CHEMICAL ENGINEERING TRANSACTIONS
VOL. 96, 2022

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: David Bogle, Flavio Manenti, Piero Salatino

ISBN 978-88-95608-95-2; **ISSN** 2283-9216

DOI: 10.3303/CET2296015

Optimizing Carbon Capture and Sequestration Chains from Industrial Sources under Seismic Risk Constraints

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Carbon dioxide is the leading anthropogenic greenhouse gas in terms of emissions from carbon-intensive industries, such as cement plants, steel mills and refineries. The deployment of CO_2 (carbon) capture and sequestration (CCS) technologies plays an important role in reducing CO_2 emissions on a global scale. When optimizing the CCS supply chains for the Italian peninsula, additional complexity is brought up by the Country seismic profile. This contribution provides a techno-economic assessment and optimization of a comprehensive CCS from Italian industrial stationary sources by aim of a multi-objective mixed-integer linear programming modeling framework. In particular, the model is conceived to simultaneously optimize the economic (i.e., minimum cost) and seismic (i.e., minimum risk) performance of a CCS system in the geographic setting of Italy. In this work, a case study aiming at a carbon reduction target of 50 % is presented by discussing the corresponding set of Pareto optimal solutions. Results show a trade-off between the two conflicting objectives, where the configuration with the minimum specific CO_2 avoidance cost (68.8 €/t) is characterized by the highest value of risk (13.5 ruptures/year).

1. Introduction

In the last decades, the atmospheric concentration of carbon dioxide (CO_2) has continued to increase, reaching annual averages of 410 parts per million (ppm), as stated in the IPCC (2021) special report. Human activities are clearly responsible for the observed increases in the greenhouse gases (GHG) concentrations and significantly contributed to global warming, causing one of the biggest environmental issues that needs facing nowadays. It has become an international goal to contain the global mean surface temperature below 2 °C during the 21st century, a scenario that would be possible if deep reductions in greenhouse gas emissions will occur in the coming years and, in particular, by reducing the anthropogenic CO_2 emissions to net-zero (IPCC, 2021). In the Global CCS Institute special report (2021), carbon capture and sequestration (CCS) technologies are described as essential climate mitigation tools and very attractive strategies that are able to decarbonize the industry and facilitate net zero CO_2 emissions by 2050 (Global CCS Institute, 2021). In particular, CCS represents a suite of technologies, namely the capture, transportation and sequestration stages. Capture stage entails separating CO_2 from a process stream by means of various methods depending on the industry and on the exploited technology, followed by transporting the captured CO_2 to areas suitable for sequestration, where CO_2 is permanently stored in deep underground geological formations (Bui et al., 2018). According to EEA (2020), cement plants, refineries and steel mills are among the largest stationary emitting sources of CO_2 from the industrial sector. For this reason, the present contribution considers these sectors as part for the Italian industry to be decarbonized. Of fundamental importance in achieving a considerable level of decarbonization is the optimization of such complex and multi-stage CCS supply chains (SCs). When optimizing CCS SCs the complexity is given by the multitude of alternatives for the three stages that are part of the CCS technology. Moreover, additional complexity into the optimization of such SCs is brought when focusing on the Italian peninsula, where there is an important seismic activity. Under these circumstances, there is an additional requirement during the planning, installation, and operation of a CCS system, particularly with regards to transporting CO_2 via pipelines, a situation that may raise public concern with respect to the possibility of

Paper Received: 21 December 2021; Revised: 4 July 2022; Accepted: 18 October 2022
Please cite this article as: Cristiu D., D'Amore F., Mocellin P., Bezzo F., 2022, Optimizing Carbon Capture and Sequestration Chains from Industrial Sources Under Seismic Risk Constraints, Chemical Engineering Transactions, 96, 85-90 DOI:10.3303/CET2296015

leakages (Psyrras and Sextos, 2018). Mixed integer linear programming (MILP) is a powerful methodology for solving large, complex problems and has been used for CCS SCs optimization in several scientific contributions. For instance, Tapia et al. (2018) provided a state-of-the-art review of the computational techniques for planning CCUS (carbon capture, utilization and storage) systems. Zhang et al. (2020) applied a MILP approach for optimizing CCUS supply chains in Northeast China, while Kalyanarengan Ravi et al. (2017) applied this method at a nation-wide level for the case of The Netherlands. d'Amore et al. (2021) proposed a MILP model for a continent-wide level optimization of CCS SCs at a European level. With concern to the problem of safety related to CCS chains, d'Amore et al. (2018) presented a MILP framework for the economical optimization of wide-scale CCS SC constrained by societal risk assessment. In the present contribution a multi-objective MILP model is proposed: the goal is to optimize a nation-wide CCS SC taking into account both economic performance and seismic risk. The study focuses on Italian emissions from the cement, steel, and oil refinery industries.

2. Model

For the economic part, the model mostly relies on the framework presented in d'Amore et al. (2021). The annual CO_2 emissions referred to 2019, and the corresponding locations of industrial plants (cement plants, steel mills and refineries) in Italy are retrieved from the EEA (2020) database. In order to reduce the computational burden, only the most important emission points were kept in such a way to account for at least 80 % of the emissions from each industrial sector. In the model, the emitting nodes are defined as the set n that is subdivided into 23 cement plants (c), 7 refineries (r) and 2 steel mills (s). In order to describe the capture stage, a set k={kc, $ks_{1,2,3}$, $kr_{1,2,3}$} was defined, which contains the components describing the different technologies for each industrial sector: kc refers to the capture plant for cement plants (oxy-fuel combustion capture plants), $ks_{1,2,3}$ describing the three capture steps for steel mills (step1=ks_1: absorption capture from power plant stack, step2=ks_1+ks_2: step1 and absorption from blast furnace stoves and coke oven flue gas, step3=ks_1+ks_2+ks_3: step2 and absorption from sinter plant), and $kr_{1,2,3}$ refers to the three capturing steps for refineries (step1=kr_1: pre-combustion capture from methane reformer, step2=kr_1+kr_2: step1 and post-combustion on power unit, step3=kr_1+kr_2+kr_3: step2 and post-combustion capture from other sources at refinery). A comprehensive description of the modeling method, together with a detailed explanation of the capturing technologies and the methodology used to compute the CO_2 avoidance costs (comprising the effect of capital cost) $CCA_{k,n}$ [€/t] of capture technology k used in the industrial node n can be found in d'Amore et al. (2021). Transportation occurs through either onshore or offshore pipelines (offshore transport cost is increased by a factor $\gamma_{n,n'}$=1.71), and to account for the scale effects on the Unitary Transport Cost UTC_p [€/km/t] the CO_2 flowrate was discretized into 4 intervals defined in the set p. The sequestration stage considers both onshore and offshore sites and the Unitary Sequestration Cost USC [€/t] (offshore sequestration cost is increased by the factor θ_n=2.5) was retrieved from Rubin et al. (2015). The sequestration stage uses deep saline aquifers whose cost and capacity are evaluated in the study of Donda et. al (2011).The seismicity-related parameters over the entire Italian peninsula are obtained through a dataset containing the coordinates of polling points and are discretized into seismic areas and used to calculate the risk specific to each pipeline in the transport grid (Gehl et al., 2014). The pipeline costs can vary depending on the terrain they are installed in. The works by Herzog and Javedan (2009) and Kim et al. (2018) are used to retrieve the cost factors to account for the increase in the pipeline installation costs when there are different obstacles along the path, such as high population density, high altitudes and protected areas. These obstacles were discretized and averaged on a square grid of 50 km size.

2.1 Mathematical formulation

The proposed MILP model is a multi-objective mathematical program that aims to simultaneously minimizing the Total Cost TC [€/year] of the CCS scheme and the total seismic risk TR [ruptures/year] associated with the pipeline network installation.

$$objective = \min\{TC; TR\} \tag{1}$$

Total Cost of Eq. (1) is divided into the three components associated with the three stages of the CCS system, namely Total Capture Cost (TCC [€/year]), Total Transportation Cost (TTC [€/year]) and Total Sequestration Cost (TSC [€/year]):

$$TC = TCC + TTC + TSC \tag{2}$$

TCC is computed taking into account the annual captured CO_2 flowrate $IN_{k,n}$ [t/year] though capture technology k in the industrial node n:

$$TCC = \sum_{k,n} \left(IN_{k,n} \cdot CCA_{k,n}\right) \tag{3}$$

TTC is calculated based on the transported CO_2 flowrate $Q_{q,n,n'}$ from node *n* to *n'*, the distance between nodes $LD_{n,n'}$ [km], the unitary cost factors and the cost factor associated with the encountered obstacles $f_{n,n'}$:

$$TTC = \sum\nolimits_{p,n,n'} \left(Q_{p,n,n'} \cdot LD_{n,n'} \cdot UTC_p \cdot \gamma_{n,n'} \cdot f_{n,n'}\right) \tag{4}$$

TSC is given by the annual sequestered quantity of CO_2 OUT_n [t/year]:

$$TSC = \sum\nolimits_{n} (OUT_n \cdot USC \cdot \theta_n) \tag{5}$$

The scenario analyzed imposes a carbon reduction target of 50 % of the annual emissions from the Italian industry; thus, the overall stored amount of CO_2 is constrained to be larger than or equal to the imposed target. *TR* is evaluated as the sum over all the nodes of the Repair Rates $RR_{n,n'}$ [ruptures/year] concerning the pipelines selected to be part of the transport grid. The selection of a pipeline is defined through the binary variable $\lambda_{p,n,n'}$ that takes the value of 1 if a pipeline of size *p* is installed between nodes *n* and *n'*:

$$TR = \sum\nolimits_{n} \left(\lambda_{p,n,n'} \cdot RR_{n,n'}\right) \tag{6}$$

The parameter $RR_{n,n'}$ is proportional to the constant K_1 that describes the contribution of transport characteristics and construction material, to the distance between the nodes $LD_{n,n'}$, and to the maximum value of the peak ground velocity *PGV* of nodes *n*, *n'* or mid-pipe *n-n'*, which is defined as the highest horizontal ground velocity during a seismic event expected in the next 50 years, with an exceedance probability of 10 % (USGS, 2021).

$$RR_{n,n'} = 0.002416 \cdot K_1 \cdot LD_{n,n'} \cdot \max\left\{PGV_n; PGV_{n,n'}^{mid}; PGV_{n'}\right\} \ \forall n, n' \tag{7}$$

PGV was determined by evaluating the Spectral Acceleration S_A [g] computed by the Istituto Nazionale di Geofisica e Vulcanologia – INGV (Stucchi et al., 2011), corresponding to the formulation proposed by Allen and Wald (2007). The Spectral Acceleration was evaluated in 16 852 points that were discretized into 280 squares of 50 km in size:

$$PGV = (386.4 \cdot S_A)/(2\pi \cdot 1.65) \tag{8}$$

3. Results

The multi-objective MILP model was implemented in the GAMS software and optimized using CPLEX solver. In order to solve the bi-objective problem, the following linear weighing formulation was adopted for combining the two conflicting objectives, where *α* ranges from 0 to 1:

$$objective = \min\left\{\alpha \cdot TC + (1 - \alpha) \cdot TR\right\} \tag{9}$$

The resulting Pareto curve is presented in Figure 1 where results are represented in terms of both yearly Total Cost [M€/year] and Specific Total Cost [€/t of captured CO_2].

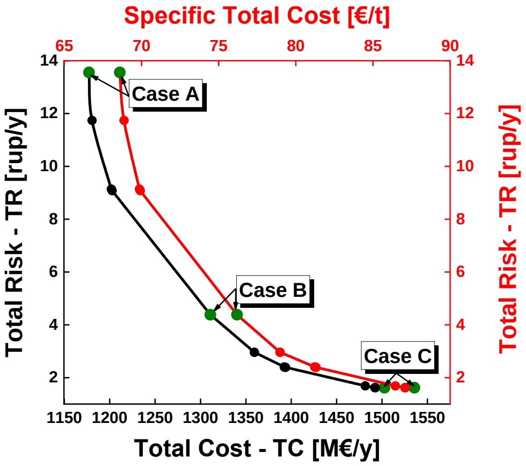


Figure 1: Pareto Curve for a 50 % carbon reduction target, with the three instances discussed in this work.

Figure 1 shows a clear trade-off between the two conflicting objectives, and for the purpose of comparison, three points on the Pareto Curve were selected and discussed. They represent:

- The economic optimum (Case A)
- The minimum seismic risk solution (Case C)
- a trade-off between the two objectives (Case B).

The detailed results of the three selected scenarios are presented in Table 1 and Figure 2. The relative optimality gap is calculated as the absolute difference of the value of the objective function of the current best integer solution and the best possible integer solution, divided by the latter one.

Table 1: Simulation results in terms of specific total costs (TC [€/t]), specific costs breakdown analysis (TCC, TTC, TSC [€/t]), total risk (TR [ruptures/year]), relative optimality gap (Opt. gap [%])

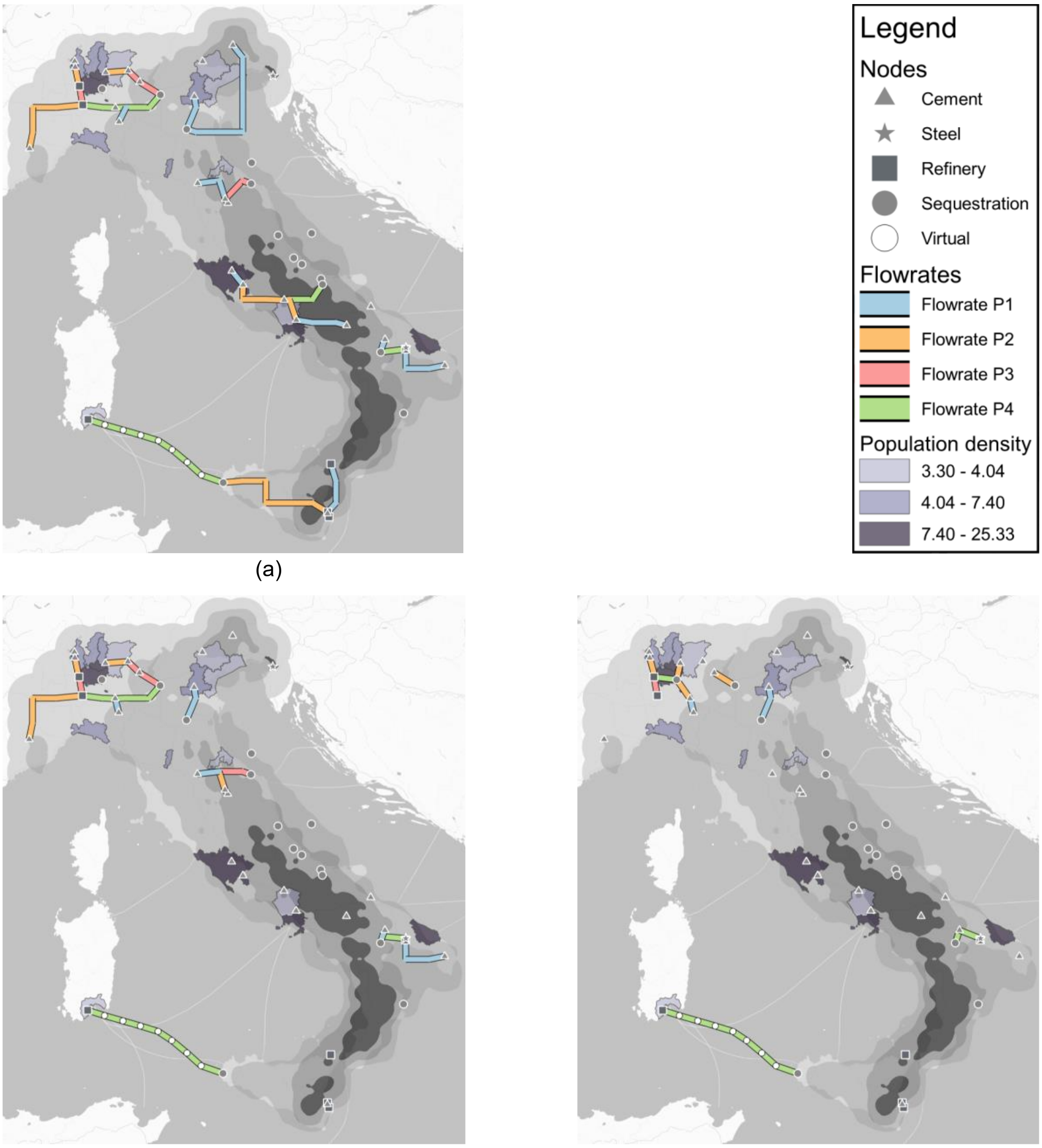
	TC [€/t]	TCC [€/t]	TTC [€/t]	TSC [€/t]	TR [rup/y]	Opt. Gap [%]
Case A	68.6	52.5	8.9	7.2	13.5	0.05
Case B	76.2	60.2	8.8	7.2	4.4	< 0.01
Case C	87.7	70.0	10.5	7.2	1.6	< 0.01

From Table 1, it can be observed that Case A, i.e. the cheapest configuration in terms of Total Cost (68.6 €/t), gives the highest risk value (13.5 ruptures/y). Case C exhibits the safest infrastructure (1.3 ruptures/y), although characterized but the highest value of Total Cost (87.7 €/t), i.e. +28 % w.r.t. Case A. Case B is characterized by a reasonable balance between the two conflicting objectives functions, with a total cost of 76.2 €/t (+11 % w.r.t. Case A) and a total risk of 4.4 ruptures/y (over 3 times those predicted in Case C). The cost breakdown reveals that the biggest contribution to the total cost is due to the capture stage in all analyzed cases, representing around 76.5 %, 79 %, and 80 % of the total cost in Case A, Case B and Case C respectively. The transportation cost contributes to the total cost with about 13 % (Case A), 11.5 % (Case B) and 12 % (Case C), while the cost of the sequestration stage can range from 8.2 % (Case C) up to 10.5 % (Case A) of the total cost.

Figure 2 shows the CCS supply chain configurations of the three analyzed cases. Figure 2a represents the best economic network, and it can be observed that the captured CO_2 comes mainly from the cement plants, capturing around 85 % of the total CO_2 emissions of cement plants. Captured CO_2 from cement plants represent about 55 % of total CO_2 avoided through all technologies. This is due to the fact that cement plants are characterized by the cheapest capture technology, followed by the steel mills capture plants. 65 % of CO_2 emissions coming from the steel sector are captured (around 26 % of the total CO_2 avoided), while only 19 % of emissions for oil refineries are captured (18 % of the total CO_2 avoided). In the case of the steel mill, a full-scale capture plant is installed ($ks_{1,2,3}$), while oil refineries are using only the first step of the capturing technology (kr_1), i.e. the cheapest one, except for the refinery located in Sardinia, where also the second step of the capturing technology in applied ($kr_{1,2}$). This configuration is characterized by the highest value of seismic risk, having a total length of 2535 km of pipelines installed and using transportation arcs that are crossing areas with high values of spectral acceleration. The total length of the system is also influenced by the fact that in Lombardia and Veneto regions, there is a higher population density and crossing these areas leads to higher transportation costs.

On the contrary, Case C (Figure 2c), which represents the safest configuration characterized by the lowest value of seismic risk, increases the percentage of the CO_2 captured from refineries up to 50 % of the total CO_2 avoided through all the technologies, capturing more than 53 % of the yearly CO_2 emissions of refineries and, in order to do so, full-scale capture plants are installed ($kr_{1,2,3}$). Even though it is the most expensive one, it brings positive consequences in terms of seismic risk since the location of the largest refinery in Italy is on Sardinia island, where there is no seismic risk. In this case, the total length of the system is about 786 km, always selecting the fastest route from an emitting node to a sequestration site, even though this may cross a protected area, fact that is penalized in terms of installation costs of pipelines, and it is one of the causes for an increased unitary transportation cost. Transporting high CO_2 flow rates using offshore pipelines is another contributing factor to higher total transportation costs.

Case B, which is shown in Figure 2b, represents a trade-off between the two conflicting objectives. This case still considers the positive consequences on the performance of this network in terms of seismic risk by installing the capture plant at the refinery in Sardinia, an area with no seismicity, and also avoids areas with high values of spectral acceleration. In terms of cost performance, the percentage of CO_2 emissions captured through the different technologies is more balanced: 39 % of the total CO_2 avoided comes from cement plants, 35 % from refineries and 26 % from steel mills. The total pipeline length in this configuration is about 1383 km. It can be observed that, also in this case, the high population density area is avoided.



(a)

(b)

(c)

Figure 2: CCS chain configuration for 50 % carbon reduction target considering a) Cost minimization – Case A, b) Trade-off scenario – Case B, c) Seismic Risk minimization – Case C

4. Conclusions

In this contribution a mixed integer linear programming model for optimizing a countrywide carbon capture and sequestration supply chain was presented. The model was formulated as a multi-objective optimization framework that aimed at minimizing simultaneously the total cost (economic objective) and the total seismic risk (risk objective). Results showed that for a carbon reduction target of 50 %, the cheapest infrastructure entailed a Total Cost of 68.6 €/t, being characterized by the highest value of risk (13.5 ruptures/y). When aiming at minimizing the Total Risk, the total cost increased up to 87.7 €/t, but the risk is greatly reduced (1.6 ruptures/y). The Pareto curve allowed assessing intermediate configurations that could present a sensible trade-off between the extreme solutions. For example, it was possible to identify a configuration that gives a reasonable balance in terms of the economic (76.2 €/t) and seismic risk (4.4 ruptures/y) performances. The proposed methodology can support investors and policy makers in finding the best solution for a CCS infrastructure in Italy.

References

Allen T.I., Wald D.J., 2007, Topographic slope as a proxy for seismic site conditions and amplification, U.S. Geological Survey Open-File Report 2007-1357, 69 p.

Bui M., Adjiman C.S., Bardow A., Anthony E.J., Boston A., Brown S., Fennell P.S., Fuss S., Galindo,A., Hackett L.A., Hallett J.P., Herzog H.J., Jackson G., Kemper J., Krevor S., Maitland G.C., Matuszewski M., Metcalfe I.S., Petit C., Puxty G., Reimer J., Reiner D.M., Rubin E.S., Scott S.A., Shah N., Smit B., Martin Trusler J.P., Webley P., Wilcox J., Mac Dowell N., 2018, Carbon capture and storage (CCS): the way forward, Energy and Environmental Science, 11, 1062–1176.

d'Amore F., Mocellin P., Vianello C., Maschio G., Bezzo F., 2018, Economic optimisation of European supply chains for CO_2 capture, transport and sequestration, including societal risk analysis and risk mitigation measures, Applied Energy, 223, 401-415.

d'Amore F., Romano M.C., Bezzo F., 2021, Optimal design of European supply chains for carbon capture and storage from industrial emission sources including pipe and ship transport, International Journal of Greenhouse Gas Control, 109, 103372.

Donda F., Volpi V., Persoglia S., Parushev D, 2011, CO_2 storage potential of deep saline aquifers: The case of Italy. International Journal of Greenhouse Gas Control, 5, 327–335.

EEA, 2020, European Pollutant Release and Transfer Register, <eea.europa.eu/data-and-maps/data/member-states-reporting-art-7-under-the-european-pollutant-release-and-transfer-register-e-prtr-regulation-23/european-pollutant-release-and-transfer-register-e-prtr-data-base> accessed 14.04.2022.

Gehl P., Desramaut N., Réveillère A., Modaressi H., 2014, Fragility Functions of Gas and Oil Networks. In: K. Pitilakis, H. Crowley, A. Kaynia (eds) SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk. Geotechnical, Geological and Earthquake Engineering, vol. 27, Springer, Dordrecht.

Global CCS Institute, 2021, The Global Status of CCS: 2021, Australia <globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf> accessed 14.04.2022.

Herzog H., Javedan H., 2009, Development of a Carbon Management Geographic Information System (GIS) for the United States, United States, <doi.org/10.2172/974322>.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Kalyanarengan Ravi N., van Sint Annaland M., Fransoo J.C., Grievink J., Zondervan E., 2017, Development and implementation of supply chain optimization framework for CO_2 capture and storage in the Netherlands, Computers and Chemical Engineering, 102, 40–51.

Kim C., Kim K., Kim J., Ahmed U., Han C., 2018, Practical deployment of pipelines for the CCS network in critical conditions using MINLP modelling and optimization: A case study of South Korea. International Journal of Greenhouse Gas Control, 73, 79–94.

Psyrras N.K., Sextos A.G., 2018, Safety of buried steel natural gas pipelines under earthquake-induced ground shaking: A review, Soil Dynamics and Earthquake Engineering, 106, 254-277.

Rubin E.S., Davison J.E., Herzog H.J., 2015, The cost of CO_2 capture and storage, International Journal of Greenhouse Gas Control, 40, 378-400.

Stucchi M., Meletti C., Montaldo V., Crowley H., Calvi G.M., Boschi E., 2011, Seismic Hazard Assessment (2003-2009) for the Italian Building Code, BSSA, 101, 1885-1911.

Tapia J.F.D., Lee J.Y., Ooi R.E.H., Foo D.C.Y., Tan R.R., 2018, A review of optimization and decision-making models for the planning of CO_2 capture, utilization and storage (CCUS) systems, Sustainable Production and Consumption, 13, 1-15.

Zhang S., Zhuang Y., Liu L., Zhang L., Du J., 2020, Optimization-based approach for CO_2 utilization in carbon capture, utilization and storage supply chain, Computers and Chemical Engineering, 139, 106885