# Optimising Carbon Capture and Storage Supply Chains for the European Industry ⋆

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**Abstract:** Carbon capture and storage is considered of fundamental importance to achieve a remarkable decarbonisation of steel, cement and refining sectors. To operate carbon capture and storage at scale and address its inherent complexity, mathematical programming techniques can be exploited to optimise such systems. This contribution proposes a Europe-wide, spatially-explicit, time-dependent, carbon capture and storage chains optimisation, based on mixed integer linear programming architecture. Capture plants can be installed in all significant industrial $CO_2$ emitters, which comprise 25 steel mills, 111 cement plants and 59 refineries. A techno-economic description of capture plants is provided, based on scale effects and different options. Transport can be operated through pipelines and offshore storage is taken into account in the North Sea and Adriatic area. The analysis allows identifying the most promising sectors and optimal specific plants where capture should be operated, and the evolution of the system throughout the time horizon. Considering a time-varying carbon reduction target, the avoidance cost is 75.6 €/t of $CO_2$ for a North Sea targeted network, and decreases by 1.9% when sequestration in the Adriatic Sea is also taken into account.

*Keywords:* Carbon capture and storage, Mixed integer linear programming, European supply chain optimisation, Steel cement refinery sectors.

## 1. INTRODUCTION

Following the indications provided by the Paris Agreement (IPCC, 2018), the emissions of anthropogenic $CO_2$ must be substantially cut to limit the global temperature increase. In Europe, this translates particularly into addressing the decarbonisation of energy and industry, since considerable $CO_2$ flowrates are generated by relatively few large scale facilities (EEA, 2020) (Fig. 1). Carbon capture and storage (CCS) emerges as a suitable array of technologies for achieving a significant decarbonisation of such $CO_2$ sources, especially industrial ones. In fact, if a transition towards carbon neutral sources is possible for power sector, upper bounds for technology and efficiency are being reached for process-related $CO_2$ generation, which leads to the consequence that the use of CCS is barely unavoidable in many industrial sectors (Leeson et al., 2017).

CCS separates and compresses the $CO_2$ from flue gases or process streams, to transport it to deep geological basins for permanent storage (IPCC, 2005). Given the inherent complexity of such systems, CCS requires the deployment of high level analyses and supply chain (SC) optimisation through mixed integer linear programming (MILP), which can be employed to design these networks at continent-

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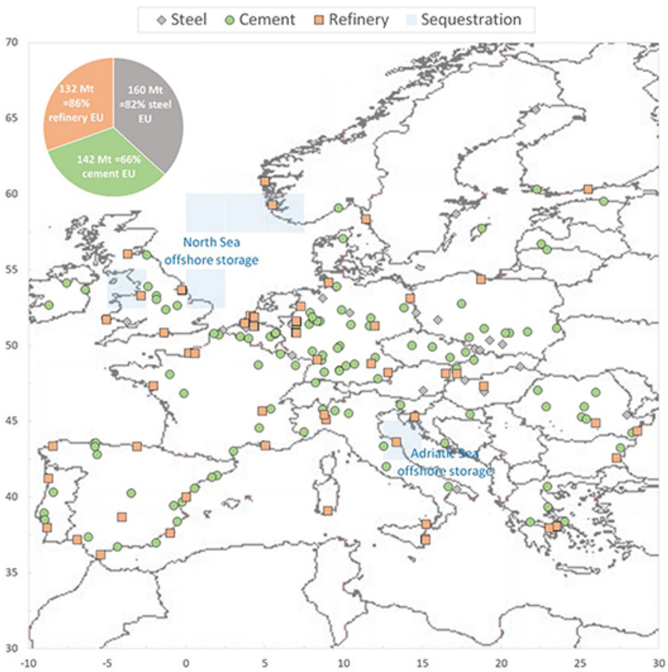



Fig. 1. Position of industrial $CO_2$ emission points and offshore storage basins in Europe. Pie chart shows emissions by sector considered in this study compared to total European ones.

wide scale (Tapia et al., 2018). Examples can be found in d'Amore and Bezzo (2017) and d'Amore et al. (2021) for the context of Europe, in Wang et al. (2020) for decarbonising Chinese coal-based power plants, and in Hasan et al. (2015) for the case of the United States. This work builds on d'Amore et al. (2021) by optimising a spatially-explicit, time-dependent, Europe-wide, CCS SC focussed on industry. The MILP modelling framework will steer relevant research and policies into correctly understanding the technological choices and costs of such system, hence the optimal capture technologies selection, transportation trajectories and sequestration locations.

## 2. MODELLING FRAMEWORK

### *2.1 Model features and assumptions*

The model optimises the CCS SC over a 10-years' time horizon discretised into 5 time periods $t_{1-5}$ of two years' each, to reduce the computational burden. Spatial characteristics are given by $n = \{s, c, r, z, o\}$ of nodes, comprising 25 steel mills $s_{1-25}$, 111 cement plants $c_{1-111}$, 59 refineries $r_{1-59}$, 6 offshore sequestration areas $z_{1-6}$ (Fig. 1), and 34 offshore zones $o_{1-34}$ needed to assess marine transportation arcs (covering the surface of European offshore zones). The geographic location and characterisation of $CO_2$ emissions are taken from EEA (2020). The location and size of storage basins $z_{1-5}$ are given in the EU GeoCapacity Project (2009), while the Adriatic Sea basin $z_6$ is described with data from Donda et al. (2011). Linear distances $LD_{n,n'}$ [km] between $n$ and $n'$ are calculated as in d'Amore and Bezzo (2017). A complete summary of symbols is given in Table 1.

Set $k$ describes the techno-economic characteristics of $CO_2$ capture plants associated to different industrial fields:

- Steel mills: $k = \{ks_{1,2,3}\}$. To consider the multiplicity of process units characterising such industries, capture is here operated in three possible and progressive steps: $ks_1$=absorption from power plant, $ks_2$=$ks_1$+blast furnace stoves and coke oven flue gas, $ks_3$=$ks_1$+$ks_2$+sinter plant (Ho et al., 2013).
- Cement plants: $k = \{kc\}$. It is here assumed to employ uniquely oxy-fuel-based capture (Gardarsdottir et al., 2019; Voldsund et al., 2019).
- Refineries: $k = \{kr_{1,2,3}\}$. Also at refineries capture is modelled to be operated in three possible and progressive steps: $kr_1$=pre-combustion capture from methane reformer, $kr_2$=$kr_1$+post-combustion capture on power unit, $kr_3$=$kr_1$+$kr_2$+further emissions from other sources (IEAGHG, 2017; NETL, 2015; Van Straelen et al., 2010).

A complete description of capture plants can be found in d'Amore et al. (2021), and the parameters determined in that previous study allow evaluating the cost $CCA_{k,n}$ [€/t] of $CO_2$ avoidance comprising scale effects on capture plant size (Figure 2).

This study considers pipelines as the unique transport option (e.g., ships are not comprised). As shown in d'Amore and Bezzo (2017), the cost of pipeline $CO_2$ transport is strongly dependent on the overall transported flowrate, which is here discretised over $q = \{q_{1-4}\}$ and unitary transport costs $UTC_q$ [€/km/t of $CO_2$] are calculated accordingly (Rubin et al., 2015). Offshore transport cost is increased by a factor $\Omega_{n,n'}$ [=1.71] if $n - n'$ is an offshore arc within subset $o_{1-34}$ (d'Amore et al., 2021).

Unitary sequestration cost $USC$ is set equal to 7.2 €/t (Rubin et al., 2015). This expenditure is increased by $\Theta$ [=2.5] to account offshore storage (ZEP, 2011).

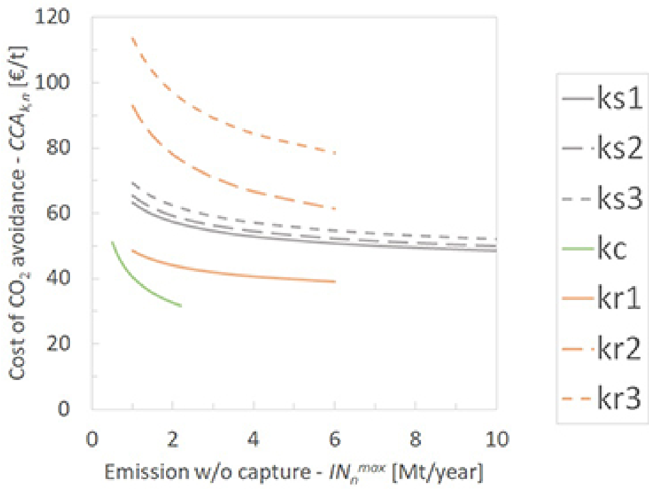



Fig. 2. Cost $CCA_{k,n}$ [€/t] of $CO_2$ avoidance over $CO_2$ emissions w/o capture $IN_n^{max}$ [Mt/year] for the investigated industrial sectors.

Table 1. List of symbols: summary of sets, subsets, parameters and variables described in the text.

| Element | Symbol | Description (Source) |
|---|---|---|
| Set | $n$ | Emission node |
| Subset | $c \in n$ | Cement plant (EEA, 2020) |
| Subset | $o \in n$ | Offshore (d'Amore et al., 2021) |
| Subset | $r \in n$ | Refinery (EEA, 2020) |
| Subset | $s \in n$ | Steel mill (EEA, 2020) |
| Subset | $z$ | Storage (EU GeoCapacity Project, 2009) |
| Set | $k$ | Capture plant |
| Subset | $kc \in k$ | Capture cement (d'Amore et al., 2021) |
| Subset | $kr \in k$ | Capture refinery (d'Amore et al., 2021) |
| Subset | $ks \in k$ | Capture steel (d'Amore et al., 2021) |
| Set | $q$ | Flowrate |
| Set | $t$ | Time period |
| Parameter | $CCA_{k,n}$ | Avoidance cost (d'Amore et al., 2021) |
| Parameter | $\eta_k$ | Capture efficiency (d'Amore et al., 2021) |
| Parameter | $IN_n^{max}$ | Node emission (d'Amore et al., 2021) |
| Parameter | $LD_{n,n'}$ | Distance (d'Amore and Bezzo, 2017) |
| Parameter | $\Omega_{n,n'}$ | Offshore pipe (d'Amore et al., 2021) |
| Parameter | $OUT_n^{max}$ | Storage capacity (d'Amore et al., 2021) |
| Parameter | $\rho_k$ | Capture emission (d'Amore et al., 2021) |
| Parameter | $USC$ | Unit. storage cost (Rubin et al., 2015) |
| Parameter | $UTC_q$ | Unit. transport cost (Rubin et al., 2015) |
| Parameter | $\Theta$ | Offshore storage (ZEP, 2011) |
| Binary | $\gamma_{k,n,t}$ | Capture through $k$ in $n$ at $t$ |
| Variable | $IN_{k,n,t}$ | Captured $CO_2$ through $k$ in $n$ at $t$ |
| Variable | $OUT_{n,t}$ | Stored $CO_2$ in $n$ at $t$ |
| Variable | $Q_{q,n,n',t}$ | Transported $q$ from $n$ to $n'$ at $t$ |
| Variable | $TC$ | Total cost |
| Variable | $TCC$ | Capture cost |
| Variable | $TSC$ | Sequestration cost |
| Variable | $TTC$ | Transport cost |

Table 2. Scenario A–B: resulting total cost $TC$ [€/t], capture cost $TCC$ [€/t], transport cost $TTC$ [€/t], sequestration cost $TSC$ [€/t], reached optimality gap (Opt. gap [%]), and solution time (Sol. t. [h]).

| | Economic results | | | | Comput. results | |
|---|---|---|---|---|---|---|
| Scen. | $TC$ [€/t] | $TCC$ [€/t] | $TTC$ [€/t] | $TSC$ [€/t] | Opt. gap [%] | Sol. t. [h] |
| A | 75.6 | 45.5 | 12.3 | 18.0 | 1.0 | 11 |
| B | 74.2 | 45.0 | 11.2 | 18.0 | 2.2 | 11 |

### *2.2 Mathematical formulation*

The objective of this MILP formulation is to minimise total cost $TC$ [€/t], given by capture cost $TCC$ [€/t], transport cost $TTC$ [€/t], and storage cost $TSC$ [€/t]:

$$TC = TCC + TTC + TSC \tag{1}$$

$TCC$ of (1) depends on the $CO_2$ captured $IN_{k,n,t}$ [t/year] at plant $k$ in $n$ at time $t$ (i.e., inlet to the transport system) and on the cost $CCA_{k,n}$ of $CO_2$ avoidance:

$$TCC = \sum_{k,n,t} (IN_{k,n,t} \cdot CCA_{k,n}) \tag{2}$$

The captured amount $IN_{k,n,t}$ is given by the initial emission w/o capture $IN_n^{max}$, capture efficiency $\eta_k$ and rate of additional emissions $\rho_k$ of capture plant $k$:

$$IN_{k,n,t} = IN_n^{max} \cdot \rho_k \cdot \eta_k \cdot \gamma_{k,n,t} \qquad \forall k, n, t \tag{3}$$

with $\gamma_{k,n,t}$ being a binary variable defining if capture plant $k$ is installed in $n$ at time $t$. The overall net captured amount must increase along the years up to the assumed European carbon reduction target, defined as a fraction $\alpha$ [%] of the total $CO_2$ European emissions w/o capture.
The mass balance between capture and sequestration nodes is given by:

$$\sum_k IN_{k,n,t} + \sum_{q,n'} Q_{q,n',n,t} = OUT_{n,t} + \sum_{q,n'} Q_{q,n,n',t} \qquad \forall n, t \tag{4}$$

for each time $t$, being $Q_{q,n,n',t}$ [t/year] the flowrate $q$ from $n$ to $n'$ at time $t$ and $OUT_{n,t}$ [t/year] the $CO_2$ stored in $n$ at time $t$. Transported flowrates allow calculating the transport cost $TTC$ of (1):

$$TTC = \sum_{q,n,n',t} (Q_{q,n,n',t} \cdot LD_{n,n'} \cdot UTC_q \cdot \Omega_{n,n'}) \tag{5}$$

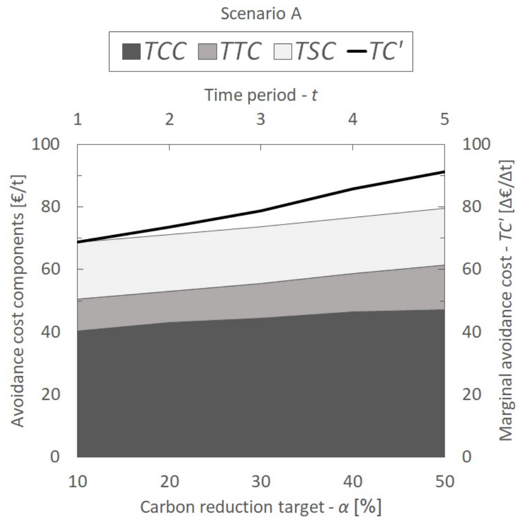
whereas sequestered amounts $OUT_{n,t}$ of (4), which must be lower than capacity of the basin $OUT_n^{max}$ [t], permit the evaluation of sequestration cost $TSC$ of (1):

$$\sum_t OUT_{n,t} \leq OUT_n^{max} \qquad \forall n \tag{6}$$

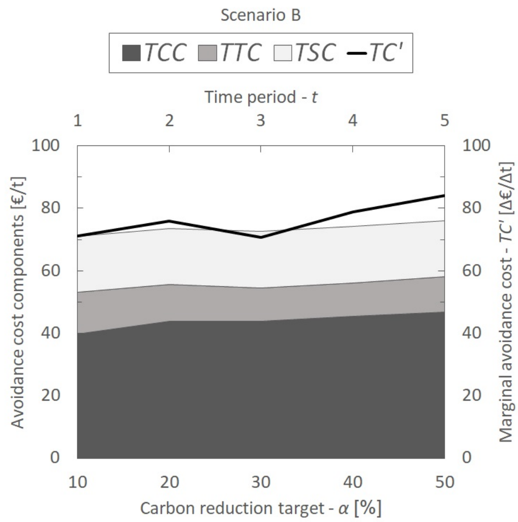
$$TSC = \sum_{n,t} (OUT_{n,t} \cdot USC \cdot \Theta) \tag{7}$$

## 3. RESULTS AND DISCUSSION

The MILP model was optimised through GAMS (CPLEX solver) on a 2.60 GHz (32 GB RAM) computer, under a dynamic linearly increasing decarbonisation target $0\% \leq \alpha \leq 50\%$ (with the upper bound of $\alpha$ compatible with Shogenova et al., 2014). Each scenario entailed 2226671 continuous and 175555 discrete variables. Since limited information are available in the open literature on the characteristics of offshore sequestration in the Adriatic Sea compared to $CO_2$ storage in the North Sea, Scenario A limits the possibility of storage to the latter, while Scenario B considers also the Adriatic Sea basin (Table 2).



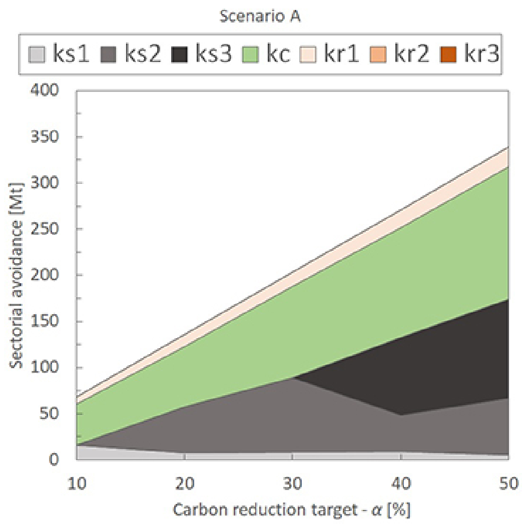

(a)



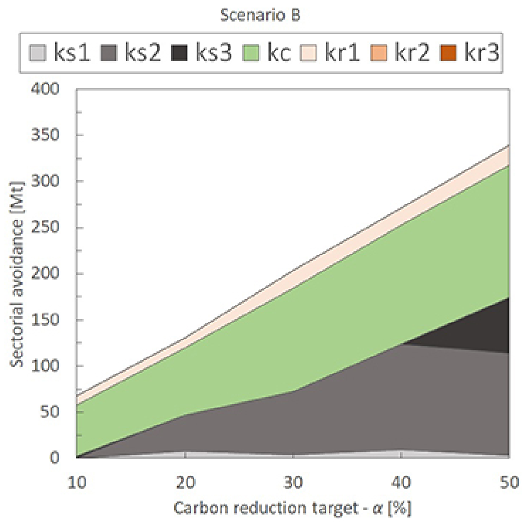

(b)

Fig. 3. Scenario A–B: time evolution of avoidance cost components and marginal avoidance cost $TC'$ [Δ€/Δt]. (a) Scenario A, (b) Scenario B.

Scenario A entails a total cost $TC$ of 75.6 €/t, majorly constituted by capture cost $TCC$ (45.5 €/t, i.e. 60.2% of $TC$), and with transport $TTC$ (12.3 €/t, i.e. 16.3% of $TC$) and storage $TSC$ (18.0 €/t, i.e. 23.5% of $TC$) exhibiting similar shares (Fig. 3a). A slight cost reduction is achieved through the introduction of the Adriatic Sea storage in Scenario B, in which $TC$ decreases to 74.2 €/t (-1.9% with respect to Scenario A), determined by small drops in $TCC$ (45.0 €/t, i.e. -1.1% with respect to Scenario A) and in $TTC$ (11.2 €/t, i.e. -8.9% with respect to Scenario A) (Fig. 3b).
The evolution in time of avoidance cost components and avoidance marginal costs $TC'$ [Δ€/Δt] in Scenario A and Scenario B are reported in Fig. 3. As long as $\alpha$ increases




(a)




(b)

Fig. 4. Scenario A–B: time evolution of contributions to capture [%] through technologies $k$ (i.e., capture from steel mills $ks_{1,2,3}$, cement plants $kc$, and refineries $kr_{1,2,3}$). (a) Scenario A, (b) Scenario B.

in years from 10% to 50%, $TC'$ raises from 68.7 to 91.2 $\Delta$€/$\Delta$t in Scenario A and from from 71.1 to 83.9 $\Delta$€/$\Delta$t in Scenario B. Interestingly, if on the one side Scenario A shows a steady increase of $TC'$, differently Scenario B exhibits a minimum for $\alpha = 30\%$, where it reaches 70.7 $\Delta$€/$\Delta$t. This drop in Scenario B is due to the arising of scale effects when increasing the decarbonisation goal from $\alpha = 20\%$ to $\alpha = 30\%$.

As for sectorial contributions to $CO_2$ capture, both scenarios show similar results, with significant installation of capture plants in steel mills (mainly $ks_{2,3}$) and cement plants ($kc$) and minor avoidance contributions from refineries (only $kr_1$). Capture plants $kr_{2,3}$ are never installed, and $ks_1$ are marginally exploited in all scenarios (Fig. 4). A noticeable difference between the two scenarios is constituted by the penetration timings of technologies $ks_{2,3}$: while in Scenario A $ks_3$ starts replacing $ks_2$ at $t_3$ (i.e., after 6 years for $\alpha = 30\%$), Scenario B exhibits a much more moderate installation of capture plants $ks_3$ and only from $t_4$ (i.e., after 8 years for $\alpha = 40\%$).

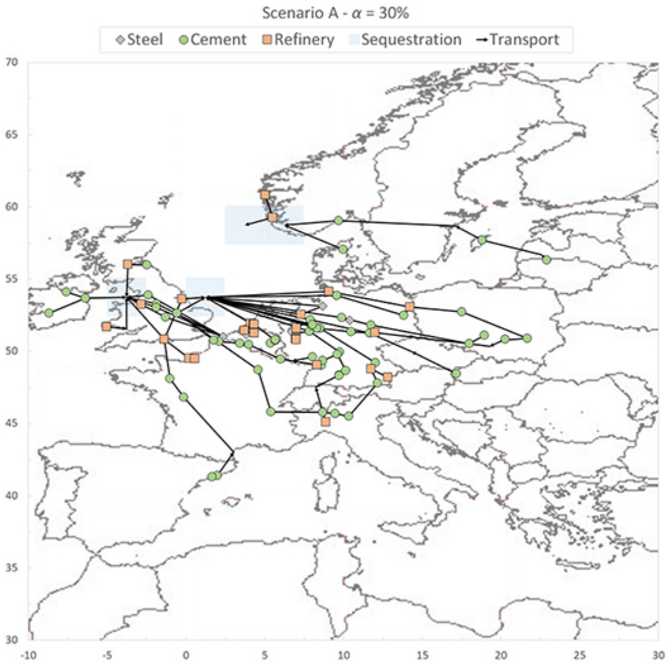
The resulting CCS SC designs show differences between Scenario A (Fig. 5) and Scenario B (Fig. 6). On the one hand, Scenario A (Fig. 5) is characterised by a North Sea-targeted network with local pipelines clusterings to exploit the beneficial effects of scale over transport costs. On the other hand, from Scenario B (Fig. 6), which includes the possibility of storage in the Adriatic area, it emerges the installation of two main SC clusters: a Northern capture system in which the $CO_2$ is directed towards the North Sea and the United Kingdom, and a Southern capture network which exploits the presence of storage in the Mediterranean. Consequently, Scenario B shows a much larger exploitation of Southern European facilities for sourcing the $CO_2$, compared to the SCs obtained from the optimisation of Scenario A, also in case of lower carbon reduction targets, e.g. for $\alpha = 30\%$ (Fig. 5a, Fig. 6a). However, it is to be highlighted that the design configuration resulting from Scenario B involves a noticeable exploitation of the Mediterranean basin, which is filled up to 56% of its capacity at $t_5$, while the North Sea storage is just marginally exploited in both Scenario A and Scenario B (since it is characterised by much larger capacities).

In general, this work proposed a model to assess and design the optimal installment of capture capacity at industrial sites owned and operated by many different entities. It also provided insights into pipeline trajectories and capacities which will eventually constitute major trans-national infrastructure projects to be built. The outcomes from this study target at a high-level understanding of the total minimum costs of a European CCS SC and constitute a preliminary analysis to foster a large-scale installation of such networks. However, the implementation of the resulting SC would not rely on a single authority, but rather on a wide range of stakeholders and decision makers. On the one side, this work demonstrates how mathematical programming can support investors and decision makers with tools for analysing and assessing in a quantitative way different scenarios and options. On the other side, we need to recognise that it represents an ideal representation of an optimal SC that can be achieved by a single player. Reality is more complex, and in an international system several factors should be taken into account; for instance, the implementation of cooperation schemes among the different entities, stakeholders and countries could be necessary for setting a trans-national infrastructure at a European level (d'Amore and Bezzo, 2020).

## 4. CONCLUSION

In this study it was proposed a mixed integer linear programming-based model for optimising a European chain for carbon capture and storage. Major industrial $CO_2$ sources were considered and different capture options taken into account. Pipelines were designed to transport the $CO_2$ towards offshore sequestration basins, located in the North Sea and Adriatic Sea.

Results show that the overall avoidance cost of a European carbon capture and storage network ranges between 74.2 and 75.6 €/t of $CO_2$, and is mainly constituted by capture cost (60%), followed by the contributions of offshore storage cost (23%) and transport cost (17%). A maximum value of marginal avoidance cost of 84-91 [$\Delta$€/$\Delta$t] was

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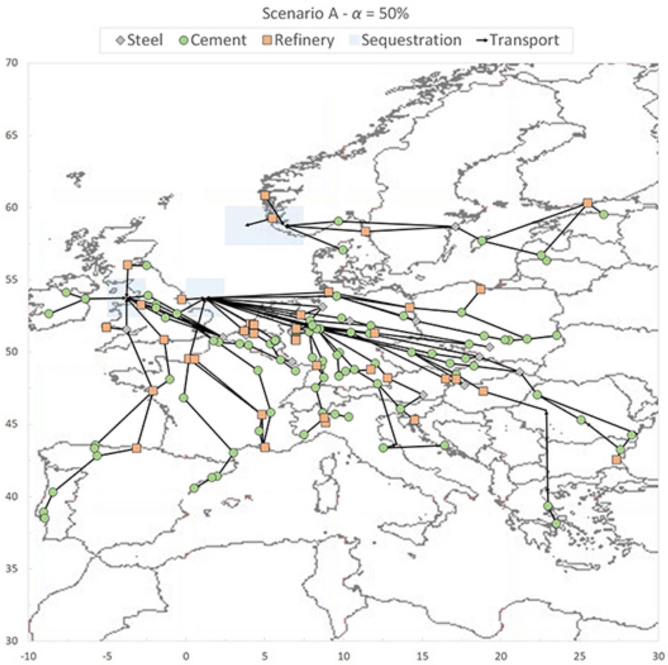
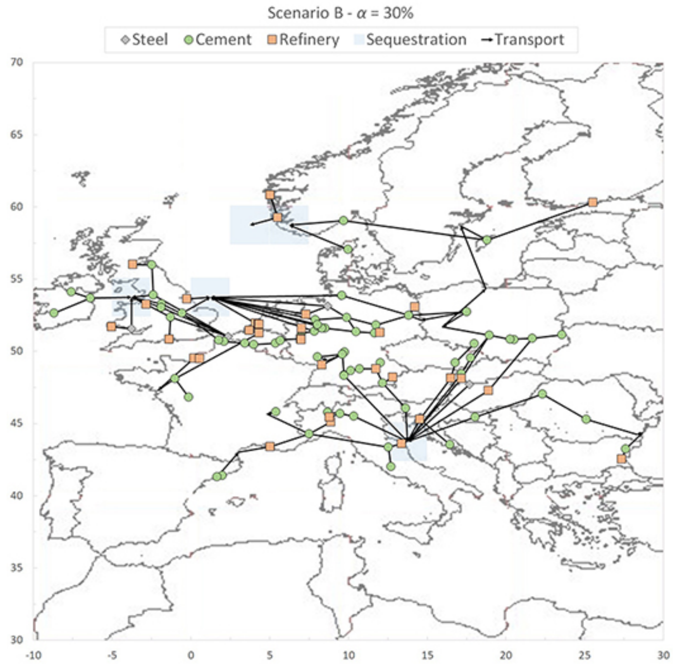



(b)

Fig. 5. Scenario A: CCS SC configuration. (a) $\alpha = 30\%$, (b) $\alpha = 50\%$.

found, which would correspond to a carbon tax to avoid 50% of $CO_2$ emissions from European large-scale industry. The inclusion of the Adriatic sequestration basin allows some costs reduction (about -2%), thanks to the creation of a Mediterranean carbon network opposed to the North Sea-targeted one.
Future work should investigate the inclusion of ships as additional offshore transport means, or consider the technological learning rates that would characterise different capture plants installations. Additionally, the model relies

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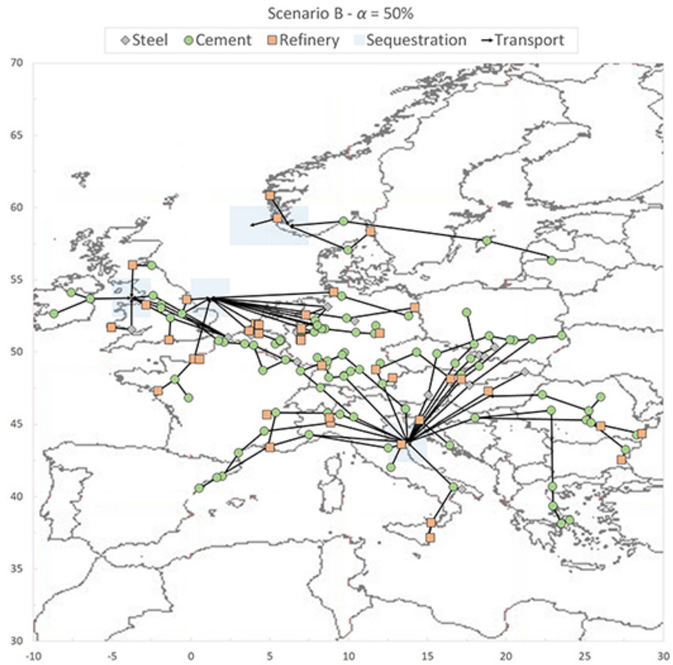


(b)

Fig. 6. Scenario B: final CCS SC configuration. (a) $\alpha = 30\%$, (b) $\alpha = 50\%$.

on a large number of techno-economic parameters, the deterministic nature of which should be further investigated (e.g., through sensitivity analyses) for a better comprehension of the robustness of the results.

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