MILP-BASED OPTIMIZATION MODEL FOR CO_2 CAPTURE, TRANSPORT AND STORAGE (CCS) CHAIN PLANNING: APPLICATION TO THE HARD-TO-ABATE INDUSTRY IN ITALY

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ABSTRACT

Carbon Capture and Storage (CCS) technologies emerge as a pivotal choice for decarbonization, especially in the context of the industrial sectors known as hard-to-abate, mostly represented by large point CO_2 emitting facilities (i.e., producing more than 100 ktCO_2/y). The full-scale CCS infrastructure deployment problem entails the optimization of all the steps of the chain that go from the carbon capture at the point of emission to the final storage site, through the appropriate transportation modes. Therefore, the design of the entire CCS chain features an intrinsic complexity that includes a multi-tier array of technological possibilities and routes that must take into consideration not only the techno-economic performance and economies of scale, but also practical constraints such as geographical limitations, the availability of modes of transportation, etc. In this work, a mixed-integer linear programming (MILP) optimization model, aiming at minimizing the cost linked to the implementation (installation and operation) of the CCS chain for a defined target of sequestration (e.g. 10 MtCO_2/y), is presented. The model is applied to the Italian case study, encompassing the major industrial carbon dioxide sources in the area: 15 cement plants, 4 refineries, 24 steel mills and 18 waste-to-energy plants. The set of variables span from capture technologies, with CAPEX and OPEX diversified by technology and sector, to transport modes selection, sizing and operation. Five possible modes of transportation have been considered: (i) barge, (ii) train, (iii) ship, (iv) truck and (v) pipeline. A single offshore storage site is hereby considered and located in the Adriatic Sea, nearby Ravenna. This comprehensive model enables the simulation and comparison of diverse scenarios that consider different targets of decarbonization and provides a flexible tool for policymakers to support the decision-making processes and the assessment of the evolution of a cost-effective chain over the long term, in harmony with the established net-zero target for 2050. The proposed scenarios take into consideration that in Italy: (i) for short-medium term targets, 1 to 10 MtCO_2/y are aligned with the recently announced Callisto CO_2 transport project and coherent with the PNIEC target; (ii) 20 MtCO_2/y of CO_2 abated could be reached by 2050 via CCS.

1 INTRODUCTION

To achieve the Paris Agreement's goals, a radical transformation of the way we produce and consume energy is required (Burger et al., 2024). Renewable energy technologies like solar and wind are keys, but alone cannot comply with the required objectives. As a result, in recent years, there has been growing momentum surrounding Carbon Capture and Storage (CCS) technologies.

CCS holds substantial strategic importance in the journey towards achieving a net-zero future for several reasons: (1) its adaptability allows for retrofitting to existing power and industrial plants; (2) it effectively addresses emissions in sectors where alternative technological solutions are constrained; (3) if coupled with CO_2 utilisation for synthetic hydrocarbon fuels, through Fischer-Tropsch synthesis to bio-diesel, direct conversion to methanol, or fermentation to ethanol, it could enable the transition to low-emission fuels.

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The significant scale-up required to achieve net-zero emissions by mid-century is a substantial endeavour, demanding essential policy support and coordination («CCUS in Clean Energy Transitions», 2020; *CCUS Policies and Business Models*, s.d.; Lyons et al., 2021). In Europe, the CCS infrastructure is in its early stages, with only eleven CO_2 capture operating facilities, seven of which are at the pilot or demonstration scale (*Facilities - Global CCS Institute*, s.d.). Early CCS projects involved one major emitter (such as a fossil-fuelled power station) placed somewhat close to a CO2 storage facility; lately, however, projects focus on the development of hubs and clusters (ZEP, s.d.) that combine production facilities, transit steams and storage sites, making the planning of this infrastructure more and more difficult.

Notably, Europe lacks a large-scale transport infrastructure, unlike the United States, which already has existing pipelines (*CCUS Policies and Business Models*, s.d.; Change et al., 2005; Consoli, 2019). Stakeholders are likely to invest only if two conditions are met: (1) sufficient CO_2 is captured to utilize the pipeline's capacity, and (2) storage sites offer the corresponding capacity. From the emitter's perspective, capturing CO_2 becomes reasonable only when there is available transport to the storage site (Reyes-Lúa & Jordal, 2021).

The challenge of coordinating the installation of capture units, the development of storage sites, and the expansion of transport infrastructure is, therefore, is mandatory and should entail the optimization of all the technological processes at once. The predicament can be partially addressed by using 'ready-to-use' transport – such as ships, trucks and trains before the development of a pipeline network.

It's important to note that not all technologies are universally applicable to all types of installations and each technology has different costs related to its installation and operation. Capture technologies can be grouped into 3 macro-categories (Becattini et al., 2022a): (1) post-combustion carbon capture, which involves capturing CO_2 after combustion (Carminati et al., 2019; Ortiz et al., 2023), is suitable for large point sources, such as coal, Waste-to-Energy (WtE) and natural gas-fired plants; (2) pre-combustion carbon capture, applied primarily in Integrated Gasification Combined Cycle (IGCC) plants and refineries, involves gasifying solid fuels and shifting gases to generate hydrogen-rich streams (Kumar et al., 2023); (3) oxy-combustion carbon capture (Nemitallah et al., 2017; Ortiz et al., 2023; Perpiñán et al., 2021), which entails burning the fossil fuels in oxygen-rich environments and producing concentrated CO_2 in flue gas, could be used in numerous applications.

Regarding CO_2 transportation, there exist many different modes that can be used. The most viable method for transporting large quantities of CO_2 over extended distances is typically through pipelines at ambient temperature, necessitating compression to 85-150 bar (Bjerketvedt et al., 2022), but it could be transported also at a gaseous phase (40-60 bar) (Kjärstad et al., 2016).

CO_2 storage options encompass both offshore and onshore locations. However, owing to safety and public acceptance considerations, the majority of envisioned storage sites prioritize offshore locations (ZEP, s.d.). Although this decision enhances safety measures, it concurrently leads to escalated costs and operational complexities (Kegl et al., 2021).

Given the intricate nature of the problem (large-scale, multiple-nodes, various available solutions, etc.), the utilization of mathematical programming techniques can provide quantitative analysis and design tools to correctly evaluate the best strategy (and infrastructure to be implemented) to decarbonize a region/country. Notably, mixed-integer linear programming (MILP) stands out as one of the most adapt techniques for optimizing highly intricate networks (Kallrath, 2000), including the planning of a European CCS system. Indeed, MILP provides a flexible and efficient way to model and solve problems that involve a mix of continuous and discrete decision variables (e.g., size and location, respectively, of the capture, transportation, and storage systems), making it a valuable tool in this field.

In the modelling of CCS networks, d'Amore et al. (d'Amore et al., 2019, 2020, 2021b, 2021a) used the MILP formulation to focus the analysis at continental level and, at the same time, make the problem computationally tractable. The proposed model allowed to have a clear vision on the efforts, costs and decisions that were needed at the European level. A more localized approach, such as at the regional level, could be beneficial to all stakeholders, as it involves investigating into the specific geographical distribution of emission sources, exploring viable transport routes, detailing transportation trajectories and multimodal transport solutions, as well as identifying available sequestration sites and potential utilization options. The increased complexity is offset by the smaller size of the considered geographical area, allowing for a comprehensive exploration of varying techno-economic assumptions. Currently,

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there are no available studies on Italy, and a more focused analysis could prove beneficial for investors and decision-makers. To facilitate this, a mapping of main emission sources and their associated costs is also imperative.

Beccatini et al. in (Becattini et al., 2022b; Gabrielli et al., 2022) proposed an optimization framework for the optimal design of CCS supply chains applied in Switzerland. These studies have underlined the impact of various policies on (a) the quantity of CO_2 stored, (b) the generation of net-negative emissions, and (c) the overall system costs. These works were used as benchmark to set the proposed work.

The effective period between making the decision – and therefore the investment – and the actuation of that decision plays a crucial role in the deployment of CCS projects; therefore, the modelling framework should also acknowledge this delay due to bureaucracy, permitting and constructing. A pipeline averagely requires 5 years to become operational (Wang et al., 2014); this could happen also for big and complex carbon capture systems.

The proposed study introduces a MILP optimization model aimed at minimizing costs associated with implementing the CCS chain for a specific decarbonization target, focusing on the Italian context, addressing major industrial CO_2 sources, including 15 cement plants, 4 refineries, 24 steel mills, and 18 waste-to-energy plants. Optimization variables encompass diverse capture technologies, with sector-specific CAPEX and OPEX, as well as the selection, sizing, and operation of transport modes – barge, train, ship, truck, and pipeline — allowing for a practical and phased infrastructure rollout. The model consists of several stage and each stage is designed to store a specific quantity of CO_2. If a carbon capture facility is activated at year *n* ¸ it must be active at year *n+1* – different capture capacity could be considered. The study assumes a single offshore storage site in the Adriatic Sea near Ravenna.

2 METHODOLOGY

There are many similarities between modelling CCS infrastructure and integrated energy systems/networks. These frameworks, usually, requires models capable to tackle the optimization of installation, sizing and operation of their components, while dealing with technological, economic and regulatory constraint or objectives: in most cases, mixed integer linear programming (MILP) is employed (Becattini et al., 2022a; d'Amore et al., 2021b; Zatti et al., 2019). Binary variables are essential for modeling the nonlinear costs of capture and transport technologies, as well as indicating their status, "installed/notinstalled".

There are many languages and framework that can be used to model and solve MILP problems; among them, the clear and concise syntax of Python was chosen for its simplicity and modularity. Pyomo is a Python-based modelling language that can be used to define symbolic problems, create concrete problem instances, and solve these instances with standard solvers. Indeed, the Pyomo package includes modelling components necessary to formulate an optimization problem: variables, objectives, and constraints, as well as other modelling components commonly supported by modern Algebraic Modelling Languages, including indexed sets and parameters (Michael L. Bynum, Gabriel A. Hackebeil, William E. Hart, Carl D. Laird, Bethany L. Nicholson, John D. Siirola, Jean-Paul Watson, David L. Woodruff, s.d.); the deployment of Pyomo language can easily leverage multiple solvers, import/export from/to various sources including Excel, CSV, Dashboard API, SQL Databases (febbraio 2013, s.d.).

2.1 Input data, decision variables and constraints

The optimization problem is fed with a set of input data, encompassing: (i) the locations and current CO_2 emissions points, (ii) target CO_2 capture rate for each considered plant, (iii) the performance, carbon footprint, and costs associated with capture, storage, and transport technologies, (iv) the availability of transport technologies, indicating connectivity between nodes, (v) the price and region-specific carbon intensity of electricity, (vi) the locations and capacities of storage site and (vi) target of CO_2 capture.

First of all, a mapping and analysis of the main industrial emissions points in Italy has been carried out, thanks to the database in refs. (*Map*, s.d.; «Projects», s.d.) and through personal communication with industrial experts, which is reported in Appendix A. In this work, only industrial points with annual CO_2 emission higher than 100 ktCO_2/y are considered. The types of Industrial sites taken into

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consideration are: production of steel, cement and refinery and waste-to-energy plants. Natural Gas Combined Cycle (NGCC) and coal fired energy production plant were not examined: NGCC works for less than 3000 h per year, on average, making the installation of capture technology for these type of plant challenging (with the exception of cogenerative plants for which CCS may be competitive); coal demand is set to fall within the next few years in the Stated Policies Scenario of IEA (*IEA – International Energy Agency*, s.d.), so the progressive decline and the total dismission of coal-fired power plants is expected by 2025 (*PNIEC - Piano Nazionale Integrato per l'energia e il clima*, s.d.) or slightly later. For each plant, different carbon capture technologies have been considered, based on the most promising and available options: for waste-to-energy (WtE), partial oxy-combustion-calcium looping hybridisation (Ortiz et al., 2023); for refinery and steel plants, post-combustion capture on flue gases with Mono-Ethanol Amine (MEA) solvent (Ho et al., 2013); lastly, for cement production plants, the full-oxycombustion process (Gardarsdottir et al., 2019). The above-mentioned assumptions affect the CAPEX and OPEX for capture systems of each plant. Economy of scale is taken into account for CAPEX modelling (Figure 1).
In a CCS chain, the captured CO_2 is transported via a multi-modal network to the storage or utilisation sites, where it could be permanently sequestered underground or used for cementitious materials and/or e-fuels production. In this work, utilization technologies have not been considered.
Five possible modes of transportation have been considered: (i) barge, (ii) train, (iii) ship, (iv) truck and (v) pipeline. Particularly, (i) barge connections are available between cities located near the Po River's shore; (ii) a rail connection is included between all provincial capitals of Italy; (iii) ship connections are available for cities located near the Adriatic Sea; (iv) truck connections are available between all sites located in Italy, however, only the connections obtained using Delaunay triangulation (Mulchrone, 2019) – in which no point of a given discrete set is inside the circumcircle of any triangle - are considered to limit the computational complexity of the problems. Lastly, (v) greenfield pipelines can be installed following the Delaunay's triangulation, as well.
As aforementioned in the Introduction Section, the study assumes a single offshore storage site in the Adriatic Sea near Ravenna, with a storage capacity of 500 $MtCO_2$ (*Eni*, s.d.).

Table 1 reports the main operating conditions at which carbon dioxide is captured, transported and stored.

Table 1: Parameters describing the technology conditions at which CO_2 is captured, transported and stored. The quantity of CO_2 considered for the specific CAPEX calculation is at a yearly rate.

Technology	Condition	Pressure [bar]	Specific CAPEX	Ref.
Oxy combustion	-	1.2	Figure 1	(Ortiz et al., 2023)
Post-combustion with MEA solvent	-	10.3	Figure 1	(Gardarsdottir et al., 2019; Ho et al., 2013)
Truck	Liquid	20-22	0.111 €/tCO_2-km + 0.48 €/km	(Becattini et al., 2022b; Stolaroff et al., 2021)
Train	Liquid	20-22	2 €/tCO_2 + 0.044 €/km	(Becattini et al., 2022b; Stolaroff et al., 2021)
Barge	Liquid	22	30 €/ km + 0.03 €/ tCO_2 -km	(Becattini et al., 2022b; Kjärstad et al., 2016)
Ship	Liquid	70	30 €/km + 0.06 €/ tCO_2 -km	(Becattini et al., 2022b; Kjärstad et al., 2016)
Pipeline	Supercritical	80-120	0.013 €/ tCO_2 -km	(Smith et al., 2021)
Storage site	-	150	0.05 €/tCO_2	(Becattini et al., 2022b)

The constraints of the optimization problem encompass (i) energy and mass balances (ii) the maximum total CO_2 emission for each year and (ii) the performance behaviour and operating limits of capture and

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transport technologies. Particularly, for each capture units, the size must vary between zero (i.e. the capture unit is not installed) and the target of CO_2 capture rate, which is fixed at 0.97 for each plant.
Decision variables in the optimization problem involve determining (i) the selection, location, and size of CO_2 capture and transport technologies, (ii) the input and output electricity and CO_2 streams of production technologies, (iii) the CO_2 flow for installed transport technologies, and (iv) the energy expenditure for CO_2 transport. Transport mode, on the other hand, is selected by the model based on its availability as defined above, the size and the length of the node. The model is, indeed, free to choose the optimal transport mode for each arch activated by the optimizer; however, when the system decides to use a pipeline at year *n*, it must continue to use the pipeline at year *n+1*. Trucks, barges and ships use gasoline as fuel, emitting, respectively, 69.3 g CO_2/t-km and 198 g CO_2/t-km: these are accounted in the overall Net CO_2 objective.
In each node, the CO_2 is first conditioned to 313.15 K and 1.5 bar and then brought to the transport conditions. The electricity for conditioning, i.e. needed for compressing, cooling and liquefying the CO_2, is also accounted.

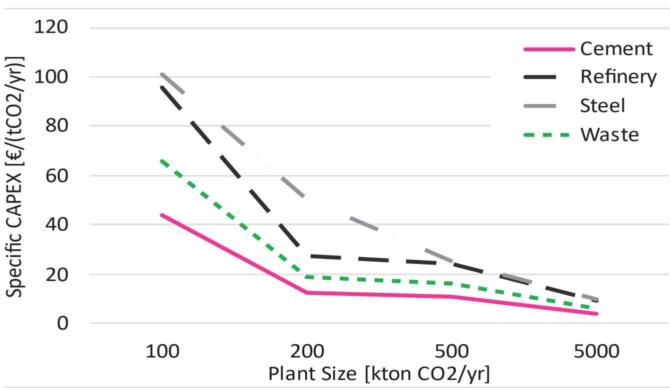

Figure 1: Specific CAPEX for capture systems of each plant - the effect of economy of scale.

2.2 Objective function

The objective function is to minimize the total annualized cost (TAC) of the system, which is the sum of the TAC for capture, transport and storage, while achieving pre-defined objectives of reduction of carbon dioxide emissions. Each TAC is calculated by summing annualized Capital Expenditures (CAPEX) and Operating Expenditures (OPEX). For capture and storage costs, these are directly related to the size of the capture/storage systems, while for transport costs the calculation does not only depend on the size of the transport systems but also on the mode selected and the length of the arc (i.e., the linear branch connecting two nodes).
As for the calculation of the OPEX, the following contributions have been considered: the calculation of electricity consumed by the selected capture technology systems as well as the assessment of electricity not produced (e.g. loss of net electric output due to steam extraction for covering the thermal duty of the CO_2 capture process) due to the capture system.
Transport costs are not directly proportional to the transport system size. For this reason, the specific linearized equations (1) and (2) for, respectively, CAPEX and OPEX calculation from node i to node i', using the mode of transport l are reported (Becattini et al., 2022a):

$$CAPEX_{i,i',l} = \alpha^1_{i,i',l} \cdot \overline{u_{i,i',l}} + \alpha^2_l \cdot l_{i,i'} \cdot y_{i,i',l} \quad (1)$$

$$OPEX_{i,i',l} = \beta^1{}_l \cdot \overline{u_{i,i',l}} \cdot l_{i,i'} + \beta^2_l \cdot \overline{u_{i,i',l}} \quad (2)$$

Where α^2_l , $\beta^1{}_l$ and β^2_l are parameters that depends on the mode of transport, $\alpha^1_{i,i',l}$ is a parameter that depends on the mode of transport and the distance between node *i* and *i'*, $l_{i,i'}$is the parameter of length from node i to node i', $\overline{u_{i,i',l}}$ is a variable that represents the rated quantity of CO_2 transported (size of the transport) and $y_{i,i',l}$ is a binary variable that is equal to 1 when the connection between node (*i,i'*) with transport l exist. For the definition of the four parameters $\alpha^1_{i,i',l}, \alpha^2_l, \beta^1{}_l$ and β^2_l , an analysis of the

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parameters has been made according to refs. (*National Energy Technology Laboratory*, s.d.; Smith et al., 2021; Stolaroff et al., 2021).
The CCS supply chain is represented as a network, where the nodes consist of the CO_2 capture sites, CO_2 storage sites and transport exchange sites. The multi-stage structure of the model considers a 20-year time horizon (t ∈ {1, 2,..., T} with T = 21). The focus is on assessing their cost-optimal time evolution while meeting specified emissions reduction targets. The CO_2 target considerers reducing both the direct emissions – by capturing carbon dioxide from considered plants – and indirect emissions – due to transport modes and consumed electricity.
To account for bureaucracy, permitting and construction of the capture facilities, a period has been assured as the minimum required for planning the infrastructure (i.e. setting the investment for capture systems and pipeline infrastructure), therefore, once the decision is taken, in the following 5 years the plants continue to emit. – the CO_2 storage objective is set to 0. From year 6, a linear objective of CO_2 sequestration, from 1 $MtCO_2$/yr to 22 $MtCO_2$/yr is set. The proposed objectives are set in order to be in the same range, proposed by on-going CCS projects, such as Longship (*Northern Lights – About the Longship Project*, s.d.), Callisto (*CCS: Il progetto Callisto, coordinato da Air Liquide, entra a far parte della lista dei Progetti di Interesse Comunitario | Air Liquide Italia - Gas tecnici*, s.d.) and HyNet (*HyNet North West, cattura e stoccaggio di CO_2 nella baia di Liverpool*, s.d.).

3 RESULTS AND DISCUSSION

Figure 2 shows the time evolution of the CCS infrastructure optimization, while complying with the aforementioned carbon dioxide yearly targets: the total CCS chain CO_2 emission vs total annual system costs. The minimum emissions level of 4 $MtCO_2$/y is achieved in the last year, i.e., year 21.
The total system cost, which is equal to 6775 M€, is mainly due to capture costs – the 89 %, while transport and storage account for 8 and 3,1% respectively. As aforementioned, to account for the time required for the decision process, the investments start at year 1, while the captured emissions begin to reduce at year 6.

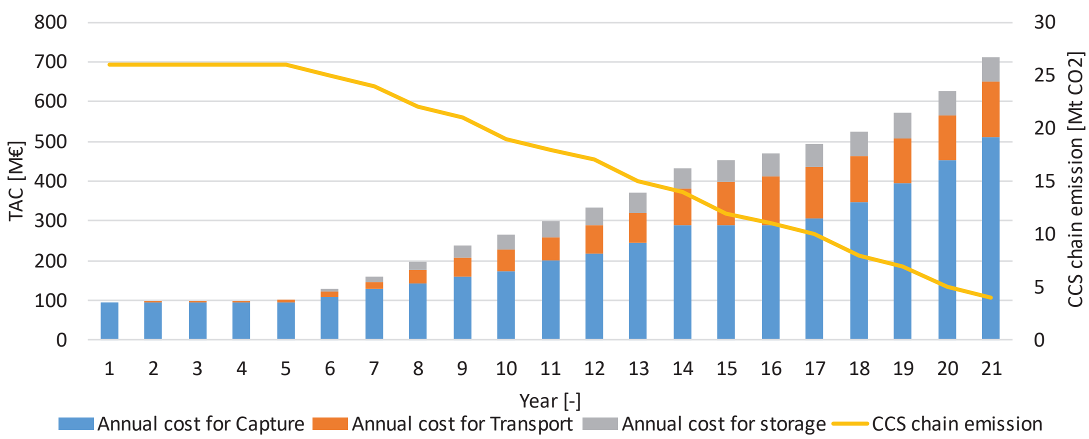

Figure 2: Breakdown of TAC in annual cost for capture, transport and storage (primary axis) vs CCS chain emission (secondary axis)

Table 2 display a summary of captured and net sequestration of carbon dioxide (that take into consideration the emission of the required electricity for capture, conditioning and storage and the emission of transports), TAC, number of captured unit and installed length and Figure 3 shows the network design of year 6 -11 -16 -21. Accordingly, the amount of captured CO_2 emissions increases with the number of installed captured unit. The indirect emission, related to transports unit and consumed electricity reaches a value of 3 $MtCO_2$/y. Trucks and ship CO_2 annual emittance account for, respectively, 19 and 18 % of total CO_2 indirect emissions at year 21. The number of CO_2 capture units installed increases over the time horizon, and in year 21 in all the 61 plants there is a capture unit, with

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the maximum recovery rate of 97%. The Annualized Cost of Stored Carbon (ACSC) is calculated by dividing the TAC with the CO_2 sequestrated (Net CO_2) in that year. ACSC reduce from year 6 to year 18 and increase till year 21 – due to the fact that the system must capture also the sub-optimal sector to meet the CO_2 objective. A calculation of the Levelized Cost of Stored Carbon (LCSC) is also calculated dividing the total cost of the proposed infrastructure with the total CO_2 captured. The LCSC is equal to 271 €/tCO_2.

Table 2: Summary of the main results of the proposed CCS optimization

Year [-]	**CO_2 Captured [MtCO_2/yr]**	**Net CO_2 [MtCO_2/yr]**	**TAC [M€/yr]**	**ACSC [€/tCO_2/yr]**	**Number of Captured Unit [-]**	**Installed Length [km]**
1	0	0	95	-	0	0
2	0	0	97	-	0	0
3	0	0	99	-	0	0
4	0	0	100	-	0	0
5	0	0	101	-	0	0
6	1	1	129	129.0	4	431
7	3	2	161	80.5	7	1065
8	4	4	199	49.8	13	1574
9	6	5	237	47.4	18	2342
10	8	7	266	38.0	14	3358
11	10	8	300	37.5	17	3764
12	11	9	334	37.1	20	4038
13	13	11	370	33.6	26	4263
14	14	12	434	36.2	31	4862
15	15	14	453	32.4	37	4862
16	18	15	469	31.3	41	4862
17	19	16	494	30.9	44	4914
18	20	18	525	29.2	49	5126
19	22	19	571	30.1	52	5406
20	23	21	628	29.9	56	5577
21	25	22	713	32.4	61	6161

In the first year, the planning of the infrastructure begins, and investment are set to install greenfield pipeline that connect nodes that are nearest to the storage location.

At year 6, with a CO_2 captured target of 1 MtCO_2/y, transport is made by pipelines and trucks. Indeed, the first installed unit are cement plants (located in the cities of Monselice, Fanna, Susegana and Pederobba), as they are the cheapest.

At year 11, with a CO_2 captured target of 8 MtCO_2/y, all the cement plants have installed CO_2 capture unit. The optimization models decided to start installing capture units in WtE (Torino, Padova, Modena, Milano, Forlì and Trieste) and big steel plants, such as the one in Cremona. Selected transport modes in year 11 are: (i) pipelines in long connections and (ii) trains that connects the further cities (i.e. Cremona, Milano, Torino) to Forlì. This last city is connected to Ravenna and the storage site through two pipelines.

It is worth noting that the selection of the train as a transport mode depends on the simplification made by Delaunay's triangulation. As explained in the methodology section, some pipeline routes, which could be viable in real life, are not considered: this reduces the complexity of the problem and increase the velocity to achieve a solution, but, on the other hand, significantly reduce the possible connection.

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For example, it is not possible, in the current formulation, to transport CO_2 via pipeline between Cremona and Forlì. Therefore, to go from Cremona to Forlì through pipelines, the model would need to activate more nodes in such a way that it would not be economically efficient. Indeed, to avoid emitting too much CO_2 related to the electricity for conditioning, which would result in another installed capture site, and, therefore, a more expensive solution, the model chose to go by train.

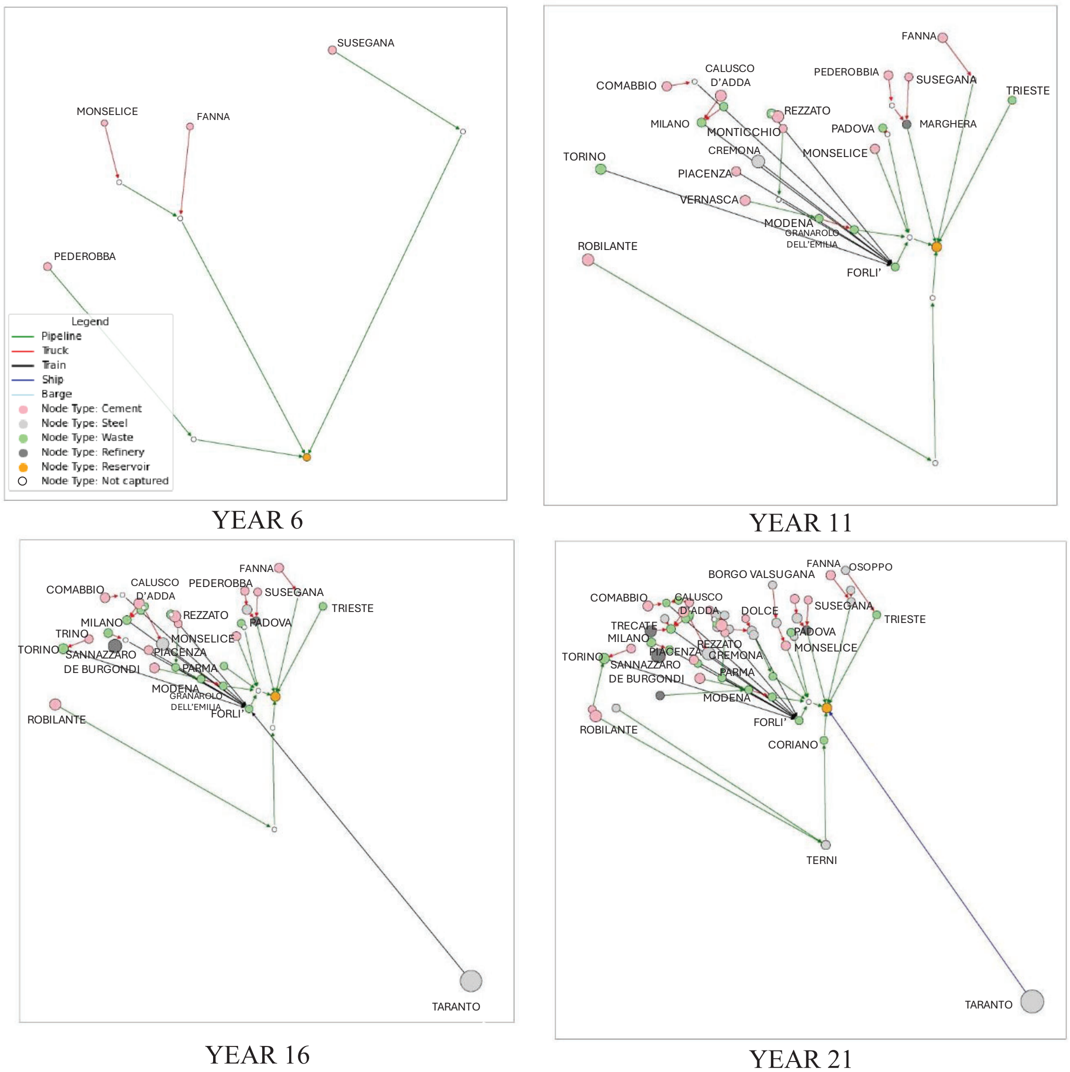

Figure 3: Infrastructure designs for years (from left to right, above to below): 6 – 11 – 16 – 21.

At year 16, the emission target is 15 $MtCO_2$/y and the system has captured all WtE and cement plants, so investments are made towards the capture of the biggest refinery plant – located in Sannazzaro de Burgondi – and the biggest steel plant – located in Taranto, with a capture rate of 4.6 $MtCO_2$/yr. Since the majority of plants are concentrated in a small area, the shortest connections are still made with trucks, increasing the emission of indirect CO_2 – which results in a higher CO_2 captured to meet the proposed objective (Table 2). Pipeline are used to connect bigger distances, alongside with trains. The choice to use train to connect Taranto to Forlì is due to the decision to recover the 88% of CO_2 of Taranto emissions. In this case, a ship (or a pipeline) between Taranto and storage site would be more expensive. At the end of simulation, i.e. year 21, as aforementioned, in each considered site a capture unit is installed and almost 2000 km are made through pipeline connections. The only connection worth of

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being used by ship is the arch between Taranto and storage location when the capture of CO_2 is 5.08 $MtCO_2$ (97% of capture rate). Indeed, ships and barges could be a viable option only if the connection is long enough and with high CO_2 capture.

4 CONCLUSIONS

The proposed MILP model for the CCS chain roll-out optimization is able to provide valuable insights, strategic recommendation on comprehensive CCS infrastructures. The decision variables of the model encompass the selection, location, and sizing of CO_2 capture, transport and storage systems. In this work the model has been applied to the Italian context, taking into account both direct – by means of hard-to-abate sectors - and indirect emission – due to electricity and means of transportation. The proposed model is versatile, inclusive, and adaptable for application across a range of hard-to-abate industrial sectors, diverse geographical regions, and varying timeframes.
The following general conclusion can be drawn:

- In cement plant, the capture unit should be first installed, as they are the cheaper; they should be followed by waste-to-energy, steel and refinery plants.
- Pipelines should be used in medium-long distances; in short route (< 20 km) truck could be still a preferred transport mode. Trains could be used to connects cities in medium-long connections (> 150 km).
- Year 18 (with a net CO_2 objective of 18 $MtCO_2$/yr allow to obtain the minimum ASCS (29.2 €/tCO_2)
- Ship and barge are extremely expensive and should be used only in long connection when high volume of CO_2 (> 5$MtCO_2$/yr) is involved.

The utilization of CO_2 is not considered in the proposed study; however, the production of synthetic fuel, such as methanol, or the usage of CO_2 to produce clinker could be of interest and will be possibly included in the future. Moreover, as Delaunay's triangulation significantly reduce the possible connections, a study of a more refined method to reduce complexity will be carried out in future.

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NOMENCLATURE

ACSC	Annualized Cost of Stored Carbon	
CAPEX	Capital Expenditure	(€)
CCS	Carbon Capture and Sequestration	
CO_2	Carbon Dioxide	
ENI	Ente Nazionale Idrocarburi	
EU	European Union	
IPCC	Intergovernmental Panel on Climate Change	
IEA	International Energy Agency	
IGCC	Integrated Gasification Combined Cycle	
LCSC	Levelized Cost of Stored Carbon	
MEA	Mono-Ethanol Amine	
MILP	Mixed-Integer Linear Programming	
NLP	Non-Linear Programming	
NGCC	Natural Gas-Fired Combined Cycle	
OPEX	Operational Expenditure	
TAC	Total annual cost	(€/yr)
U	Capacity	(tCO_2/yr)
WtE	Waste-to-Energy	
Y	Binary decision variable	
Subscript		
i	Nodes	
l	Transport mode	

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APPENDIX A - CO_2 emissions of all major Italian plants in 2021

N	E (tCO_2/y)	Type	N	E (tCO_2/y)	Type	N	E (tCO_2/y)	Type
0	1.40E+05	Cement	21	5.25E+06	Steel	42	3.91E+05	Steel
1	7.90E+05	Cement	22	2.45E+05	Steel	43	1.95E+05	Steel
2	5.37E+05	Cement	23	5.59E+05	Steel	44	1.24E+05	Waste
3	1.27E+05	Cement	24	1.05E+05	Steel	45	1.28E+05	Waste
4	4.38E+05	Cement	25	2.56E+05	Steel	46	1.30E+05	Waste
5	2.03E+05	Cement	26	1.44E+05	Steel	47	1.44E+05	Waste
6	3.52E+05	Cement	27	2.00E+05	Steel	48	1.67E+05	Waste
7	4.06E+05	Cement	28	4.05E+05	Steel	49	1.87E+05	Waste
8	9.19E+05	Cement	29	1.95E+05	Steel	50	1.87E+05	Waste
9	1.97E+05	Cement	30	2.54E+05	Steel	51	1.06E+05	Waste
10	1.28E+05	Cement	31	4.69E+05	Steel	52	3.39E+05	Waste
11	2.44E+05	Cement	32	1.01E+05	Steel	53	1.28E+05	Waste
12	5.87E+05	Cement	33	4.88E+04	Steel	54	1.79E+05	Waste
13	9.34E+05	Cement	34	3.09E+05	Steel	55	1.58E+05	Waste
14	4.08E+05	Cement	35	2.97E+05	Steel	56	1.91E+05	Waste
15	3.22E+05	Cement	36	1.95E+05	Steel	57	2.24E+05	Waste
16	2.59E+05	Refinery	37	1.25E+06	Steel	58	6.01E+05	Waste
17	1.60E+06	Refinery	38	1.95E+05	Steel	59	3.24E+05	Waste
18	2.70E+05	Refinery	39	4.07E+05	Steel	60	1.20E+05	Waste
19	8.50E+05	Refinery	40	3.76E+05	Steel	61	4.00E+05	Waste
20	4.07E+05	Steel	41	2.93E+05	Steel			

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