Ambition or mid-way scenario trajectories. In this respect Germany and Belgium acts as transshipment nodes between other capturing countries and storing countries, particularly Norway and Netherlands. These two main connections between these pairs happen even in the worst-case scenario (Figure13 (b))

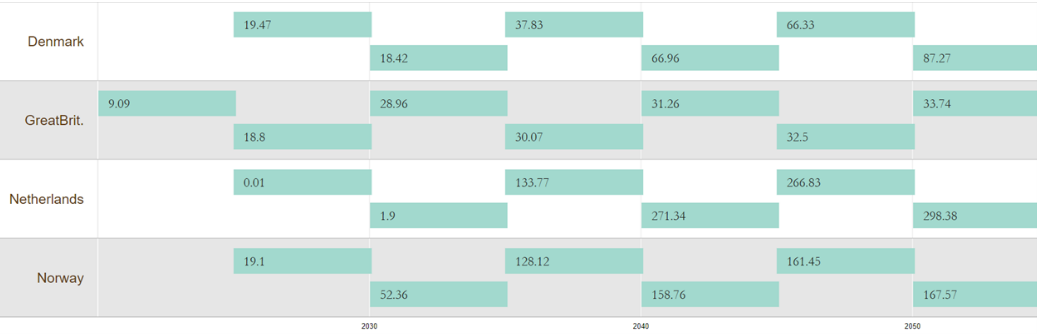
The transport investments that connect Belgium to the Netherlands are projected to be completed between 2035-2045 with slightly differing capacities 21-116 MtCO_2 per period across scenarios (Figure 13). On the other hand, the Germany-Norway connection is projected to be kicked-off as early as 2025 for EU Ambition and by 2030 for the other pathways. This connection is to be built with increasing capacity investments and continues to the end of the horizon. Since Norway is modelled with more details, i.e. five separate regions, some internal connections are also generated in the results for this country.



(a) SSP1-1.9 Wm^{-2}

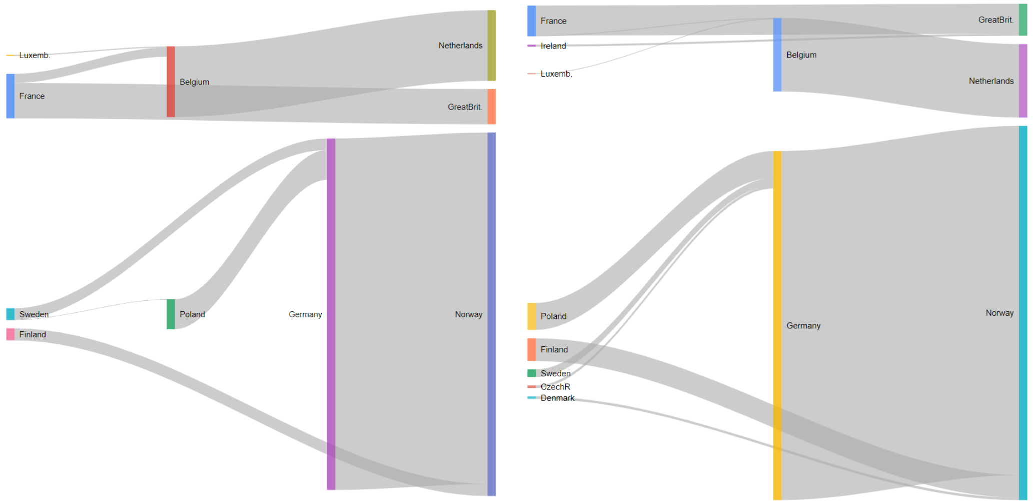


(b) SSP4-3.4 Wm^{-2}



(c) SSP5-8.5 Wm^{-2}

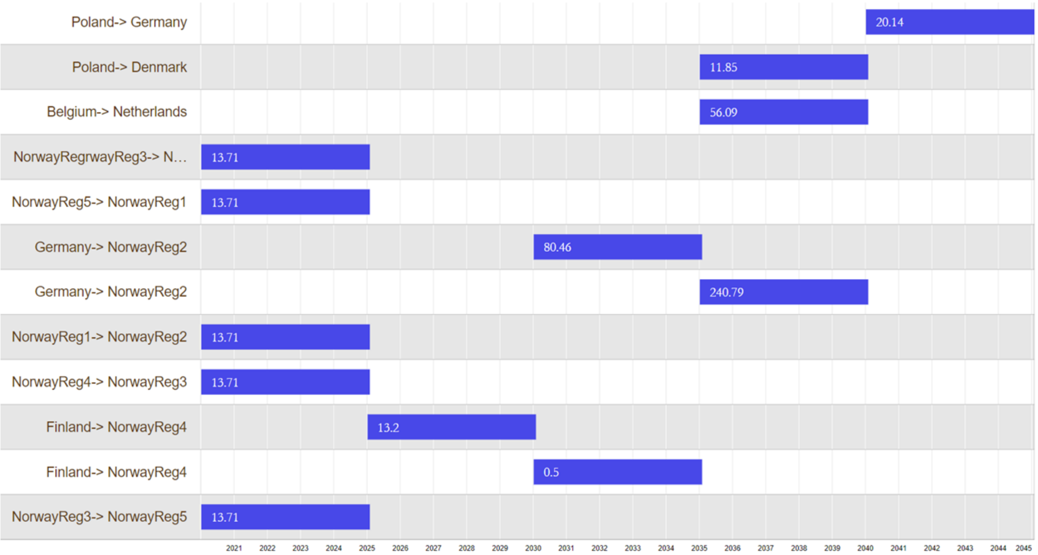
Figure 11: Timeline of CO_2 stored amount ($MtCO_2$: (a) ‘sustainability’ scenario (EU Ambition) (b) the ’mid-way’ scenario (SSP4-3.4 Wm^{-2}) (c) the ’worst-case’ scenario (SSP5-8.5 Wm^{-2})



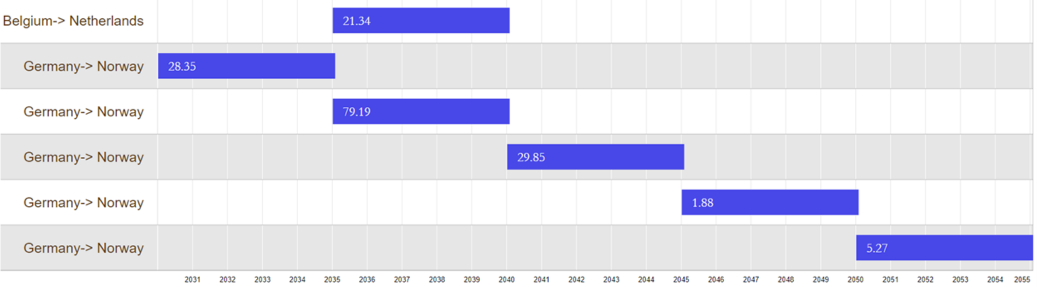
(a) EU Ambition

(b) SSP4-3.4 Wm^{-2}

Figure 12: Major transportation connections (MtCO$_2$: (a) for ’sustainability’ scenarios (ex: EU Ambition) (b) the ’mid-way’ scenario (SSP5)



(a) SSP1-1.9 Wm^{-2}



(b) SSP5-8.5 Wm^{-2}

Figure 13: Timeline of CO_2 transport capacity investments ($MtCO_2$: (a) for 'sustainability' scenarios (ex: SSP1-1.9 Wm^{-2}) (b) the 'worst-case' scenario (SSP5)

5. Conclusion

The decarbonization of the industry sectors steel, refineries, and cement is challenging, as they have process-related emissions in addition to the energy-related emissions. The recommendations published by the High-Level Group of energy-intensive industries recently, highlighted the EU's commitment to support sustainability goals of these sectors. This study contributes to the literature through showing how CCS might evolve in the power sector and industry of Europe, scrutinizing details such as stochasticity of renewable supply and loads of energy, and industrial demand for CCS in a regional analysis for the first time. Four different emission pathways are investigated in order to shed light on the future of CCS, outlining their effects on the different countries and timing of investments for CCS in four sectors: power, cement, steel, and refineries. The steel sector has the lowest unit capture cost and shows consistent behavior across the different pathways playing a major role in industrial emission reduction. It is followed by cement sector which starts as early as 2025 regardless of the scenario but is more volatile in terms of the capture levels of involved countries. For refineries capturing country mix stays same across all climate pathways which consist of Netherlands and Norway. The worst-case climate scenario no capture from refineries is observed.

Availability of CO_2 storage locations, shapes the results to a great extent. Here, only four European countries with offshore CO_2 storing potentials are considered due to social acceptance challenges of onshore CO_2 storage [50]. Among those, Norway is providing storage to Germany. Similarly Netherlands provides storage to Belgium. Norway is the only country which captures from three of the sectors at significant levels. On the other hand the UK is projected to be an early mover for CCS, both for capture and storage of CO_2. The model is built allowing fully connected CO_2 networks. However, results indicate interactions between some countries are useful based on their emission level and geographical locations. In particular, results indicate that Germany ships to Norway and Belgium ships to the Netherlands to store. These two connections need to be invested even in the worst-case scenario. There are various countries involved in capturing on broad scale of captured amount which are connecting to the CCS network through Belgium and Germany as well as shipping directly to Norway and Netherlands.

Moreover, it should be noted that decarbonizing the power system through construction of new fossil plants with CCS is promoted with the synergy created with industrial sectors. Still, renewable technologies such as solar, wind and hydro are projected to be dominating the power sector. New power investments with CCS is anticipated to follow these with 4% share among all new power investments. As the next step, we plan to implement retrofitting in the power sector and also introduce the possibility to trade emission reductions between industry and the power sector. While retrofitting will make CCS more attractive in the power sector, the effect of trading will depend on the assumptions on the capture cost. With current costs it is to be expected that this will increase the ambition of emission reduction in the power sector while delaying ambition in industry. Another future extension might be about extending the studied scenario set with more focused and regional decarbonization projections.

6. List of Abbreviations

CCS: Carbon Capture and Storage IPCC: Intergovernmental Panel on Climate Change's IAM: Integrated Assessment Models SSPs: Shared Socioeconomic Pathways IEA: International Energy Agency CTS: Clean Technology Scenario EU: European Union GESTCO: Geological Storage of CO_2 from Combustion of Fossil Fuel CASTOR: From Capture to Storage; EU funded CCS project between 2004-2008.

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8. Nomenclature

Table 3: CCS related sets

PT	:	Set of industrial plant types (Steel, cement, refinery)
GCCS	:	Generator technology set for technologies with carbon capture
ERG	:	Generator technology set for technologies without carbon capture, i.e. pure emitting and renewable technologies
CLA	:	Directional CO_2 transport channel between countries, i.e. from n1 to n2
N	:	Set of all countries
NC	:	Subset with the countries around the North Sea
I	:	Set of investment periods

Table 4: Decision variables in addition to the standard EMPIRE model

	Long term variables in investment step
$tpCO2inv_{n1,n2,i}$	Invested capacity for transport of CO_2 from one country, $n1$ to another, $n2$, at period i
$tpCO2inst_{n1,n2,i}$	Cumulative invested capacity for transport of CO_2 from one country,$n1$ to another, $n2$, up until period i
$tpNSCO2inv_{n,i}$	Invested capacity for transport of CO_2 at one North Sea country, n at period i
$tpNSCO2inst_{n,i}$	Cumulative invested capacity for transport of CO_2 at one North Sea country, n, up until period i
	Short-term variables for operation
$f_{(n1,n2),i,w}$:	CO2 flow from node $n1$ to node $n2$ where $(n1, n2) \in CLA$ at period i and year y for scenario w.
$p_{n,pt,i,w}$:	Industrial CO_2 capture percentage at plant type pt of node n at period i for scenario w, which $p \in [0, 1]$.
$powEmiss_{n,i,w}$	CO_2 Emission from power sources at country n at period i for scenario w.
$indEmiss_{n,i,w}$	CO_2 Emission from industrial sources at country n at period i for scenario w.
$powCapt_{n,i,w}$	CO_2 Capture from power sources at country n at period i for scenario w.
$indCapt_{n,i,w}$	CO_2 Capture from industrial sources at country n at period i for scenario w.
$stor\mathrm{CO}_{2n,i,w}$	CO_2 storage at country n at period i for scenario w.

Table 5: Parameters in addition to the EMPIRE‘s existing set

Cui_{pt}	:	Unit carbon capture cost for industry (Euro/tCO_2)
$Cuis$	:	Unit CO_2 storage cost (Euro/tCO_2)(i.e. steady level which is only multiplied by discount factors)
$Cf_{n1,n2}$	:	Per period capital cost (Euro/tone) of transport investment from one country $n1$ to country $n2$
$Co_{n1,n2}$	:	Unit operating cost for transporting one tone of CO_2 from one country $n1$ to country $n2$
$CfNS_n$	:	Per period capital cost (Euro/tone) transport investment at country n around North Sea
E^{CCS}	:	Capture efficiency of CCS technology ct.
E_g^{gen}	:	Generator efficiency of g
$StorCap_n^{CO2}$		Total CO_2 storage capacity of country n
$FuelCont_g$		CO_2 content of the fuel used in generator g
$PP_{pt,n,i}$	:	Emission from plant type pt at country n at period i
$Emission$ $BoundInd_i$	:	External emission bound for industrial sources (i.e. from the valid SSP used for the current analysis) at period i
$Emission$ $BoundPow_i$	:	External emission bound for power sources from the valid SSP scenario at period i
$Learn$ $RedRate_i$	:	Multiplier to represent cost reduction due to learning at period i

Appendix A. Input Data for Power and Energy Modelling

Below we include the parameter values used in the power and energy model.

Table A.6: Fuel Costs (Euro/GJ)

	2020	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Liginiteexisting	1.40	1.40	1.50	1.50	1.50	1.50	1.50
Lignite	1.40	1.40	1.50	1.50	1.50	1.50	1.50
LigniteCCSadv	1.40	1.40	1.50	1.50	1.50	1.50	1.50
Coalexisting	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Coal	2.39	2.39	2.39	2.39	2.39	2.39	2.39
CoalCCSadv	2.39	2.39	2.39	2.39	2.39	2.39	2.39
CoalCCS	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Gasexisting	5.05	6.00	6.47	6.11	6.45	6.67	6.03
GasOCGT	5.05	6.00	6.47	6.11	6.45	6.67	6.03
GasCCGT	5.05	6.00	6.47	6.11	6.45	6.67	6.03
GasCCSadv	5.05	6.00	6.47	6.11	6.45	6.67	6.03
Oilexisting	12.50	14.20	15.60	16.30	17.30	17.70	18.10
Bioexisting	8.23	9.05	9.96	10.95	12.05	13.25	14.58
Bio10cofiring	2.97	3.47	4.07	4.35	4.60	4.85	5.08
Bio10cofiringCCS	2.97	3.47	4.07	4.35	4.60	4.85	5.08
Nuclear	1.04	1.06	1.08	1.10	1.13	1.15	1.17
Wave	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geo	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydroregulated	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrorun-of-the-river	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bio	8.23	9.05	9.96	10.95	12.05	13.25	14.58
Windonshore	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Windoffshore	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A.7: Capital Investment Cost (Euro/MWatt). Source (ZEP, 2013);Fraunhofer ISE (2015);Gerbaulet Lorenz (2017).

	2020	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Liginiteexisting	0	0	0	0	0	0	0
Lignite	1600	1600	1600	1600	1600	1600	1600
LigniteCCSadv	2600	2600	2530	2470	2400	2330	2250
Coalexisting	0	0	0	0	0	0	0
Coal	1500	1500	1500	1500	1500	1500	1500
CoalCCSadv	2500	2500	2430	2370	2300	2230	2150
CoalCCS	3523	3523	3523	3523	3523	3523	3523
Gasexisting	0	0	0	0	0	0	0
GasOCGT	400	400	400	400	400	400	400
GasCCGT	800	800	800	800	800	800	800
GasCCSadv	1350	1350	1330	1310	1290	1270	1250
Oilexisting	0	0	0	0	0	0	0
Bioexisting	0	0	0	0	0	0	0
Bio10cofiring	1600	1600	1600	1600	1600	1600	1600
Bio10cofiringCCS	2600	2600	2530	2470	2400	2330	2250
Nuclear	6000	6000	6000	6000	6000	6000	6000
Wave	5288	4906	4525	4144	3763	3381	3000
Geo	5500	5500	5500	5500	5500	5500	5500
Hydroregulated	3000	3000	3000	3000	3000	3000	3000
Hydrorun-of-the-river	4000	4000	4000	4000	4000	4000	4000
Bio	2250	2250	2250	2250	2250	2250	2250
Windonshore	1033	1002	972	942	912	881	851
Windoffshore	3205	2770	2510	2375	2290	2222	2172
Solar	826	653	481	463	445	427	409

Table A.8: Fixed O& M Cost (Euro/GJ). Source (ZEP, 2013).

	2020	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Liginiteexisting	32.40	32.40	32.40	32.40	32.40	32.40	32.40
Lignite	32.40	32.40	32.40	32.40	32.40	32.40	32.40
LigniteCCSadv	51.37	51.37	50.04	48.71	47.39	46.06	44.73
Coalexisting	31.05	31.05	31.05	31.05	31.05	31.05	31.05
Coal	31.05	31.05	31.05	31.05	31.05	31.05	31.05
CoalCCSadv	46.96	46.96	45.85	44.73	43.62	42.50	41.39
CoalCCS	78.30	78.30	78.30	78.30	78.30	78.30	78.30
Gasexisting	19.50	19.50	19.50	19.50	19.50	19.50	19.50
GasOCGT	19.50	19.50	19.50	19.50	19.50	19.50	19.50
GasCCGT	30.38	30.38	30.38	30.38	30.38	30.38	30.38
GasCCSadv	46.88	46.88	46.88	46.88	46.88	46.88	46.88
Oilexisting	19.50	19.50	19.50	19.50	19.50	19.50	19.50
Bioexisting	46.34	45.33	44.33	43.32	42.31	41.30	40.30
Bio10cofiring	32.40	32.40	32.40	32.40	32.40	32.40	32.40
Bio10cofiringCCS	51.37	51.37	50.04	48.71	47.39	46.06	44.73
Nuclear	126.99	123.26	119.52	115.79	112.05	108.32	104.58
Wave	153.85	153.85	153.85	153.85	153.85	153.85	153.85
Geo	92.31	92.31	92.31	92.31	92.31	92.31	92.31
Hydroregulated	125.00	125.00	125.00	125.00	125.00	125.00	125.00
HydroRoR	125.00	125.00	125.00	125.00	125.00	125.00	125.00
Bio	46.34	45.33	44.33	43.32	42.31	41.30	40.30
Windonshore	52.63	51.74	50.85	49.97	49.08	48.19	47.30
Windoffshore	127.57	122.37	117.16	111.96	106.76	101.56	96.36
Solar	18.57	17.14	15.71	14.29	12.86	11.43	10.00

Table A.9: Variable O&M Cost. Source (ZEP, 2013).

GeneratorTechnology	**VariableOMcosts_in_euro_per_MWh**
Liginiteexisting	0.48
Lignite	0.48
LigniteCCSadv	3.28
Coalexisting	0.46
Coal	0.46
CoalCCSadv	2.46
CoalCCS	1.16
Gasexisting	0.45
GasOCGT	0.45
GasCCGT	0.45
GasCCSadv	1.85
Oilexisting	0
Bioexisting	0
Bio10cofiring	0.48
Bio10cofiringCCS	3.28
Nuclear	1.5
Wave	0
Geo	0
Hydroregulated	0
Hydrorun-of-the-river	0
Bio	3
Windonshore	0
Windoffshore	0
Solar	0

Table A.10: Lifetime of Technologies

Technology	**Lifetime (yr)**
Liginiteexisting	40
Lignite	35
LigniteCCSadv	35
Coalexisting	40
Coal	35
CoalCCSadv	35
Gasexisting	30
GasOCGT	35
GasCCGT	35
GasCCSadv	35
Oilexisting	40
Bioexisting	40
Bio10cofiring	35
Nuclear	35
Wave	30
Geo	35
Hydroregulated	35
Hydrorun-of-the-river	35
Bio	30
Windonshore	30
Windoffshore	30
Solar	30
CoalCCS	35
GasCCS	35

Appendix B. Emission projections for three industrial sectors (based on assumption that current growth rate of manufacturing stays same until 2055)

Table B.11: Emission projections from Cement Industry (MtCO_2) per 5 yr period

CEMENT (MtCO_2)

	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2055
Austria	18.10	18.79	19.50	20.24	21.01	21.81	22.64
BosniaH	-	-	-	-	-	-	-
Belgium	32.60	33.84	35.12	36.46	37.84	39.28	40.78
Bulgaria	9.85	10.22	10.61	11.02	11.43	11.87	12.32
Switzerland	5.95	6.18	6.41	6.65	6.91	7.17	7.44
CzechR	17.35	18.01	18.69	19.40	20.14	20.91	21.70
Germany	132.50	137.54	142.76	148.19	153.82	159.66	165.73
Denmark	10.25	10.64	11.04	11.46	11.90	12.35	12.82
Estonia	1.75	1.82	1.89	1.96	2.03	2.11	2.19
Spain	77.23	80.16	83.21	86.37	89.65	93.06	96.59
Finland	4.90	5.09	5.28	5.48	5.69	5.90	6.13
France	66.15	68.66	71.27	73.98	76.79	79.71	82.74
GreatBrit.	38.25	39.70	41.21	42.78	44.40	46.09	47.84
Greece	30.27	31.42	32.61	33.85	35.13	36.47	37.86
Croatia	8.90	9.24	9.59	9.95	10.33	10.72	11.13
Hungary	5.93	6.15	6.38	6.63	6.88	7.14	7.41
Ireland	14.35	14.90	15.46	16.05	16.66	17.29	17.95
Italy	65.51	68.00	70.58	73.27	76.05	78.94	81.94
Lithuania	3.71	3.85	3.99	4.14	4.30	4.46	4.63
Luxemb.	2.96	3.07	3.18	3.30	3.43	3.56	3.70
Latvia	2.53	2.63	2.73	2.83	2.94	3.05	3.16
Macedonia	-	-	-	-	-	-	-
Netherlands	2.20	2.28	2.36	2.45	2.55	2.64	2.75
Norway	4.85	5.03	5.23	5.42	5.63	5.84	6.07
Poland	98.50	102.24	106.13	110.16	114.35	118.69	123.20
Portugal	15.21	15.79	16.39	17.01	17.66	18.33	19.02
Romania	26.79	27.80	28.86	29.96	31.09	32.28	33.50
Serbia	-	-	-	-	-	-	-
Sweden	13.80	14.32	14.87	15.43	16.02	16.63	17.26
Slovenia	2.91	3.02	3.14	3.25	3.38	3.51	3.64
Slovakia	15.25	15.83	16.43	17.06	17.70	18.38	19.07

Table B.12: Emission projections from Steel Industry (MtCO_2) per 5 yr period

STEEL (MtCO_2)

	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2055
Austria	13.85	14.38	14.92	15.49	16.08	16.69	17.32
BosniaH	-	-	-	-	-	-	-
Belgium	23.85	24.75	25.69	26.67	27.68	28.73	29.83
Bulgaria	0.55	0.57	0.59	0.61	0.63	0.66	0.68
Switzerland	-	-	-	-	-	-	-
CzechR	28.75	29.84	30.98	32.15	33.38	34.64	35.96
Germany	163.34	169.54	175.98	182.67	189.61	196.82	204.30
Denmark	-	-	-	-	-	-	-
Estonia	-	-	-	-	-	-	-
Spain	30.70	31.86	33.07	34.33	35.63	36.99	38.39
Finland	15.90	16.50	17.13	17.78	18.46	19.16	19.89
France	107.86	111.95	116.21	120.62	125.21	129.97	134.90
GreatBrit.	33.60	34.88	36.20	37.58	39.01	40.49	42.03
Greece	-	-	-	-	-	-	-
Croatia	-	-	-	-	-	-	-
Hungary	3.65	3.79	3.93	4.08	4.24	4.40	4.57
Ireland	-	-	-	-	-	-	-
Italy	43.70	45.36	47.08	48.87	50.73	52.66	54.66
Lithuania	-	-	-	-	-	-	-
Luxemb.	1.90	1.97	2.05	2.12	2.21	2.29	2.38
Latvia	-	-	-	-	-	-	-
Macedonia	-	-	-	-	-	-	-
Netherlands	-	-	-	-	-	-	-
Norway	23.00	23.87	24.78	25.72	26.70	27.71	28.77
Poland	37.55	38.98	40.46	42.00	43.59	45.25	46.97
Portugal	-	-	-	-	-	-	-
Romania	21.20	22.01	22.84	23.71	24.61	25.55	26.52
Serbia	-	-	-	-	-	-	-
Sweden	21.19	22.00	22.83	23.70	24.60	25.53	26.50
Slovenia	-	-	-	-	-	-	-
Slovakia	44.35	46.04	47.78	49.60	51.49	53.44	55.47

Table B.13: Emission Projections from Refineries (MtCO_2) per 5 yr period

	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2055
Austria	14.90	15.47	16.05	16.66	17.30	17.95	18.64
BosniaH	-	-	-	-	-	-	-
Belgium	30.19	31.33	32.52	33.76	35.04	36.37	37.76
Bulgaria	8.20	8.51	8.84	9.17	9.52	9.88	10.26
Switzerland	0.60	0.62	0.65	0.67	0.70	0.72	0.75
CzechR	1.71	1.77	1.84	1.91	1.98	2.05	2.13
Germany	118.43	122.93	127.60	132.45	137.48	142.71	148.13
Denmark	2.16	2.24	2.32	2.41	2.50	2.60	2.70
Estonia	-	-	-	-	-	-	-
Spain	70.85	73.54	76.34	79.24	82.25	85.37	88.62
Finland	15.81	16.41	17.03	17.68	18.35	19.05	19.77
France	54.16	56.22	58.35	60.57	62.87	65.26	67.74
GreatBrit.	60.28	62.57	64.94	67.41	69.97	72.63	75.39
Greece	29.34	30.45	31.61	32.81	34.06	35.35	36.70
Croatia	7.68	7.97	8.27	8.58	8.91	9.25	9.60
Hungary	6.85	7.11	7.38	7.66	7.95	8.25	8.57
Ireland	1.57	1.62	1.69	1.75	1.82	1.89	1.96
Italy	92.85	96.38	100.04	103.84	107.79	111.88	116.14
Lithuania	9.15	9.50	9.86	10.23	10.62	11.03	11.44
Luxemb.	-	-	-	-	-	-	-
Latvia	-	-	-	-	-	-	-
Macedonia	-	-	-	-	-	-	-
Netherlands	55.19	57.29	59.46	61.72	64.07	66.50	69.03
Norway	4.25	4.41	4.58	4.75	4.93	5.12	5.32
Poland	9.50	9.86	10.24	10.62	11.03	11.45	11.88
Portugal	17.14	17.79	18.47	19.17	19.90	20.65	21.44
Romania	12.20	12.66	13.14	13.64	14.16	14.70	15.26
Serbia	-	-	-	-	-	-	-
Sweden	13.05	13.55	14.06	14.59	15.15	15.73	16.32
Slovenia	-	-	-	-	-	-	-
Slovakia	7.25	7.53	7.81	8.11	8.42	8.74	9.07

Table B.14: Fuel Content of Generators. Source EIA

EmittingGenerators	fuelCO2content
Lignite	0.102
Coal	0.109
GasOCGT	0.075
GasCCGT	0.075
Oil	0.077
Bio10cofiring	0.088
Bio	0.088

Appendix C. SSP Scenario Summaries and Storylines

These are based on IAMC scenarios [2] Shared Socio-economic Pathways [31].

SSP1-19 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation, radiative forcing target of 1.9 W/m^2)

The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP4-3.4 A Road Divided (Low challenges to mitigation, high challenges to adaptation, radiative forcing target 1.9W/m^2 in 2100):

Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor-intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high-income areas

SSP5-19 Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation, radiative forcing target 3.4W/m^2 in 2100:

This world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy-intensive lifestyles around the world. All these factors lead to a rapid growth of the global economy, while the global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including geo-engineering if necessary.

Table C.15: Power emission bounds for four different climate scenarios

	SSP5- 8.5	**SSP4- 3.4**	**SSP1- 1.9**	**EU Ambition**
	Emissions from Power for Europe (GtCO_2/5yrs)			
2020-25	3.19	3.12	2.86	1.10
2025-30	3.53	2.88	2.14	0.99
2030-35	3.87	2.64	1.42	0.77
2035-40	4.46	1.98	0.8	0.33
2040-45	5.06	1.32	0.18	0.07
2045-50	6.07	0.74	0	0.06
2050-55	7.08	0.16	0	0.03

Table C.16: Industrial emission bounds for four different climate scenarios

	SSP5- 8.5	**SSP4- 3.4**	**SSP1- 1.9**	**EU Ambition**
	Emissions from Steel, Cement & Refineries for Europe (GtCO_2/5yrs)			
2020-25	0.85	0.70	0.79	1.79
2025-30	0.91	0.64	0.60	1.39
2030-35	0.99	0.59	0.42	0.60
2035-40	1.10	0.54	0.31	0.12
2040-45	1.25	0.49	0.21	0.10
2045-50	1.31	0.43	0.15	0.06
2050-55	1.36	0.36	0.09	0.04

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