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Multi-objective economic and environmental assessment for the preliminary design of CO_2 transport pipelines

Francesco Zanobetti [a,b], Sergey Martynov [a], Valerio Cozzani [b], Haroun Mahgerefteh [a,*]

[a] Department of Chemical Engineering, University College London, London, WC1E 7JE, UK
[b] LISES - Laboratory of Industrial Safety and Environmental Sustainability, Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, via Terracini 28, 40131, Bologna, Italy

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ABSTRACT

A methodology based on the multi-objective optimisation of economic and environmental aspects is presented to support the preliminary design of CO_2 transport pipelines employed as part of Carbon Capture and Storage (CCS) systems. Pareto optimal design solutions are determined for a realistic point-to-point CO_2 pipeline using Level Diagrams and choosing the Nominal Pipe Size (NPS) as a decision variable. A quantitative procedure entailing the definition of economic and environmental key performance indicators is defined to allow the identification of an optimum pipeline design. The outcome is compared against the minimisation of single-objective indicators based on the CO_2 avoided and carbon pricing concepts. The results of a case-study concerning a 70 km long pipeline transporting 10 Mt yr^{-1} of supercritical CO_2 show that the multi-objective method yields an optimum NPS equal to 30, higher than the NPS 28 deriving from the alternative indexing methods. The proposed multicriteria approach effectively considers case-specific environmental sustainability constraints, which result in determining 46% of the overall performance measure of the identified optimum solution. The results show that conventional single-objective methods underestimate the contribution of environmental factors up to 2.6% of the overall performance index value. A Monte Carlo probabilistic analysis is performed to verify the robustness of the results with respect to the possible uncertainties.

1. Introduction

Carbon Capture and Storage (CCS) is widely considered as being pivotal in meeting the ambitious 2050 net zero emission target (Global CCS Institute, 2021; IEA, 2021b). Logistics permitting, long distance pressurised pipelines are the most cost-effective and safest method for transporting the large amounts of captured CO_2 for subsequent geological storage (Lazic et al., 2014; Metz et al., 2005). It is estimated that meeting the internationally agreed emission reduction targets by 2050 will require CCS to handle an average of 6 Gt yr^{-1} CO_2, supported by a rate of 70–100 capture facilities built per year and nearly 200,000 km of pipelines (Global CCS Institute, 2020). However, existing uncertainty in fully understanding the technological challenges and reducing the investment costs for CCS are significant barriers to full-scale commercial deployment (Bui et al., 2018; Wilberforce et al., 2019). Notably, cost of CO_2 transport can vary significantly according to the volumes of CO_2 transferred, transport distances and the geological storage characteristics (IEA, 2021a). A comprehensive techno-economic assessment of such transport infrastructures with the aim of substantially reducing costs is therefore of paramount importance.

Pipeline diameter is widely regarded as a key variable in the cost assessment and hence economical design of high-pressure CO_2 transport pipelines (Peletiri et al., 2018). Optimal diameter selection procedures can be generally distinguished based on whether the calculation method relies on hydraulic laws or the minimisation of transportation costs (Vandeginste and Piessens, 2008). Alongside purely hydraulic approaches, CO_2 pipeline design dictated by cost optimisation is crucial in facilitating the construction and deployment of CCS infrastructures worldwide (Zhang et al., 2012). Zhang et al. (2006) employed an 'economic pipeline diameter' calculation to investigate cost-effective CO_2 transportation under variable operating and climatic conditions. Their analysis led to an expression for determining the optimal pipeline diameter corresponding to the minimum total transport cost. Pipeline inlet conditions of 15.0 MPa and 40 °C were assumed for the calculation. Despite its straightforward applicability, the model developed incorporates case-specific economic and operational data, which

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* Corresponding author.
E-mail address: h.mahgerefteh@ucl.ac.uk (H. Mahgerefteh).

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ultimately restrict its range of applicability. Moreover, the expression developed tends to underestimate the optimal diameter when compared against other established pipeline design tools (Vandeginste and Piessens, 2008).

Knoope et al. (2013a) presented a comprehensive review of cost models applicable for the economic optimisation of CO_2 pipeline designs. Nine different cost models presenting the pipeline diameter as independent variable were selected and categorized as linear cost models, based on the weight of the pipeline, quadratic equations, and logarithmic models. A 25 km pipeline routed on a flat agricultural terrain was assumed to assess and compare the results produced using the different pipe diameter-based models considered. The analysis showed that CO_2 pipeline costs determined using the various models varied significantly, especially for large pipe diameters (e.g., 0.8–5.5 $M€_{2010}$/km for a 0.8 m pipe diameter). Moreover, nearly all the cost models tested were based on data for U.S. natural gas pipelines installed in the ’90s and in the following decade, rendering their applicability to newly designed CO_2 pipelines uncertain. To overcome such limitation, Knoope et al. (2014) developed a cost model for CO_2 pipeline transport based on more recent material and construction cost data, taking into account also the different physical states of the transported fluid and steel grade types. The model’s applicability was demonstrated as a pipeline transport cost minimisation tool considering inlet pressure, diameter, steel grade and number of pumping units. Different pipeline configurations spanning point-to-point pipelines, pipelines crossing multiple terrains and pipeline networks were assumed for this purpose. The results indicated that CO_2 transport in the dense liquid phase tends to be more cost-effective than the gaseous phase when the required injection pressure into the storage site is above 8 MPa, as is the case with injection in an aquifer. Despite its versatility in optimising a wide variety of CO_2 pipeline configurations, the impact of the CO_2 stream impurities on the pipeline material costs and operational requirements were not considered.

Skaugen et al. (2016) investigated the impact of CO_2 stream impurities on pipeline transport costs. A case-study involving a 500 km pipeline transporting 13.1 MTPA CO_2 was employed to analyse the economic consequences of two different levels of CO_2 impurities. Costs related to the compression, cooling and purification of CO_2 prior to pipeline transport were included in the assessment, showing that the level of impurities in the CO_2 mixture may increase the pipeline transport costs by up to 22%.

It is important to note that the economic viability and public acceptability of large-scale CCS deployment is also strongly influenced by the net greenhouse gas emissions reduction that such technology can deliver (de Coninck et al., 2009). The latter may be expressed according to the Global Warming Potential (GWP) metric, which is able to account for the overall amount of greenhouse gas emissions attributable to the CCS facility spanning its construction, operation and ultimate decommissioning (Singh et al., 2011). In the case of CO_2 pipelines, a significant factor governing the GWP is the indirect equivalent CO_2 emissions associated with the very high energy demand required for pressurising the captured CO_2 up to supercritical pipeline transport conditions (Weisser, 2007; Zhang et al., 2012). It is estimated that the energy penalty associated with the compression of CO_2 can be as high as 12% (Martynov et al., 2016).

Accordingly, when cost-optimising the pipeline transport design, it is essential to factor in the GWP. In this context, the “cost of CO_2 avoided” approach (Ho et al., 2011) has been largely used in the literature as an effective metric to minimise costs against the net greenhouse gas emissions related to operating CCS systems. Such concept has been adapted in CO_2 transportation by defining a “CO_2 avoided transport cost” as a performance indicator, guiding the selection of the most effective CO_2 transportation modes (e.g., pipeline, marine shipping) while considering annualised emitted CO_2 equivalents (Roussanaly et al., 2013, 2014). Other design approaches (Chaabane et al., 2012; Zhang et al., 2017) present carbon pricing under Emission Trading Scheme (ETS) as an alternative valuable tool to strike a balance between environmental impacts and economic evaluations. It is also proposed that the decision-making process for the various design alternatives should account for both site-specific impact burdens and local sustainability policies, leading to different weighing of economic, environmental, and societal factors according to the prevailing local issues (Tugnoli et al., 2008).

An integrated and systematic evaluation of economic and environmental aspects is therefore paramount for large-scale deployment of CO_2 pipeline infrastructures. In this study, a multicriteria approach is developed and tested to determine the least cost and environmentally impacting options during the preliminary design of high-pressure CO_2 transport pipelines. The above involves an analysis of the Pareto Front (Chiandussi et al., 2012; Tusar and Filipic, 2015) to evaluate the different optimal trade-offs, followed by a comparative assessment of the identified alternatives with respect to economic and environmental aspects. A performance-based ranking of optimal trade-offs is ultimately obtained to enable the selection of the appropriate design solution. A case study involving the determination of the optimum pipe diameter for a large-scale point-to-point CCS pipeline is presented to exemplify the developed procedure.

Given that economic and financial parameters used for determining CO_2 pipeline transport cost are key uncertainties, a Monte Carlo probabilistic analysis is applied to assess the propagation of such uncertainties on the outcome of the analysis. Two alternative indexing methods, based on the CO_2 emission avoided and carbon pricing concepts, are applied to elucidate the differences with the presented multicriteria approach when balancing economic and environmental aspects. Overall, the proposed tool provides a flexible and structured design approach where economic and environmental aspects are addressed based on the case-specific decision-making criteria adopted.

2. Methodology

2.1. Multi-objective optimisation

The optimal CO_2 pipeline design with respect to economic and environmental aspects can be formulated in terms of a multi-objective optimisation problem as follows:

$$\min_{\theta \in \Omega} J(\theta) \tag{1}$$

$$J(\theta) = [J_1(\theta), J_2(\theta)] \tag{2}$$

$$\theta = [\theta_1, \ldots, \theta_n] \tag{3}$$

where J_1, J_2 and θ are respectively the economic and environmental objective functions and the vector of design decisional variables. Ω represents the decision space.

Modelling of the pertinent economic and environmental objectives will be addressed respectively in sections 2.2 and 2.3, whilst the selection of the decision variables for the problem will be introduced in the context of the sample case study definition in section 3.

In order to obtain effective representations of the final results, the mathematical Level Diagrams visualisation technique is applied (Zio and Bazzo, 2011). This involves computing metric distances quantifying how far a given configuration is from the ideal solution simultaneously optimising both objectives.

The following norms are considered in this study:

- 1-norm:

$$J(\theta)_1 = \sum_{i=1}^{2} |\overline{J_i}(\theta)|, \quad 0 \le J(\theta)_1 \le 2 \tag{4}$$

- Infinite norm (∞-norm):

$$J(\theta)_{\infty} = max[\overline{J_i}(\theta)], \quad 0 \le J(\theta)_{\infty} \le 1 \tag{5}$$

where,

$$\overline{J_i}(\theta) = \frac{J_i(\theta) - J_i^{min}}{J_i^{max} - J_i^{min}}, \quad i = 1,2 \tag{6}$$

$$J_i^{min} = \min_{\theta \in \Omega} J_i(\theta), \quad i = 1,2 \tag{7}$$

$$J_i^{max} = \max_{\theta \in \Omega} J_i(\theta), \quad i = 1,2 \tag{8}$$

The normalised objective functions resulting from Eq. (6) are summed in the formulation of the 1-norm whereas the ∞-norm considers only the worst affected (i.e., the farthest from its respective ideal value). Level Diagrams are then obtained by plotting separately each norm against the objective functions and decision variables.

2.2. Economic assessment

The economic objective function of the problem J_1 (see Eqs. (1)–(3)) is mathematically defined as a Levelized Cost (LC) of CO_2 transport, as follows:

$$LC = \frac{I \times CRF + O\&M + E}{G} \tag{9}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{10}$$

where I, CRF and $O\&M$ are respectively the overall investment cost, the capital recovery factor and the operational and maintenance cost. On the other hand, E and G are the energy cost and the mass flow rate of transported stream, respectively. The annual discount rate (i) is set at 8% while a lifetime (n) of 25 years is assumed for the pipeline system. Investment and operating (e.g., energy and operational & maintenance) costs are given in 2020 prices (€$_{2020}$). In particular, the Chemical Engineering Plant Cost Index (CEPCI) (Garrett, 2012) is used to update capital costs of the pipeline and other auxiliary equipment items (e.g., compressors, pumps).

The investment cost (I) for CO_2 transportation consists of the investment cost of the pipeline (I_{pipe}) and those of compressors (I_{comp}) and pumping stations (I_{pump}), as follows:

$$I = I_{pipe} + I_{comp} + I_{pump} \tag{11}$$

The pipeline investment cost is estimated according to the following set of equations, as derived from the cost model developed by Knoope et al. (2014):

$$I_{pipe} = I_{material} + I_{labour} + I_{ROW} + I_{miscellaneous} \tag{12}$$

$$I_{material} = \frac{\pi}{4} \times \left[D_O^2 - (D_O - 2t)^2\right] \times L \times C_{steel} \times \rho_{steel} \tag{13}$$

$$I_{labour} = C_{labour} \times D_O \times L \tag{14}$$

$$I_{ROW} = C_{ROW} \times L \tag{15}$$

$$I_{miscellaneous} = 0.25 \times (I_{material} + I_{labour}) \tag{16}$$

$I_{material}$ is the pipe material cost, whose estimate is based on the pipeline outer diameter (D_O), pipe thickness (t), and overall length (L). The X70 carbon steel is assumed as the pipe material, for which the density (ρ_{steel}) and cost (C_{steel}) are 7900 kg m^{-3} and 1.62 €$_{2020}$ kg^{-1} respectively. In this study, the pipeline thickness (t) is calculated as follows (US DOT, 2022):

$$t = \frac{MAOP \times D_O}{2 \times S \times F \times E} \tag{17}$$

where $MAOP$, S and E are respectively the maximum allowable operating pressure, the minimum yield stress for the pipe material and the longitudinal joint factor. On the other hand, F corresponds to the design factor, which is aimed at introducing a safety margin in the calculation of the pipeline thickness (McCoy and Rubin, 2008). For the sake of preliminarily estimating the pipe wall thickness, $MAOP$, E and F are assumed equal to 15.3 MPa, 1.0 and 0.72, corresponding to the case of a pipeline constituted by pipe segments with ASME-ANSI 900# flanges deployed in scarcely populated areas or offshore (McCoy and Rubin, 2008; Mohitpour et al., 2007; US DOT, 2022). A minimum yield stress (S) equal to 483 MPa is assumed, which corresponds to the X70 carbon steel considered in the analysis.

I_{labour} is the labour cost for construction, welding, and installation of the pipeline, calculated as the unitary labour cost (C_{labour}) of 22.9 €$_{2020}$ in^{-1} m^{-1}, multiplied by the pipeline length (L) and the pipeline outer diameter (D_O) (Knoope et al., 2014).

I_{ROW} is the pipeline Right of Way (ROW) cost, which is related to the acquisition of legal rights to site the pipeline and obtained by multiplying a unitary ROW cost (C_{ROW}) with the pipeline length (L). In this study, C_{ROW} is set equal on average to 90.4 €$_{2020}$ m^{-1}, as determined by Knoope et al. (2014) based on historical cost data of onshore pipelines.

Finally, $I_{miscellaneous}$ includes other types of cost (e.g., surveying, engineering, supervision, contingencies, taxes, etc.) and can be expressed as a fixed percentage of the sum of material and labour costs, taken as an average value of 25%, in accordance with the findings from Knoope et al. (2014).

The investment cost for the compressors (I_{comp}) is calculated using Eq. (18) (Knoope et al., 2014). The number of the required upstream compressors (n) is determined using Eq. (19), based on a maximum power load for one single compressing unit equal to 35 MW$_e$ (McCollum and Ogden, 2006). A multiplication factor (me) is introduced in the cost equation to account for the economic advantage given by installing n units in parallel configuration (Knoope et al., 2014).

$$I_{comp} = I_0 \times \left(\frac{W_{comp}}{n \times W_{comp,0}}\right)^y \times n^{me} \tag{18}$$

$$n = ROUND\_UP\left(W_{comp} / 35\right) \tag{19}$$

In Eq. (18), I_0, W_{comp}, and $W_{comp,0}$ are respectively the base cost (23.7 M€$_{2020}$), the compression power consumption and the base scale of the compressor (13 MW$_e$) (Knoope et al., 2014). On the other hand, y, me and n are the scaling factor (0.67), the multiplication exponent (0.9) and the number of parallel units, respectively (Knoope et al., 2014; McCollum and Ogden, 2006).

Pumping investment cost (I_{pump}) can be estimated from Eq. (20), considering the maximum capacity of a single unit equal to 2.0 MW$_e$ (IEA, 2012):

$$I_{pump} = 80.5 \times W_{pump}^{0.58} \times n^{me} \tag{20}$$

where W_{pump}, n and me are the capacity of a single unit (kW$_e$), the number of units in parallel and the multiplication exponent (0.9), respectively.

Operational and Maintenance ($O\&M$) costs are calculated by summing up the contributions related to the pipe ($O\&M_{pipe}$), compressors ($O\&M_{comp}$) and pumps ($O\&M_{pump}$), as follows:

$$O\&M = O\&M_{pipe} + O\&M_{comp} + O\&M_{pump} \tag{21}$$

The annual operational and maintenance costs corresponding to CO_2 pipelines and pumping equipment (i.e., compressors and pumps) are assumed to be respectively 2.5% and 4% of their investment cost (McCollum and Ogden, 2006).

Ultimately, the energy consumption cost (E) for CO_2 transportation is computed as follows:

$$E = p_e \times \left(W_{comp} + \sum_i W_{pump,i} \right) \times OH \tag{22}$$

where p_e, W_{comp} and $W_{pump,i}$ are the electricity price, assumed to be on average 100 € MW^{-1} h^{-1} (Knoope et al., 2013b), the power consumed by the upstream compression plant and the power consumption associated with the *i*-th pumping unit installed throughout the pipeline, respectively. On the other hand, *OH* represents the number of operation hours (8760 h/yr). The methodology for determining W_{comp} and W_{pump} is described in section 3.

2.3. Environmental assessment

The amount of greenhouse gas (GHG) emissions generated from electrical power consumption constitute the environmental objective of the problem J_2 (see Eqs. (1)–(3)) and is determined as follows:

$$GHG_{emitted} = EF_{GHG} \times \left(W_{comp} + \sum_i W_{pump,i} \right) \times OH \tag{23}$$

where $GHG_{emitted}$ are the annual GHG emissions expressed as CO_2 equivalents (t yr^{-1}). On the other hand, EF_{GHG} is the emission factor (t MW^{-1} h^{-1}) for the indirect GHG emissions resulting from electricity demand. This can be quantified according to either common sets of standardised procedures, such as the Guidelines for National Greenhouse Gas Inventories promulgated by the IPCC, or alternative approaches such as the more complete Life Cycle Assessment (LCA) (Cellura et al., 2018; Chuang et al., 2018; Ji et al., 2016). Locally available energy sources, types of fuels as well as power generation efficiencies all significantly affect the emission factor, expected to change annually depending on the most up-to-date energy portfolio data (Chuang et al., 2018).

In this study, an European LCA emission factor equal to 0.578 t MW^{-1} h^{-1} is assumed (The Covenant of Mayors, 2010).

2.4. Comparative analysis of alternative design options

A quantitative methodology based on the definition of impact indicators (Tugnoli et al., 2008) is used to compare economic and environmental performances of the selected design options.

The above procedure is summarised in four main steps as shown in Fig. 1 and described as follows:

1) *Definition of design options.* Data on the levelized cost of CO_2 transport (objective function J_1) and GHG emissions (objective function J_2) are collected for the design options to be compared.

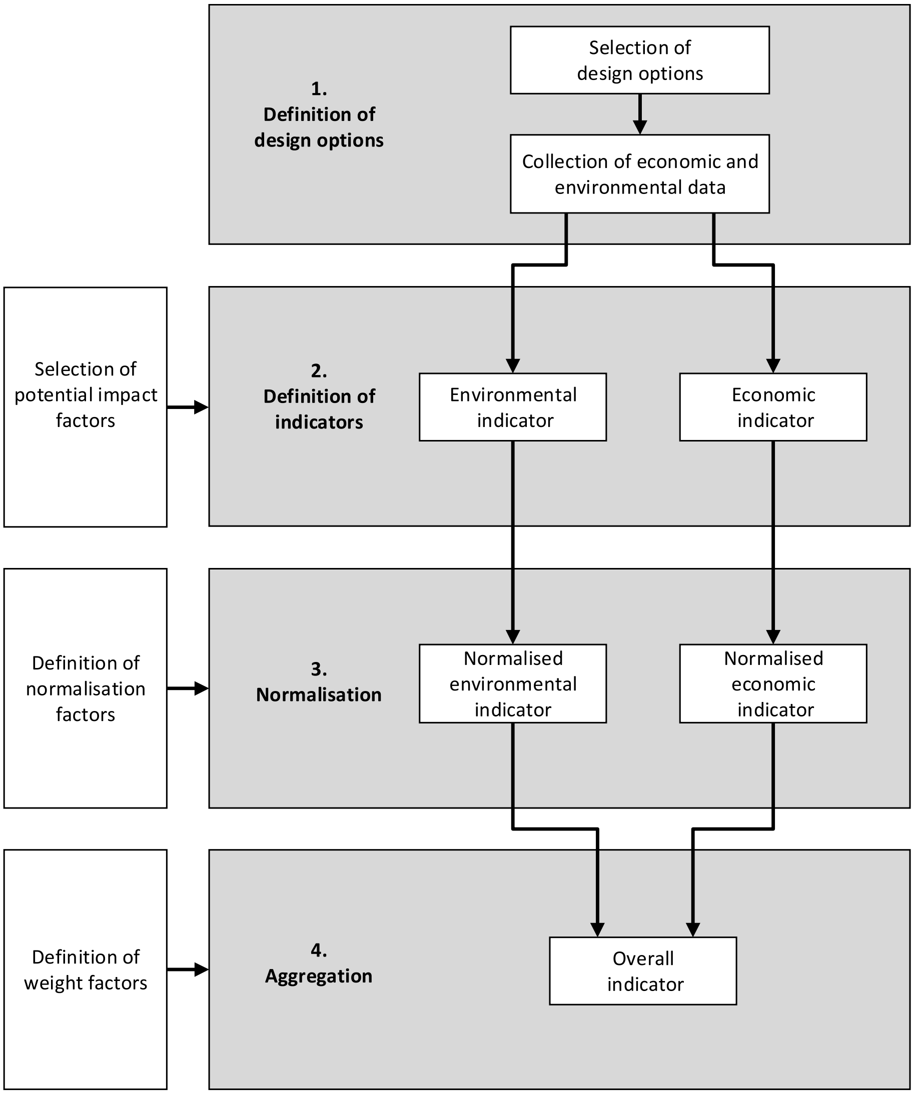

Fig. 1. Flowchart of the procedure proposed for the comparative analysis of alternatives.

2) *Definition of indicators.* An indicator accounting for the contribution of the CO_2 pipeline system in fuelling global warming is selected to represent the environmental impact. This is calculated as a potential impact factor multiplied by the GHG emissions produced during the system's operation, as follows:

$$I_{GW} = PIF_{GW} \times GHG_{emitted} \tag{24}$$

where I_{GW} and PIF_{GW} are respectively the global warming impact indicator and the potential impact factor for global warming. Specifically, PIF_{GW} associated with CO_2 emissions is equal to 1 (Tugnoli et al., 2008).

On the other hand, the levelized cost of transport is set as the net potential economic impact indicator (I_{NPEI}).

Table 1 summarizes the economic and environmental impact indicators defined in this study.

3) *Normalisation.* The indicators listed in Table 1 are then normalised with respect to a reference value acting as Normalisation Factor (NF):

$$NI_i = \frac{I_i}{NF_i} \tag{25}$$

where NI_i, I_i and NF_i are respectively the normalised indicator, the indicator to be normalised and the normalisation factor for the i-th impact category (e.g., global warming and net potential economic impact for the environmental and economic domains, respectively). The normalisation procedure can be either internal, where an impact indicator is normalised with its maximum value computed in the analysis, or external, involving the selection of an externally defined reference value. In this study, since the analysed alternatives are referred to the same CO_2 transportation process, an internal normalisation criterion is assumed for both indicators.

4) *Aggregation.* The normalised indicators are combined through a multicriteria weighted summation method, to generate an overall performance indicator for each design option, as follows:

$$I_{aggr,k} = \sum_i W_i NI_{i,k} \tag{26}$$

where $I_{aggr,k}$ and W_i are respectively the aggregated index for the k-th design option and the weight factor for the i-th impact category. The weight factors sum up to 1 and represent the relative importance of the considered impact domains. The magnitudes of such weighing terms are determined by case-specific constraints, such as experts' judgment and local sustainability policies. In this study, an equal weight factor is attributed to environmental and economic aspects based on a realistic reference sustainability management perspective (Tugnoli et al., 2008).

A hierarchy of overall indicators $I_{aggr,k}$ is finally obtained, providing a common metric to compare performances of the considered alternatives.

The results are then considered against those obtained based on the application of two alternative approaches involving the evaluation of single indicators, using the CO_2 avoided and carbon pricing concepts.

The CO_2 avoided transport cost indicator ($LC_{avoided}$) (Roussanaly et al., 2013; Rubin et al., 2003) quantifies the overall performance of the CO_2 pipeline by relating the annual transport cost to the difference between the transported mass flow rate and the greenhouse gases (expressed as CO_2 equivalents) emitted annually:

$$LC_{avoided} = \frac{I \times CRF + O\&M + E}{G_{transported} - G_{emitted}} \tag{27}$$

Table 1
Indicators employed to compare alternative design options.

Domain	Impact category	Indicator
Environment	Global warming	I_{GW}
Economy	Net Potential Economic Impact (NPEI)	I_{NPEI}

where $G_{transported}$, and $G_{emitted}$ are the mass of captured CO_2 transferred annually by the pipeline system (t yr^{-1}) and the amount of CO_2 equivalents emitted per year (t yr^{-1}).

The second indicator considered computes the environmental impact by monetising GHG emissions according to carbon pricing schemes. Carbon emissions can be priced based on specific international carbon markets, which have been gaining increasing popularity over the last decade as effective tools to curb GHG emissions (Bayer and Aklin, 2020; MacKenzie, 2009). Among such carbon pricing institutions, the European Union's Emissions Trading System (EU ETS) is currently deemed the most ambitious and credible, whose EU Allowance (EUA) metric quantifies the cost of 1 tonne of CO_2 emitted in Europe (Bayer and Aklin, 2020). In this study, an average value of EUA equal to 29 € is considered based on historical data for the year 2020 (QUANDL, 2021), in agreement with the 2020 € prices considered for computing CO_2 transport costs in section 2.2.

An index ($LC_{carbon\ pricing}$) based on the carbon pricing concept is therefore calculated expressing the environmental impact as an apparent cost contribution to be added to the annual cost of CO_2 transport, as written in the following:

$$LC_{carbon\ pricing} = \frac{I \times CRF + O\&M + E + p_{carbon} \times G_{emitted}}{G_{transported}} \tag{28}$$

where p_{carbon} is the carbon price (€ t^{-1}) according to the EU ETS system.

2.5. Sensitivity analysis

The comparative analysis of alternative design options may be affected by uncertainties associated with economic input parameters (Crivellari and Cozzani, 2020; McCoy and Rubin, 2008). As such, in this study, a sensitivity analysis for the CO_2 transport cost (objective function J_1) is developed to test the robustness of the results obtained. An arbitrary fluctuation of ±20% with respect to their base value is considered for the main cost parameters to select the key input variables to be included in the analysis.

A probabilistic Monte Carlo investigation is then undertaken to simulate the propagation of uncertainties affecting the identified critical input variables on the CO_2 transport cost.

The above involves assigning a probability distribution to each uncertain economic parameter, then repeating the calculation for a sufficiently high number of times, randomly sampling in each run the input variables in their uncertainty ranges (Crivellari and Cozzani, 2020; Dal Pozzo et al., 2017). The uncertain variables are considered stochastic variables following a triangular distribution, which is deemed suitable to evaluate cost risks due to its simple formulation and its ability in approximating a lognormal distribution (Lee et al., 2018). Random numbers are generated and attributed to the uncertain parameters, the latter providing the input values to calculate the probability and cumulative probability curves. A total of 10^6 Monte Carlo simulations is performed, found to be sufficient to obtain robust results without requiring excessive computational demand (Crivellari et al., 2021; Crivellari and Cozzani, 2020; Scarponi et al., 2016).

3. Case study

The following presents a realistic case study demonstrating the application and versatility of the proposed multi-objective methodology.

A 10 Mt yr^{-1} dense-phase CO_2 stream is assumed to be compressed and transported using a point-to-point, 70 km pipeline for injection into a geological storage site. For simplification, no intermediate pumping is considered. This assumption is plausible for offshore pipelines, for which subsea pumps are not generally an economically viable option, and also for onshore pipelines routing over short/medium transportation distances (e.g., up to 100 km) (Knoope et al., 2014). The CO_2

stream is considered as pure, representing a reasonable approximation of those produced by post-combustion and advanced oxy-fuel capture technologies (Martynov et al., 2016). The feed is assumed to enter the pipeline at 37 °C, with the inlet pressure set above the minimum pressure required to ensure supercritical CO_2 flow along the entire length of the pipeline (Martynov et al., 2015). The pipeline surface roughness and outlet pressure are taken as 0.0475 mm (McCoy and Rubin, 2008) and 90 bar respectively. Table 2 summarizes the cases study conditions.

Fig. 2 presents the multi-objective optimisation algorithm flow diagram developed for the case study. The Nominal Pipe Size (NPS) is set as the problem decision variable, varied discretely, in increments of 2 in the range 8–48 according to standardised values (The American Society of Mechanical Engineers, 2004). PipeTech CFD software (PipeTech, 2023) is employed to iteratively determine the pipeline inlet pressure needed to ensure 90 bar delivery pressure. Following Knoope et al. (2013b), the average CO_2 flow velocity at any point along the pipeline is limited to below 6 m/s to avoid pipe erosion and vibration, and above 0.5 m/s to ensure a minimum flow of CO_2 per unit time throughout the pipeline system. If a simulated pipeline transportation scenario does not follow the above constraints, the corresponding NPS is excluded from the feasible decisional space.

The compressor power demand is calculated based on the multi-stage compression thermodynamic model proposed by Martynov et al. (2016). The gaseous CO_2 leaving the conditioning section of the capture unit is assumed to be compressed in a single stage compressor with 0.8 isentropic efficiency, starting from an initial pressure of 15 bar, up to the supercritical pipeline inlet pressure obtained from the optimisation algorithm. Based on the computed compression power requirements, the levelized cost of CO_2 transport and the corresponding GHG emissions are assessed for each design option according to the procedures described in sections 2.2 and 2.3 respectively. The norm metrics $\|J(\theta)\|_1$ and $\|J(\theta)\|_\infty$ are then computed (see Eqs. (4) and (5)) for all the pipe configurations deemed feasible according to the above operational constraints, thus allowing the identification of the solutions for the multi-objective optimisation problem.

Finally, the determined optimal solutions are ranked by the comparative assessment procedure described in section 2.4 to identify the optimum design option resulting in the lowest overall impact index $I_{aggr,k}$ (see Eq. (26)).

4. Results and discussion

4.1. Multi-objective optimisation

The levelized cost of CO_2 transport and the amount of CO_2 equivalents emitted annually are numerically sampled for 14 feasible NPS sizes ranging from 18 to 44. Fig. 3 shows the corresponding results.

As observed from Fig. 3a, Normalised GHG emissions, J_2, decrease almost exponentially as NPS is raised from 18 to 44. Increasing NPS lowers the pressure drop along the pipeline, thus decreasing the compression power requirements and hence the observed reduction in the GHG emissions.

Returning to Fig. 3a, the Normalised Transport Cost, J_1, decreases steeply with the increase in NPS (hence the pipe outer diameter) up to a value of 28 before rapidly increasing as NPS increases to the maximum prescribed value of 44. The observed initial drop in J_1 is due to the fact that the compression costs, which dominate the transport costs (Martynov et al., 2016), diminish with increase in pipe diameter. The subsequent rapid, almost linear rise in the cost is due to the dominant contribution of pipeline material and fabrication costs as the pipeline diameter increases.

Fig. 3b shows the results obtained by mapping the values of J_1 and J_2 into a bi-objective space. As it may be observed, considering values of J_2 below 0.2, a decrease in the Normalised Transport Cost, J_1, would inevitably lead to an increase in the Normalised GHG emissions, J_2, and vice versa. Indeed, reducing J_1 in this region of the bi-objective space requires the selection of a smaller pipe diameter. However, as expected, this results in a higher J_2 due to the increased compression power demand required to overcome the pressure drop along the pipeline. Such condition identifies the solution of the multi-objective optimisation problem, called Pareto Front, where neither of the optimal trade-off points is suitable for minimising both objectives.

Fig. 4 shows the 1-norm and Infinite norm Level Diagram representations for the optimisation problem. Once the multi-objective optimisation problem is solved, the introduction of appropriate decision-making criteria is required to identify one or more design options of preference within the Pareto Front (Zio and Bazzo, 2011). In this study, the above are evaluated based on the lowest computed values of the norms. Analysing the two trends in the figure, three design options sharing a similar and significantly low value of both norms, namely NPS 28, NPS 30 and NPS 32, may be considered as optimal. The selected Pareto trade-offs are then assessed using the quantitative methodology described in section 2.4 to establish a single most effective solution based on the introduced economic and environmental decision-making preferences.

4.2. Comparative assessment of alternatives

The environmental and economic impact indicators calculated for the comparative analysis of NPS 28, 30 and 32 are reported in Table 3. The table also includes the normalisation factors considered in this study.

Table 4 reports the normalised and overall indices resulting from the implementation of the defined normalisation and aggregation criteria. As shown in the table, the NPS 30 design option emerges as the optimum solution, scoring the lowest value of overall impact index in the comparative assessment. It is worth noting that all the three alternatives exhibit very marginal differences in their overall impact index. As such, the observed ranking of performances of alternative design options may be highly sensitive to the criteria used for the normalisation and aggregation of indices as well as to the input data assumed for the analysis.

Therefore, the impact of uncertain cost variables on the results of the comparative assessment is dealt with in the form of the probabilistic sensitivity analysis described in section 2.5, whose results are presented in section 4.3.

The presented multicriteria optimisation approach is discussed with respect to the alternative single-objective minimisation pathway for the two considered CO_2 avoided and carbon pricing transport cost indicators, as described in the following.

Fig. 5 shows the variation of the above indicators with the Nominal Pipe Size (NPS). As it may be observed, both identify NPS 28 as the optimal alternative. Nevertheless, computing the transport cost of the optimal NPS 28 solution by accounting for GHG emissions through carbon pricing leads to a value *ca* 8.4% higher than the corresponding transport cost of CO_2 avoided emissions. This suggests that the index-based method monetising the GHG emissions appears to emphasise a greater influence of the environmental impacts compared to the CO_2 avoided approach. It is however worth noting that the above comparison may be affected by the value considered for carbon pricing, which is

Table 2
Main data assumed for the CO_2 pipeline case study.

Variable	Value
Inlet pressure	To be determined
Inlet temperature	37 °C
Mass flow rate	10 Mt y^{-1}
Pipe length	70 km
Pipe outer diameter	To be optimised in compliance with NPS
Pipe roughness	0.0475 mm
Angle of inclination relative to horizontal	0°
Stream composition	Pure CO_2
Outlet pressure	90 bar

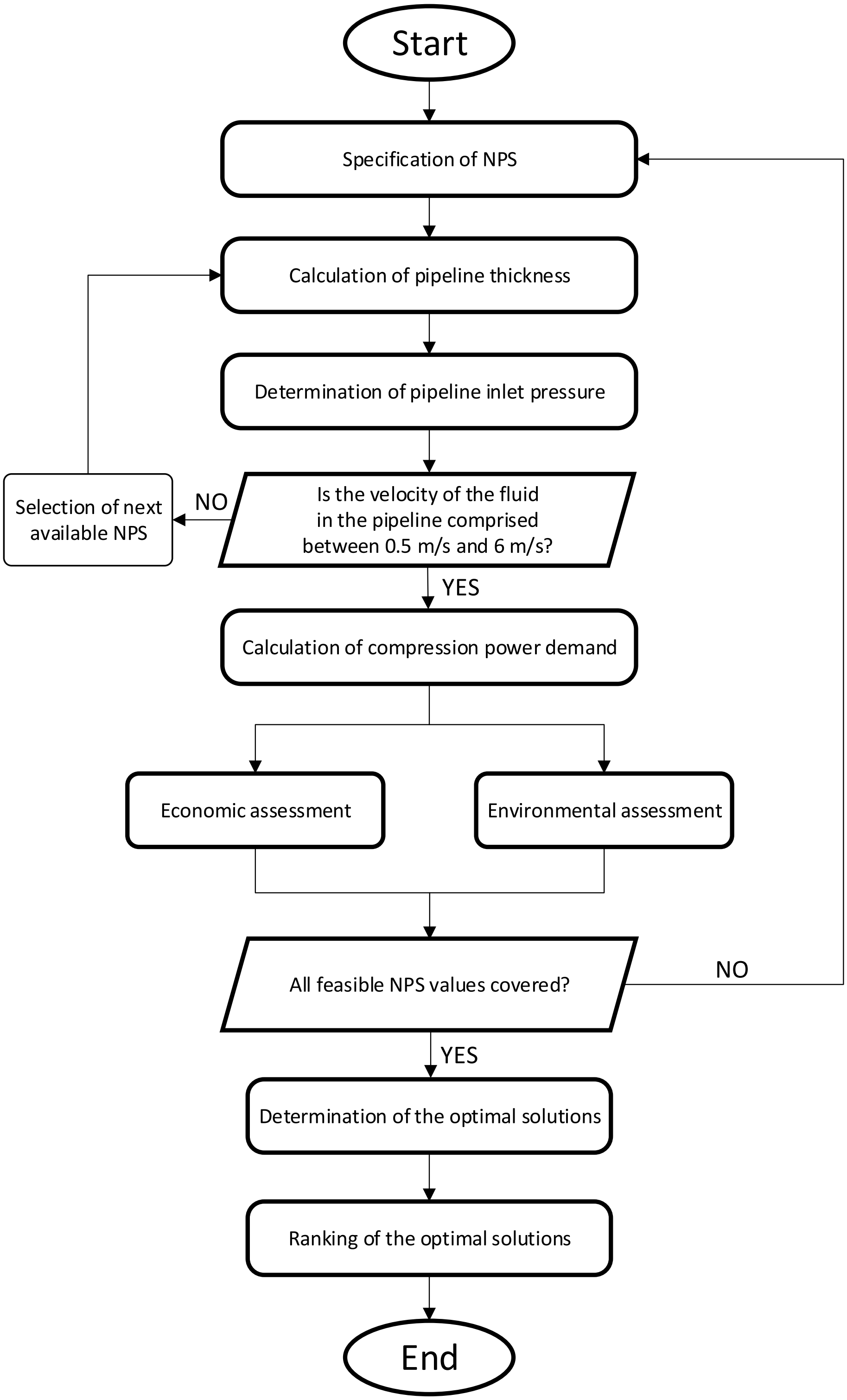

Fig. 2. Pipeline multi-objective optimisation calculation flow algorithm.

expected to fluctuate over the years (Bayer and Aklin, 2020).

Fig. 6 shows the influence of environmental and economic aspects on the overall performance of the optimum design option identified according to the different methods compared in the study. The presented multicriteria approach builds on a realistic sustainability management policy, equally weighting economic and environmental concerns (Tugnoli et al., 2008). The results indicate that the impacts due to GHG emissions account for nearly half the expected performance of the optimum design solution. Conversely, the optimisation methods based on the CO_2 avoided and carbon pricing concepts (Bayer and Aklin, 2020; Ho et al., 2011) appear to marginally consider environmental issues, accounting for up to *ca* 10% of the total index value. This suggests that optimising the pipeline design by conventional approaches, incorporating the economic and environmental factors in a single indicator, may result in underestimating the impact on the environment when accounting for case-specific sustainability constraints addressing the reduction of emissions.

Moreover, the two alternative single-objective indexing approaches,

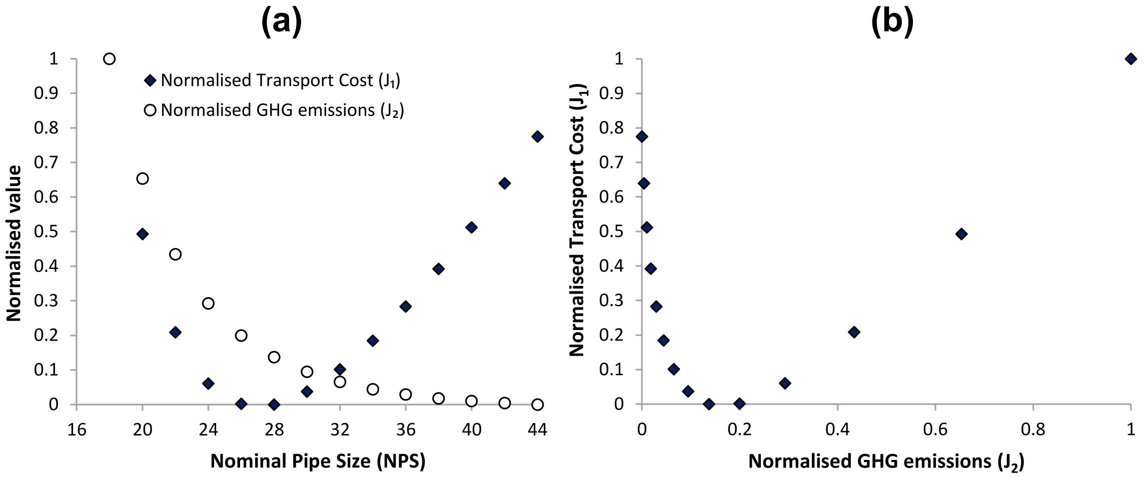

Fig. 3. Pipeline diameter multi-objective optimisation results. (a) Variation of Normalised Transport Cost (J_1) and Normalised GHG emissions (J_2) with Nominal Pipe Size (NPS); (b) Sampled values of the functions mapped in the objective space.

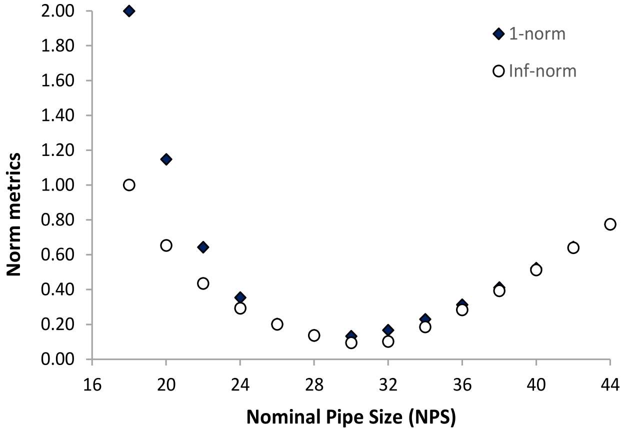

Fig. 4. 1-norm and Infinite norm Level Diagram representations for the decision variable.

Table 3
Values of impact indicators calculated for the compared design options.

Aspect	Impact indicator	NPS 28	NPS 30	NPS 32	Unit	Norm. factor
Environment	I_{GW}	2.66×10^5	2.62×10^5	2.60×10^5	t $_{CO2}$/yr	3.45×10^5
Economy	I_{NPEI}	6.75	6.79	6.85	€/t$_{CO2}$	7.78

Table 4
Normalised and aggregated indicators calculated for the compared design options.

Normalised indicator	NPS 28	NPS 30	NPS 32	Weight factor
Environment	0.772	0.760	0.753	0.5
Economy	0.867	0.872	0.880	0.5
Overall	1.00	0.996	0.997	–

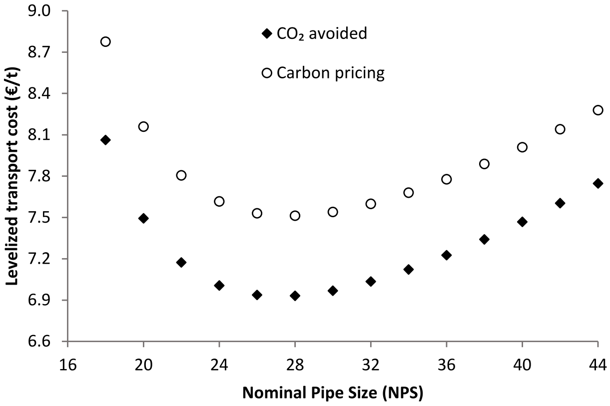

Fig. 5. Levelized CO_2 avoided and carbon pricing-based cost indicators as functions of NPS.

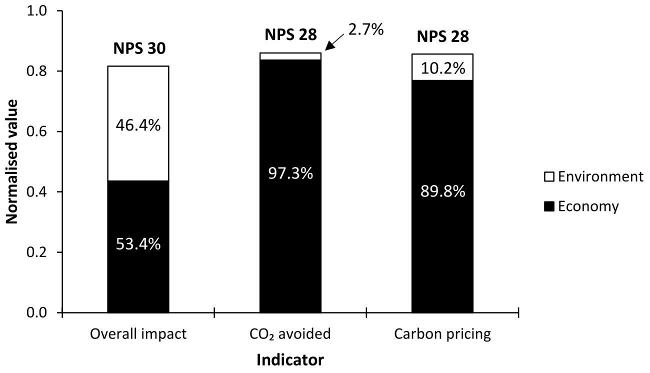

Fig. 6. Contribution of the environmental and economic domains to the calculation of the different indicators compared for the optimisation of the case study. The optimum design solution resulting from each indicator is indicated above the corresponding bar on the chart. Values on the y-axis are rescaled applying an internal normalisation to each method.

as shown in Fig. 6, are incapable of incorporating economic and environmental weighting criteria in the optimisation process. Indeed, the percentage contribution of environmental impacts on the optimum design solution (see Fig. 6) is univocally fixed once the indices implementing the CO_2 avoided and carbon pricing concepts are specified. Conversely, the multicriteria optimisation approach proposed in the present study enables a structured and flexible evaluation of economic and environmental impacts, based on their relative importance as determined either by case-specific expert judgment or by the sustainability management policy in force for the area of concern.

4.3. Sensitivity analysis

Fig. 7 shows the tornado sensitivity analysis chart obtained by varying the different input parameters affecting the transport cost by ±20% of their base value for the NPS 30 design case. The following economic variables are considered in this study: CAPEX and O&M costs of the pipeline and the compressing equipment, electricity price and discount rate. As shown in the figure, at *ca* ±13%, the electricity price is the most dominant parameter impacting the Levelized Cost (*LC*) of CO_2 transport. The above is more than three times higher than that resulting from varying the pipeline CAPEX (*ca* ±4%), followed by ±3.3% for Discount rate, ±2.8% for Compressor CAPEX, ±0.83% for Compressor O&M and ±0.82% for Pipeline O&M. It is noteworthy that O&M costs are the least influential parameters governing the transport LC.

All the above six identified cost variables are selected as key input parameters for the following probabilistic analysis. The Monte Carlo simulation approach is applied here to obtain a probabilistic ranking of economic performances among alternatives.

Fig. 8 shows the cumulative probability curves versus the differences in *LC* (in € t^{-1}) among the different NPS values. The solid curve shows the data for $LC_{\text{NPS 28}} - LC_{\text{NPS 30}}$ whilst the dashed curve shows the data for $LC_{\text{NPS 32}} - LC_{\text{NPS 30}}$. According to the figure, NPS 28 shows a *ca* 49% probability of increasing the CO_2 transport cost as compared to the reference alternative, NPS 30, whilst a slightly higher probability of *ca* 53% is predicted for NPS 32. The above probabilistic results are consistent with the economic performance-based ranking of the alternative trade-offs resulting from the analysis. This ultimately proves the robustness of the presented multicriteria optimisation approach with respect to uncertainties affecting the evaluation of cost input data.

5. Conclusions

A multi-objective approach to optimise economic and environmental impacts during the preliminary design stage of CO_2 pipelines as part of the CCS chain is developed and tested. The cost of CO_2 transport and the amount of greenhouse gases emitted due to electrical energy demand are set as the problem objective functions. The procedure involves a preliminary identification of optimal solutions based on the analysis of Level Diagrams, followed by a quantitative comparative assessment entailing the definition of economic and environmental impact indicators. The introduction of reference criteria for the normalisation and aggregation of indicators allows the assessment and ranking of the overall performance of the alternative optimal trade-offs.

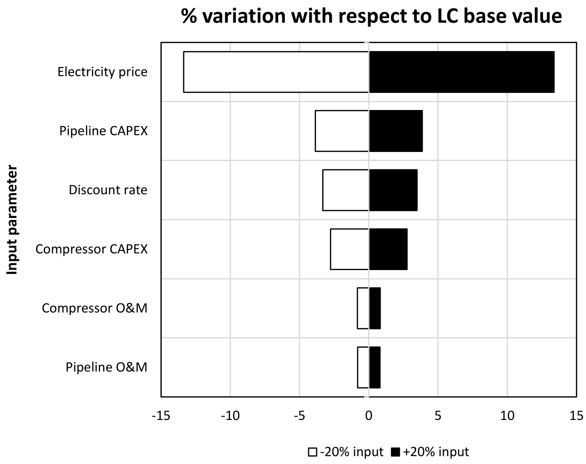

Fig. 7. Tornado chart for the preliminary sensitivity analysis on the Levelized Cost (*LC*) of CO_2 transport for NPS 30 alternative.

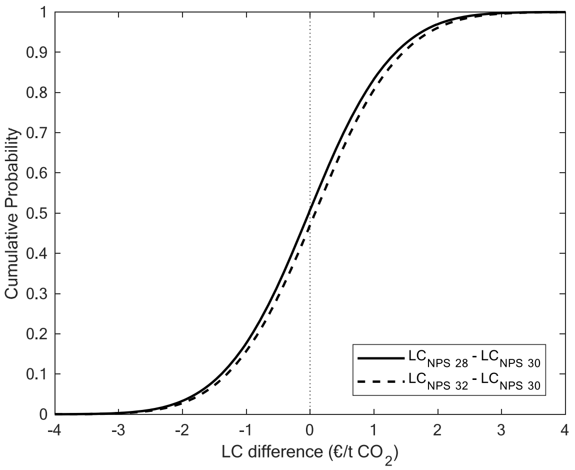

Fig. 8. Cumulative probability of the values of the differences among the levelized transport costs of NPS 28 and NPS 32 options with respect to the base case NPS 30.

As a case study, the methodology developed was applied to identify the optimum Nominal Pipe Size (NPS) for a point-to-point CO_2 pipeline, for which a dedicated optimisation algorithm was developed. A realistic sustainability management perspective equally weighting economic and environmental aspects was implemented to compute an overall performance index for each alternative NPS value. Two single-objective indexing methods, implementing the CO_2 avoided and the carbon pricing principles, are considered as benchmarks to demonstrate the capability of the proposed multicriteria method.

Results indicated that the application of the alternative approaches tends to identify an optimum NPS primarily based on economic aspects, at the cost of possibly underestimating the environmental concerns when sustainability decision-making perspectives are considered. Conversely, the multi-objective approach presented is shown to improve pipeline design procedures mainly driven by techno-economic considerations, by integrating environmental constraints related to the reduction of emissions imposed by either local sustainability policies or case-specific expert judgment. The application of the Monte Carlo method showed that the assessment of an optimum pipe size by the proposed multicriteria method is not likely to be influenced by key uncertainties in the analysis.

In conclusion, the work presents an innovative decision-making tool aimed at identifying the optimum pipeline design parameters striking a balance between cost and environmental impacts during the critically important early stages of the design lifecycle of CO_2 pipelines. The implementation of an indicator addressing greenhouse gas emissions allows to objectively monitor and communicate to stakeholders the environmental fingerprint expected from the future operation of the CO_2 pipeline design. Each step of the multicriteria optimisation procedure (e.g., definition of the impact categories, selection of criteria for weighting and normalisation of impacts) is tuned with the limited level of detail on the economic and operational aspects of the system typically available during early design stages. Advantageously, the methodology presented has the flexibility to readily evolve as the project progresses through its lifecycle and as more detailed information becomes available. As an example, additional environmental impacts, such as land use, can be easily incorporated as objectives functions in the optimisation process once the pipeline routing has been finalised. More in general, the proposed assessment using impact indicators could be used to support various environmental impact analyses, e.g., the identification of criticalities in the environmental profile of a design option and their determinants, the selection of the more environmentally sustainable technologies, and the verification of the performance improvement resulting from design modifications (Tugnoli et al., 2011, 2013). For the sake of simplicity, the multicriteria optimisation approach proposed in this study considers a point-to-point CO_2 pipeline for which a single decision variable (i.e., pipe diameter) needs to be optimised. By incorporating case-specific multi-objective optimisation algorithms, the same methodology can be readily extended to deal with multiple decision variables (e.g., fluid phase and number of pumping stations) and cover more complex systems such as pipeline networks.

Credit author statement

Francesco Zanobetti: Conceptualization, Methodology, Software, Writing – original draft, Validation, Investigation. **Sergey Martynov**: Visualisation, Validation, Investigation. **Valerio Cozzani**: Supervision, Methodology, Writing – review & editing. **Haroun Mahgerefteh**: Conceptualization, Methodology, Supervision, Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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