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Research Paper

Techno-economic evaluation for development of onshore carbon dioxide pipeline networks

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Abstract: The southern part of Iran has many CO2 emission sources and considerable potential for storage and utilization demand of CO2 such as oil and gas wells. Based on the importance of CO2 pipeline transport in CCS projects, this study was conducted to develop a budget-type techno-economic model for CO2 transmission through pipelines on the southern coasts of Iran. Although the design of a pipeline project with detailed economic investigations has a lower error, it needs spending a lot of time and cost. Therefore, it is necessary to create a budget-type techno-economic model that includes key technical and economic specifications of CO2 transmission pipelines for Iran like similar studies for other countries. In the present study, first, the requirements and the process of construction of a pipeline were described. Then, different economic budget-type models were developed based on the results of different technical models and the investment costs of the pipelines, booster stations, etc. It is worth mentioning that the developed budget-type techno-economic models have uncertainties due to various technical and economic parameters involved in the modeling. Therefore, a stochastic analysis was performed based on the input parameters of the model. For the case study, the pipeline diameter, the investment cost for the 110-km pipeline, and the levelized cost were calculated to be 0.273 m, 18.37 million €, and 1.55 €/ton, respectively which can be for the basic design of CO2 pipelines.

keywords: CO2 transmission pipeline, carbon dioxide capture, and storage, techno-economic models, levelized cost, stochastic analysis.

Nomenclature

API	American Petroleum Institute	C_O	Annual operating cost (energy consumption cost)
C_M	Annual repair and maintenance costs	$C_{capital}$	Investment costs
CCS	Carbon Capture and Storage	**CRF**	Capital recovery factor
CI	Cost index	C_{steel}	Cost of raw materials
CMU	Carnegie Mellon University	**CPI**	Consumer Price Index
$C_{Auxiliary}$	Ancillary costs	C_{exc}	Drilling costs
C_{hydro}	Cost of hydrostatic testing	C_{Labour}	Construction and labor costs
C_{string}	Stirring costs	$C_{Transport}$	Transportation costs
C_{Valve}	Costs of valves	$C_{booster}$	Cost for the booster station
D	Diameter of the pipeline (m)	Δh	Height difference (m)
EOR	Enhanced oil recovery	**E**	Seam factor
F	Design factor	f_F	Coefficient of friction
F_{r_1}	Correction coefficients for construction operations	F_{r_2}	Correction coefficients for additional costs for manpower
H	Drilling depth	**L**	Pipeline length (m)
LC	Levelized costs per ton of CO2 transport	P_1 **and** P_2	Inflow and outflow pressures of the pipeline

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			(Pa)
PD	Project duration (months)	P_{elec}	Price of electricity
$\mathbf{P}_{ave}$	Average flow pressure	$\boldsymbol{P_{max}}$	Maximum pressure e in the pipeline (Pa)
μ	Dynamic viscosity	$\boldsymbol{\rho_{steel}}$	The density of steel used in the pipeline (kg / m^3)
M	Mass flow rate passing through the pipeline (kg/s)	$\boldsymbol{M_o}$	Fluid molecular mass (kg/$kmol$)
$\mathbf{P_{Transport}}$	Equipment transportation costs	**PD**	Project duration (months)
R	Gas constant	**Re**	Reynolds number
S	Minimum yield strength	$\mathbf{T}_{ave}$	Average fluid temperature (K)
W	Capacity of the pressure boosting station (kW)	$\mathbf{X_i}$	Number of manpower
ε	Pipeline roughness	**t**	Pipeline thickness (m)

1. Introduction

Climate change in recent years has impacted all areas of the world. Among the main mitigation of climate change methods, the use of carbon capture and storage (CCS) technology is one of the promising technologies. This process is a robust way to reduce the emission of CO_2 into the atmosphere. To reduce CO_2 emissions in each sector of the economy, the International Energy Agency has proposed the utilization share of each technology in the world by 2050. According to this study (IEA, 2015), 5 effective solutions have been identified to reduce CO_2 emissions in 5 different sectors of the economy; power plants, heavy industry (such as steel and cement industry), transportation, construction, and refining and petrochemical industries, which are: utilization of renewable energy (Rahimi et al., 2021) (Nikoomaram et al., 2021), changing the fuel consumed in power plants (Rahimi et al., 2019) (Shariati, 2018), industries, etc., utilization of nuclear power plants, increasing energy efficiency (Rahimi and Alibabaee, 2021) (Shariati and Amidpour, 2016), and CO_2 capture and storage. According to the conditions of each country, all methods of mitigating CO_2 emissions have their limitations in the implementation phase. It should be noted that for Iran due to its huge oil and gas resources and a high share of power generation from fossil fuels, the importance of developing CCS technology would be even greater (IEA, 2015).

The use of CCS technology is a promising way to reduce the amount of CO_2 in the atmosphere and mitigate the effects of climate change. CCS technology includes three main phases, which are: Capture of CO_2 from existing emission sources, Transmission of CO_2, and Storage and operation of CO_2. In CO_2 transport, there are different methods such as transport through pipeline and ship, which vary according to the volume transferred and the distance from the source of emissions to the place of exploitation of CO_2. However, according to existing experiences, a pipeline is used for large volumes. To achieve these goals, preliminary estimates indicate that between 20,000 and 50,000 km of pipelines are needed in 2050 globally to transport CO_2 (IEA, 2010a) (IEA, 2010b).

Historically, the United States, Canada, and Norway have been leaders in CCS technology. One of the most internationally important projects is that done in the Permian Basin (USA) for EOR by CO_2 injection. Another important project is the Weyburn in Canada, which has also been done with the aim of EOR. Table 1 demonstrates some of the most important CO_2 pipeline projects and the purpose of their implementation (IEA, 2016).

Table 1. Some of the most important CCS projects in the world (IEA, 2016)

The Project Name	Operational beginning year	Annual captured carbon (million tons)	Goal of project
Natural Gas Plants - Val Verde (USA)	1972	1.3	EOR
Gas Processing Facility - Shute Creek (USA)	1986	7	EOR
CO_2 Storage Project - Sleipner (Norway)	1996	0.9	deep saline reservoir
Weyburn-Midale Project and Great Plains Syn-fuel Plant(Canada)	2000	3	EOR
CO_2 Storage - In Salah (Algeria)	2004	1	Depleted Gas Reservoir
CCS Project - Petrobras Lula Oil Field (Brazil)	2013	0.7	EOR
Quest (Canada)	2015	1	saline aquifer and possible EOR
CO_2 EOR Demonstration Project - Uthmaniyah (Saudi Arabia)	2015	0.8	EOR
CCS Project - Abu Dhabi (UAE)	2016	0.8	EOR

It is noteworthy that Iran is one of the most important CO_2 emitters among the countries of the world. According to the data, industry, refineries, and power plants accounted for 48.5% of the total emissions. As the prominent role of CCS in the power plant and industry sector was emphasized above, there is an opportunity for Iran to use this technology and enjoy its benefits in these sectors (Firozeh Amini et al. 2015). Jafari et al. studied the performance of different CO_2 capture processes from the flue gas and evaluated their economic aspects (Jafari et al., 2019). The capital cost of the membrane unit of flow gas carbon capture is much higher than the capital cost of carbon capture through the absorption process for Iran (2.3 times higher). In another study, Salehi et al. used multi-criteria analysis to prioritize different applications for CO_2 utilization based on technical, economic, and environmental criteria (Salehi et al., 2020). It was found that methanol production is the best option.

Due to the proximity of the southern part of Iran to CO_2 emission sources and suitable storage and operation areas such as oil and gas wells for Enhanced Oil Recovery (EOR), high CO_2 emissions by power plants and industries, and the country's needs (Table 2) to control and reduce CO_2 emissions, this research was conducted to develop a budget-type techno-economic model for CO_2 transmission through pipelines in the southern coasts of Iran.

Table 2. CO2 emissions and share of different emission sources in Iran (2015) (Firozeh Amini et al., 2015)

CO2 emission sources	Amount of CO2 emission (Megatons)	Percentage of CO2 emission sources
Industries, refineries, and power plants	283	48.5%
Total amount of CO2 emission	584	100%

Different studies in the literature were performed to assess the economic aspects of natural gas pipeline networks for China (An and Peng, 2016) (Li et al., 2020), Italy (Copiello, 2018), and Brazil (Vasconcelos et al., 2013). According to the literature, the cost of CO_2 pipeline projects is generally divided into three main sections, the cost of pipeline investment, the cost of maintenance, and the cost of pressure booster stations. It should be noted that the investment sector accounts for a significant share of costs, so in most existing economic models, the cost of the other two sectors (especially maintenance costs) is applied as a percentage of the investment costs. It should be noted that the modeling studies do not lead to the exact cost of the CO_2 pipeline, and the modeling results of a CCS system and CO_2 pipeline have a range of variations for investment and operation costs. Here are mentioned five types of techno-economic modeling that include all existing models:

- **Linear modeling**

Van den Broek et al. conducted a study entitled about storing CO_2 feasibility in the Utsira formation (van den Broek et al., 2010). One of the most significant studies of linear modeling is element energy research. This modeling has been done to optimize the transfer of CO_2 from emission sources to injection and storage sites worldwide by 2030 and 2050.

- **Modeling based on pipeline weight**

Gao et al. examined all scenarios of CO_2 emissions, such as maritime, rail, and pipeline transportation in China (Gao et al., 2011). The project site was located in China without considering the correction factors. As mentioned, in this study, the feasibility of different transfer methods such as ship transport, rail transport, and pipelines were studied. It is worth mentioning that in the CO_2 transfer method by ship and train, respectively, at the end of the route, CO_2 is transferred to the desired oil fields with a pipeline of 25 and 20 km in length.

- **Modeling based on quadratic equations**

Parker conducted research on the transport of natural gas, oil, and petroleum products, specifically in the field of hydrogen transport (Parker, 2015). Like most of the models, the investment costs of pipeline construction in this study were divided into four main sections, the costs of raw materials and equipment, workforce, land ownership, and ancillary costs. Due to the existing similarities, the results of this study can also be used for CO_2 transmission. There were found significant changes in the distribution of all costs except for labor cost, which was mainly between 40 to 50% depending on changes in the pipeline diameter.

- **CMU model**

One of the most significant techno-economic models is found in the research by (McCoy & Rubin, 2008). The main purpose of this study was to estimate the cost of CO_2 pipeline for different regions of the United States without considering the correction coefficients.

- **Flow modeling based on flow rate**

Dohowski et al. studied a CCS system in a study (Dahowski et al. 2004). The main purpose of this study was to analyze the modeling results by presenting different curves of the estimated CO_2 transfer and storage cost according to different parameters. In this modeling, the distance between the emission source and the injection or storage site was considered a straight line. Since this would not be possible in the real condition for a variety of reasons, a correction factor was applied in the modeling to correct it. In addition, to correct the length of the path to the suitable storage location, a distance of 16 km (10 miles) was added to the pipeline length when estimating the cost of constructing the pipeline. In another study, carbon dioxide transport via pipelines was reviewed with similar modeling. Pipeline design, risk, safety, process, standard, and specification of CO_2 pipelines were studied (Lu et al., 2020). Yuan et al. and Zhou et al. worked on the future of multiproduct pipelines in China for CO_2 abatement (Yuan et al., 2019) and (Zhou et al., 2020).

Due to the importance of CO_2 pipeline transmission in CCS projects, technical and economic analysis of transmission pipelines is inevitable. Although the project design and detailed economic investigation has a lower error rate but requires spending a lot of time and cost. Therefore, it is necessary to develop a budget-type techno-economic model that includes key technical and economic features of the CO_2 transmission pipeline. The advantage of techno-economic models is the estimation of important parameters in CCS projects without the need to consider technical and economic details and project design, which saves time and money. Similar studies were performed for many countries as it was mentioned above. But there are no studies about Iran as one of the GHG emitters. Unlike most models, standardization and nominal diameters of the pipelines were considered in the study which results in the diagrams having several jump points. Also, stochastic analysis in this paper is another novelty the paper considering uncertainties of the techno-economic models. Therefore, this study was conducted to estimate the cost of CO_2 transfer based on technical and economic characteristics and parameters.

2. Budget-type techno-economic model of CO_2 pipelines

2.1. Conditions and properties of CO_2 for pipeline transmission

According to theoretical principles, CO_2 can be transported through pipelines in liquid, gaseous, supercritical, and biphasic (liquid-gas) states, although there are limitations and recommendations in this regard. Note that for pipeline transmission, it is very important to study the CO_2 phase curve, so the following is a detailed analysis of the limitations and operational recommendations in this field. The critical point of CO_2 is at a temperature of 31.1 °C and a pressure of 7.3 MPa, above which it transforms into the supercritical state. If the pressure remains above 7.3 MPa and the temperature drops below 31.1 °C using coolers, the liquid phase is formed, which is called dense liquid. Operational experiences in the field of pipeline transmission show that CO_2, due to its high density and low viscosity, is transported in pipes mainly in two states supercritical and dense liquid (Zhang et al., 2006). As a result, large amounts of CO_2 can be transported with low losses. For more insight, the properties of CO_2 in different states with respect to operating temperature and pressure are given in Table 3 below (Wang et al., 2016).

- Supercritical fluid: pressure and temperature more than 7.3 MPa and 31.1°C, respectively
- Dense liquid: pressure more than 7.3 MPa and temperature less than 31.1 °C and more than -56 °C
- Liquid phase: pressure less than 7.3 MPa and more than 0.52 MPa, temperature less than 31.1 °C and more than -56 °C.

Table 3. Thermodynamic Properties of CO_2 (Veritas, 2010)

CO_2 thermodynamic properties	Amount
Molar mass	44.01 $g.mol^{-1}$
Critical pressure	73.8 bar
Critical temperature	31.1 °C
Critical density	467 $kg.m^{-3}$
Triple point pressure	5.18 bar
Triple point temperature	-56.6 °C
Density in the gas state (at 0 °C and 1 bar)	1.976 $kg.m^{-3}$
Density in the liquid state (at 0 °C and 70 bar)	995 $kg.m^{-3}$

2.2. CO2 emission sources in the southern coasts of Iran

As described in the previous sections, in this study, the southern coasts of Iran were selected due to the existence of refinery and power plants with a large volume of CO_2 emissions, as well as the capacity of the southern part of the country to use CO_2 in different ways. This section will first describe the sources of CO_2 emissions along with the number of emissions.

2.2.1. CO_2 emission sources

In the southern part of Iran, especially the southern coasts, there are many sources of CO_2 emissions. Among these, industries and power plants have a significant share (48.5% of total emissions) and the southern parts account for a larger part due to the centralization of industries and power plants. Considering the criteria of "distance to suitable operation and storage sites" as well as "emission volume per year", the possible emission resources were analyzed to select suitable ones. Table 4 shows the selected power plant emission sources along with the emission rates calculated through CO_2 emission intensity (Firozeh Amini et al., 2015) (Tavanir, 2018).

Table 4. Selected on-shore power plants in southern Iran (Tavanir, 2018)

	Power Plant Name	CO_2 emissions (tons per year)	Actual average power output (MW)
1	Bandar Abbas power plant	4718008	1280
2	Bistoon power plant	2833974	640
3	Ramin power plant	6817528	1823
4	Khalije Fars gas power plant	2712879	871
5	Abadan Combined cycle power plant	1987592	674
6	Khorramshahr power plant	2661148	818
7	Asalooyeh gas power plant	3156784	826
8	Eslamabad gharb (Shian) power plant	209465	82
9	Isin power plant	2012932	550
10	Sanandaj Combined cycle power plant	2076368	769
11	Bushehr gas power plant	31028.5	36
12	Kerman Combined cycle power plant	5227317	1451
13	Bandar Abbas gas power plant	73454.7	33
14	Fars Combined cycle power plant	2518854	794
15	Hafez power plant	2798810	716
16	Chabahar gas power plant	833515	338
17	Behbahan power plant	208422	269
18	Zargan power plant	182434.5	82
19	Zagros power plant	1415881	521
20	Genaveh power plant	1932907	415
21	Kazeroon Combined cycle power plant	3479681	1111
22	Jahrom Combined cycle power plant	1979329	720

According to calculations, the total CO_2 emission from the selected power plants in the southern part of the country is about 48 million tons per year. This amount of emissions is very significant and creates many opportunities for the exploitation of CO_2 as well as environmental measures to reduce emissions. However, there are other important sources of emissions on the southern coast of the country, such as refineries. According to available sources, the amount of CO_2 emissions from the country's refineries in 2015 was about 15 million tons, which considering the concentration of a large number of refineries in the south, it can be said that refineries are important sources of emissions on the southern coasts. These refineries are (Firozeh Amini et al., 2015):

- Abadan, Bandar Abbas, Lavan, Emam Khomeini, Shazand, Kermanshah, and Shiraz Oil Refineries
- Fajr-e-Jam, Parsian, Ilam, Bid Boland, Assaluyeh (different phases), Sarkhon, and Qeshm Natural Gas Refineries

In addition, the petrochemicals in the south of the country, due to pure CO_2, are considered attractive sources of emissions for the exploitation of CO_2. The global gas flaring emissions from the petroleum refineries, natural gas processing plants, and petrochemical plants on the southern coasts of Iran were reviewed previously (Soltanieh et al., 2016).

3. Budget-type techno-economic model of CO_2 pipeline in the southern costs of Iran

According to the previous techno-economic models, the costs of CO_2 pipelines in this project were divided into three main categories of pipeline investment cost, maintenance cost, and cost of booster stations. Since investment cost accounts for a significant share of costs, in some economic models, the cost of the other two sectors (especially maintenance costs) is applied as a percentage of investment costs. The advantage of techno-economic modeling is the estimation of important parameters in CCS projects without the need for technical and economic details and project design, which saves time and money. It should be noted that economic modeling does not give us the exact cost of the CO_2 pipeline, and the modeling results have a range of variations for investment and operation costs (Figure 1) (Knoope et al., 2013).

In the modeling, the pipeline diameter was first obtained through an iterative algorithm. Then, based on the relevant standard, the calculated diameter was modified according to the nominal diameter of the pipe, and then the modeling is continued according to the obtained values, and next, the modeling was continued based on the obtained values. The techno-economic parameters of modeling are given in Table 5. For ease of understanding, the modeling method is described in detail below.

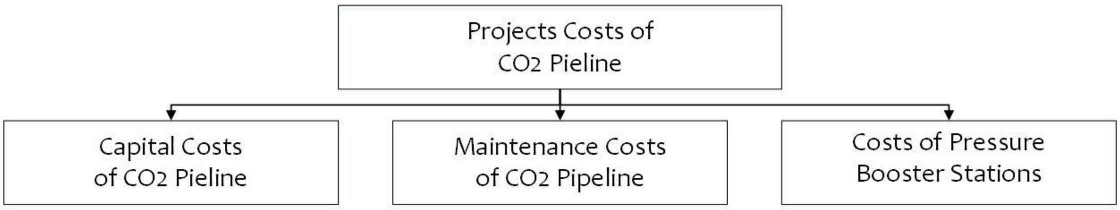

Figure 1. Configuration of the economic model of pipeline construction (Knoope et al., 2013)

3.1. Calculation of the pipeline diameter

To obtain the pipeline diameter, Equations (1) to (3) are solved simultaneously according to the iterative algorithm shown in Figure 2 (McCoy & Rubin, 2008):

$$D = \left(\frac{-64\, Z_{ave}^2\, R^2\, T_{ave}^2\, M^2\, f_F\, L}{\pi^2 [M_o\, Z_{ave}\, T_{ave}\, R(P_2^2 - P_1^2) + 2g\, P_{ave}^2\, M_o^2\, \Delta h]}\right)^{\frac{1}{5}} \tag{1}$$

$$\frac{1}{2\sqrt{f_F}} = -2log\left\{\frac{\frac{\varepsilon}{D}}{3.7} - \frac{5.02}{Re} log\left[\frac{\frac{\varepsilon}{D}}{3.7} - \frac{5.02}{Re} log\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{13}{Re}\right)\right]\right\} \tag{2}$$

$$Re = \frac{4M}{\mu \pi D} \tag{3}$$

Where; D= diameter of the pipeline (m), Z_{ave}= average condensability of the fluid, R= *gas* constant that is equal to 8.31 $m^3/mol.K$, T_{ave}= average fluid temperature (K), M=mass flow rate passing through the pipeline (kg/s), f_F= coefficient of friction, L= pipeline length (m), M_o= fluid molecular mass (kg/kmol), Δh=height difference (m), P_1 and P_2= inflow and outflow pressures of the pipeline (Pa), ε= Pipeline roughness assumed to be 0.0457 mm for this pipeline, Re= Reynolds number, µ= dynamic viscosity, and P_{ave}= average flow pressure in the pipeline calculated from Equation (4) (McCoy & Rubin, 2008).

$$P_{ave} = \frac{2}{3}\left(P_2 + P_1 - \frac{P_2 \times P_1}{P_2 + P_1}\right) \tag{4}$$

The thickness of the pipeline was also calculated from Equation 5. According to the above-mentioned iterative algorithm by creating a set of data based on the API 5L standard, the diameter, and nominal thickness were calculated (McCoy & Rubin, 2008).

$$t = \frac{P_{max} \times D}{2SEF} \tag{5}$$

In which, t is the pipeline thickness (m), S is the minimum yield strength, P_{max} is the maximum pressure in the pipeline (Pa), D is the pipeline diameter (m), and E and F are seam and design factors, which were assumed to be 1 and 0.72, respectively (McCoy & Rubin, 2008). The results of the calculations are shown in Figure 3. The resulting diagram shows the nominal diameters at different lengths and flow rates of the pipeline. As observed, unlike most models, the diagrams have different jump points due to considering standardization and nominal diameters of the pipes. Using the results from calculating the diameter, economic modeling and budget estimation are discussed below.

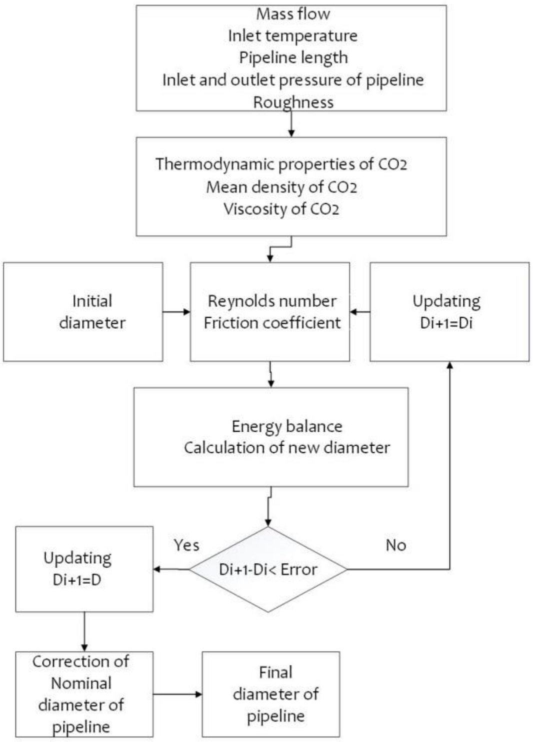

Figure 2. Algorithm for calculating pipeline diameter

Table 5. Modeling parameters (Climatic and historical data of Iran, 2020) (Calculation of thermodynamic state variables of carbon dioxide, 2020) (API, 2016) (IEA, 2020) (API 5L X70 Seamless Line Pipeline | X70 Grade Steel Pipeline | API5L X70 Pipeline | AesteironSteel, 2018) (Foreign Exchange Rates, 2019) (CPI and Inflation, 2019) (Management, 2018) (Research and Technology of the Ministry of Oil of Iran, 2018b) (Research and Technology of the Ministry of Oil of Iran, 2018a)

Parameter	Amount	Unit
Mass flow	1-35	$Mt.a^{-1}$
Pipeline length	50-2000	Km
Pipeline diameter	Calculation from the results of technical modeling	m
Input Pressure	14	MPa
Output pressure	10	MPa
Mean Temperature	22	°C
Average distance between pressure boosting stations	200	km
Carbon dioxide compressibility coefficient	0.26	-
Density of carbon dioxide	845	$kg.m^{-3}$
Type of pipeline used based on API 5L Standard	X70	-
Steel yield stress	483	MPa
Density of steel	7.9	$g.cm^{-3}$
X70 Steel pipeline price	1.75	€/kg
Cost of transportation of materials and equipment (pipes)	2	€/ton
Correction factor of civil operations	1.05	-
Manpower correction factor	1.3	-
Number of working days per month	22	day
Monthly salary of manpower	Depending on the type of civil works and technical specifications of the pipeline	€
Cost of civil works	Depending on the type of civil works and technical specifications of the pipeline	€
Drilling depth	2	m
Pipeline lifetime	25	year
Inflation rate	9.6	%
Electricity price	0.02	€/kW.h
Capacity factor	0.8	-

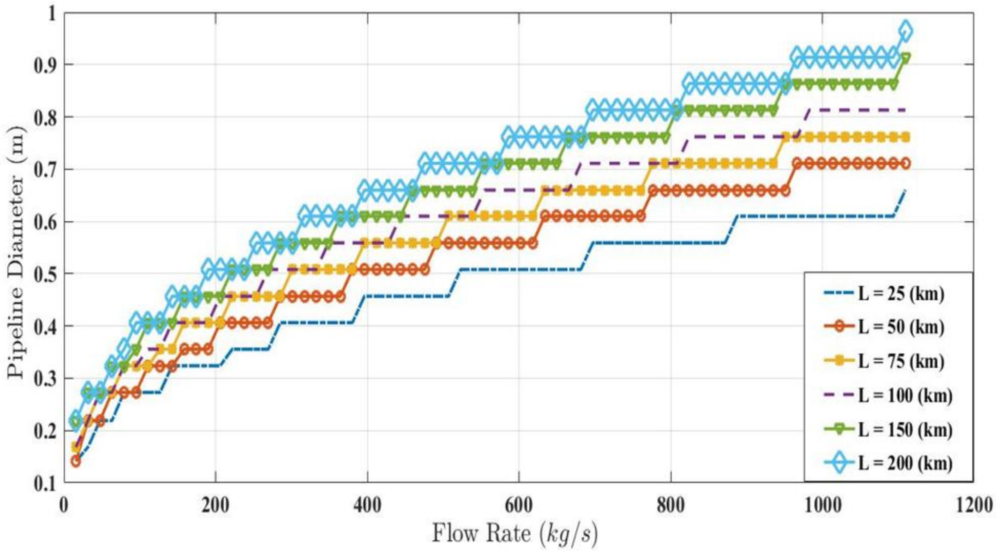

Figure 3. Results of technical modeling (calculation of nominal diameter in different flow rates and pipeline lengths)

3.2. Economic modeling

3.2.1. Pipeline investment costs

This section is generally divided into four main subsections, including the cost of raw materials and equipment, construction and manpower costs, access road costs (right of easement), and miscellaneous and ancillary costs, which are defined and detailed below. There is limited information available worldwide regarding CO_2 pipelines and the costs of their various sections, which may be due to the low experience and proximity of the project implementation process to natural gas pipeline projects (Knoope et al., 2013). Generally, considering a series of correction factors, theoretical models, and segmentation, the investment costs of natural gas pipelines are also used for the CO_2 pipelines. However, enough attention should be paid to the operational differences between the two projects. Among the major differences between natural gas and CO_2 pipelines are type of steel, type of pipes, coating and insulation of the pipes, operating pressure, temperature, and pipeline buffer area. For example, the operating pressure of a CO_2 pipeline is higher than that of a natural gas pipeline, which leads to a greater thickness of the CO_2 pipeline (Knoope et al., 2013). In addition, crack propagation in the CO_2 pipeline is a serious problem that could be caused by corrosion or an earthquake. To prevent this, the thickness of the pipeline is increased, or crack arresters are used (to reduce the length of the cracks). Another difference is the legal buffer area of the pipeline to the residential units as the environmental and safety regulations impose more restrictions on the CO_2 pipelines. These differences make the cost of a CO_2 pipeline higher than a natural gas pipeline if the pipeline diameter is the same. In the present model, due to the lack of sufficient information, the available data of oil and gas pipelines were used for budget type calculation of the pipeline (Veritas, 2010) (Smith, 2006) (C.E. Smith, 2010) (True, 1995). It should be noted that in the modeling and economic analysis ahead, whenever the reference equations were used (in the comparison of different modeling and cost estimation of pressure boosting station), cost estimation was done according to the year of publication of the equation using Equation 6 and the price change index provided by Marshall and Swift.

$$C_{new} = C_{base} \times CI \tag{6}$$

where the CI value represents the ratio of the price coefficient announced by authorities such as Marshall Swift. The CI value can be calculated using Equation (7).

CI= Cost index for the required year (Cost index for reference year) (7)

- **Cost of raw materials and equipment**

This section includes the costs of pipes, coating, cathodic protection, and insulation of pipes. Other costs include blocking valves, crack arrestors, and other miscellaneous equipment.

For example, if the diameter of the pipeline increases, distribution costs in different parts of the CO_2 pipeline investment models will change so that the cost of raw materials and equipment will increase and the share of manpower costs in the distribution costs will decrease, as well. These changes can be seen in the results of this modeling. The cost estimate of raw materials and equipment was done using the following equations et al., 2016).

Raw material cost (pipe):

$$C_{steel} = P_{steel} \times W_{steel} = P_{steel} \times \pi \times \rho_{steel} \times (D^2 - D_i^2) \times \frac{L}{4} \tag{8}$$

Where, C_{steel} is the cost of raw materials (€), ρ_{steel} is the density of steel used in the pipeline (kg / m^3), the price of X70 steel pipe, and D_i the inner diameter (m), which is calculated according to the standardized diameter and thickness in the technical modeling stage.

Ancillary costs (insulation, cathodic protection, and miscellaneous costs) and transportation of pipes and equipment (assumed for a distance of 30 km) and valves:

$$C_{Transport} = P_{Transport} \times \pi \times \rho_{steel} \times (D^2 - D_i^2) \times \frac{L}{4} \tag{9}$$

$$C_{Auxiliary} = 0.12 \times C_{steel} \tag{10}$$

$$C_{Valve} = 0.16 \times C_{steel} \tag{11}$$

In which, $C_{Transport}$, $C_{Auxiliary}$, and C_{Valve} are respectively transportation costs, ancillary costs, and the costs of valves (€) and $P_{Transport}$ is the unit of equipment transportation costs.

Finally, the cost of raw materials and equipment was defined as follows:

$$C_{Material} = C_{steel} + C_{Transport} + C_{Auxiliary} + C_{Valve} \tag{12}$$

- Construction and manpower costs:

This section includes the two main sub-sections of project construction costs and labor costs. The reason for this division is the effectiveness of construction costs so in some models, this sub-section is considered as a separate section. Construction and labor costs include annual labor salaries and costs related to necessary infrastructure, pipeline installation, pipeline welding, and ancillary construction works.

Most pipelines are installed underground to limit the impact on their surroundings, so in this type of project, excavation, burial, and clearing steps are performed to install the pipes. It is worth mentioning that the technical and economic principles governing the construction of the carbon dioxide pipeline generally follow the principles of the oil and gas pipelines. The costs considered in this section include the costs of groups of welders, workshop supervision, pipeline bending, drivers of heavy machinery and transportation, stringing of pipes, hydrostatic testing, construction of infrastructure for pipeline construction, canal drilling, etc. The duration of the project was calculated according to Equation 13 (McAllister, 2009).

$$PD = \frac{L}{S \times D} \tag{13}$$

Where PD is the duration of the project (months), L is the length of the pipeline (km), S is the daily progress of the construction of the pipeline (0.6 km), and D is the number of working days per month. Due to the inseparability of construction and labor costs, in this model, the cost of these two parts was estimated together under one group, as this assumption is common in these models. To estimate the construction and labor costs, based on available sources and a function of pipeline specifications such as pipeline diameter, pipeline length, etc., a data set was formed including project duration, number of labor required for each section, monthly salary, and construction operations required for pipeline construction. Using the dataset and the results of technical modeling, the cost of this section was calculated.

$$C_{exc} = F_{r_1} \times (D + 0.4) \times H \times L \times P_{exc} \tag{14}$$

$$C_{string} = F_{r_1} \times P_{string} \times L \tag{15}$$

$$C_{hydro} = F_{r_1} \times P_{hydro} \times L \tag{16}$$

$$C_{Labour} = \left(F_{r_2} \times \sum (X_i \times P_i \times PD)\right) + C_{exc} + C_{string} + C_{hydro} \tag{17}$$

In which, C_{Labour}, C_{exc}, C_{string}, and, C_{hydro} are respectively construction and labor costs, drilling costs, stirring costs, and the cost of hydrostatic testing (€), X_i is the number of manpower in each section, P_i is the monthly salary of manpower in each section (€), L is the length of the pipeline (m), H is drilling depth, PD is project duration (months), F_{r_1} and F_{r_2} are respectively correction coefficients for construction operations and additional costs for the manpower (hardship pay for the harsh environmental conditions in the southern regions of Iran and accommodation), and P_{exc}, P_{string}, and P_{hydro} are respectively the costs of drilling, stirring the pipelines, and hydrostatic testing, which is a function of pipeline diameter (m/€). The cost of land ownership and miscellaneous and ancillary costs are expressed as a percentage of investment costs (C.E. Smith, 2009).

$$C_{ROW} = 0.07 \times C_{Total} \tag{18}$$

$$C_{Miscellaneous} = 0.20 \times C_{Total} \tag{19}$$

Finally, the investment cost of the pipeline is defined as follows:

$$C_{Total} = C_{Material} + C_{Labour} + C_{ROW} + C_{Miscellaneous} \tag{20}$$

3.2.2. Investment cost of pressure boosting station

Long CO_2 pipelines need pressure-boosting stations to compensate for the pressure drop along the route. Therefore, onshore pipelines have pressure-boosting stations due to pressure drops. However, for pipelines that are installed and operated at sea, due to technical complexities and reduced investment costs, it is recommended to compensate for the pressure drop by increasing the inlet pressure and pipeline diameter and preventing or limiting the installation of booster stations (Knoope et al., 2013). There is a relationship between the number of pressure boosting stations based on the overall pressure drop and the characteristics of the booster station. Given that no specific route was determined in the present study, the distance between each pressure boosting station was assumed to be 200 km, which seems reasonable given the previous studies. To obtain the investment cost, booster stations were modeled at different assumed flow rates in HYSYS software. Using the capacity of the modeled pressure boosting stations, the investment cost of the pipeline was calculated from the following equation and the price change index provided by Marshall and Swift (Chandel, Pratson, & Williams, 2010).

$$C_{booster} = (\mathrm{W} \times 2.3 + 0.15) \times 10^6 \tag{21}$$

Where; $C_{booster}$ is the investment cost for the booster station (€$_{2010}$) and W is the capacity of the booster station (MW$_e$).

- **Operating cost of the pressure boosting station:**

The operating cost and energy consumed by the pressure boosting station depend on the price of electricity and the capacity of the station, which is calculated by the following equation (Knoope et al., 2013).

$$C_O = W \times 10^3 \times Hours \times P_{elec} \tag{22}$$

In which; C_O is the annual operating cost (energy consumption cost), W capacity of the pressure boosting station (kW), and Hours and P_{elec} were assumed to be the operating hours (7500 hours per year) and the price of electricity (0.02 €/kW.h), respectively.

3.2.3. Repair and maintenance cost of pipeline and pressure boosting station

Repair and maintenance costs include the cost of repairing valves, pipes, possible leaks, etc., which are part of the operational costs of the pipeline project. These types of costs, due to the probability of various failures and repairs in pipeline construction projects, are expressed in most models annually and as a percentage of pipeline investment costs or a fixed cost per unit length of the pipeline. For the pressure boosting station, the repair and maintenance cost is generally expressed as a percentage of pipeline investment costs. According to the literature, the maintenance cost was assumed to be 2.5% of the pipeline investment cost and 4% of the pressure boosting station investment cost, respectively (McCollum & Ogden, 2006).

3.2.4. Levelized cost

After calculating the costs of each section, the levelized cost per ton of CO_2 transport was calculated according to the following procedure.

$$C_M = 0.025 \times C_{total} + 0.04 \times C_{booster} \tag{23}$$

$$C_{capital} = C_{Total} + C_{booster} \tag{24}$$

$$\text{Annualized capital cost} = C_{capital} \times CRF \tag{25}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{26}$$

$$LC = \frac{(\text{Annualized capital cost} + C_M + C_O)}{CF \times M} \tag{27}$$

In the above equations, CRF is the capital recovery factor, $CF$is capacity factor, M is the flow rate in terms of millions of tons per year and, C_M, $C_{capital}$, and LC are respectively the annual repair and maintenance costs, investment costs, and levelized costs per ton of CO_2 transport (€). The diagrams in Figures 4 and 5 show the levelized costs modeled for different lengths and different flow rates. As expected in the same flow rate, the cost of the project increases with increasing the pipeline length. In addition, at a given length, with increasing flow rate to a certain level, the levelized cost decreases and after which point the cost will remain almost constant.

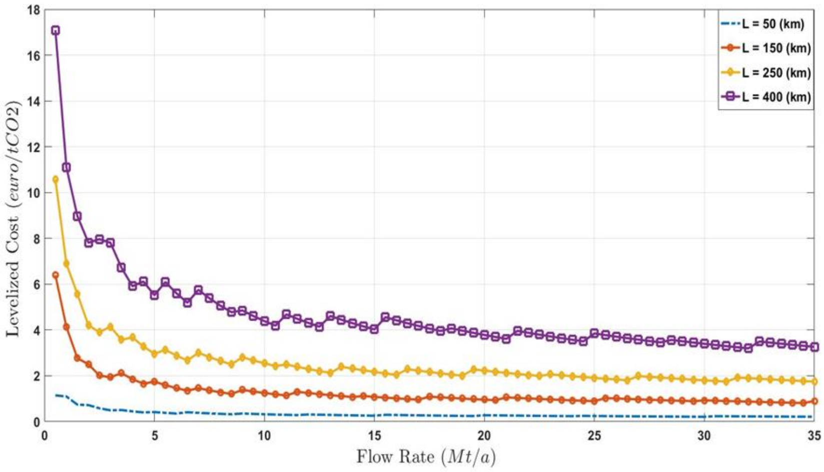

Figure 4. levelized cost per ton of CO_2 transport (at different pipeline lengths and flow rates)

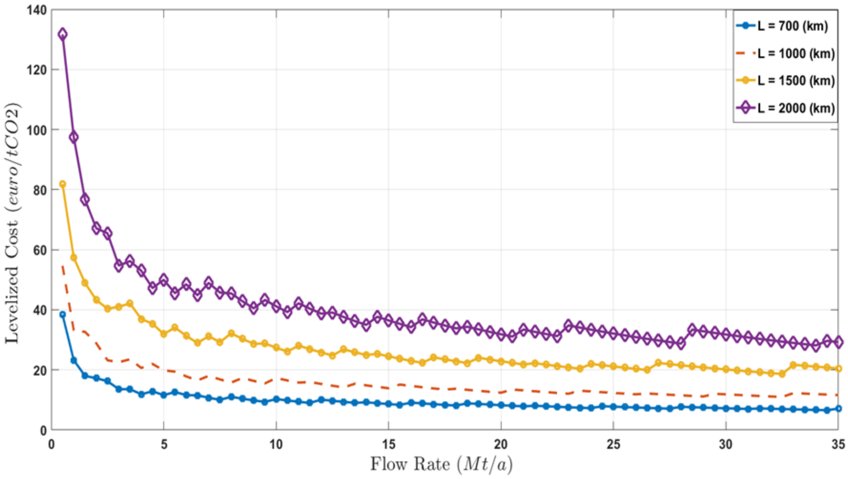

Figure 5. levelized cost per ton of CO2 transport (at different pipeline lengths and flow rates)

3.2.5. Obtaining the economic function

In this section, according to the results of economic modeling using the least-squares estimation method, the economic function was obtained. In this method, the dependent variable (y) is considered as a linear function of the independent input variables and ϵ error (Türkşen, 2008):

$$y = \beta_0 + \beta_1 x_1 + \cdots + \beta_{nv} x_{nv} + \epsilon \tag{28}$$

Where; j = 1,…, nv are indices of input variables, nv is the number of inputs, and ϵ is an independent error term that was assumed to be normally distributed. The purpose of this method is to estimate anonymous parameters. ßj shows the effect of changing the independent variable on the dependent variable. In the matrix display, the general linear model would b as follows:

$$Y = Xb + \epsilon \tag{29}$$

Where Y is a vector [nd, 1] of the response values, X is a matrix [nd, nv + 1] of inputs with fixed constants, nd is the number of input and output vectors in the training data category, nv is the number of selected inputs, b is a vector [nv + 1, 1] of the parameters, and ϵ is a vector [nd, 1] of errors, for example:

$$\begin{aligned} y_{nd,1}^T &= [y_1, y_2, \dots y_{nd}] \\ \beta_{nv+1,1}^T &= [\beta_0, \beta_1, \beta_2, \dots, \beta_{nv}] \\ \epsilon_{nd,1}^T &= [\epsilon_1, \epsilon_2, \dots, \epsilon_{nd}] \\ X_{nd,nv+1} &= \left[1, x_{k,j} \mid k = 1,2, \dots, nd; j = 1,2, \dots, nv\right] \end{aligned} \tag{30}$$

The main goal is to minimize the residual error in estimating the model parameters, i.e.:

$$Min\ Q \sum_{k}^{nd} \left(y_k - (\beta_0 + \beta_1 x_1 + \cdots + \beta_{nv} x_{knv})\right)^2 \tag{31}$$

In the matrix representation, the above expression was rewritten and a partial derivative with respect to b was taken from it:

$$\begin{aligned} &Min\ Q = (y - X\beta)^T (y - X\beta), \\ &\frac{\partial}{\partial \beta}[(y - X\beta)^T (y - X\beta)] = 0, \\ &2(X^T X)\beta = 2X^T y, \\ &\beta = (X^T X)^{-1} X^T y \end{aligned} \tag{32}$$

According to this algorithm, the economic function was obtained as follows:

$$LC = \beta_0 + \beta_1 M^1 + \beta_2 M^2 + \beta_3 M^3 \tag{33}$$

$$\begin{aligned} \beta_0 &= \beta'_{11} + \beta'_{12} L + \beta'_{13} L^2 \\ \beta_1 &= \beta'_{21} + \beta'_{22} L + \beta'_{23} L^2 \\ \beta_2 &= \beta'_{31} + \beta'_{32} L + \beta'_{33} L^2 \\ \beta_3 &= \beta'_{41} + \beta'_{42} L + \beta'_{43} L^2 \end{aligned} \tag{34}$$

L and M in these equations are the length and flow, respectively, in meters and million tons per year. The coefficients of the above equations are given in Table 6.

- Comparing the developed model with other available models for different lengths

This section presents and compares the levelized-cost diagrams of this model with those of other available models (Figures 6 to 13). As observed, this model is less expensive than the other models. The reason for this difference is the area assumed for the project and other related details such as topographic conditions, the level of details included in the model, lower manpower costs in Iran than in other countries, etc.

Table 6. Coefficients of economic equations

Coefficients	Amount	Coefficients	Amount	Coefficients	Amount	Coefficients	Amount
β'_{11}	-0.3331	β'_{21}	-0.0846	β'_{31}	0.0064	β'_{41}	-0.00011894
β'_{12}	26.0502	β'_{22}	-2.2561	β'_{32}	0.1001	β'_{42}	-0.0015
β'_{13}	10.0359	β'_{23}	-1.0548	β'_{33}	0.0533	β'_{43}	-0.00083993

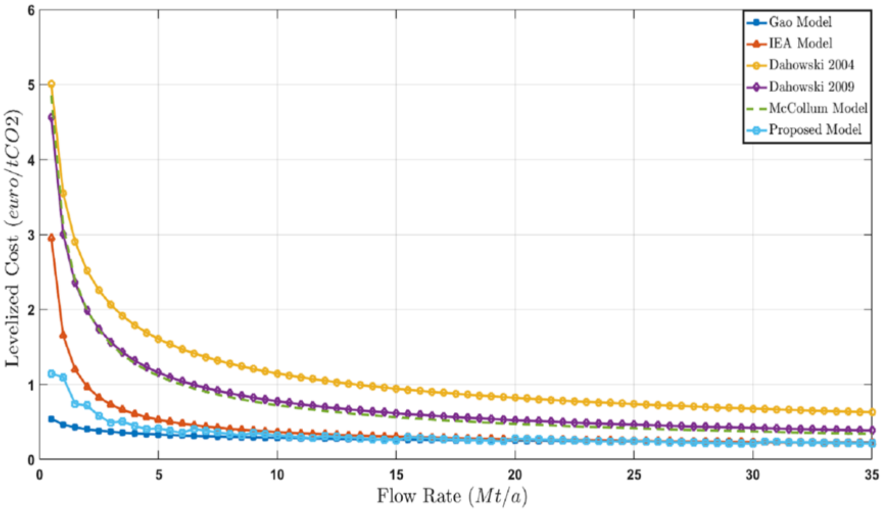

Figure 6. Comparing the levelized costs of different techno-economic models (for a pipeline length of 50 km)

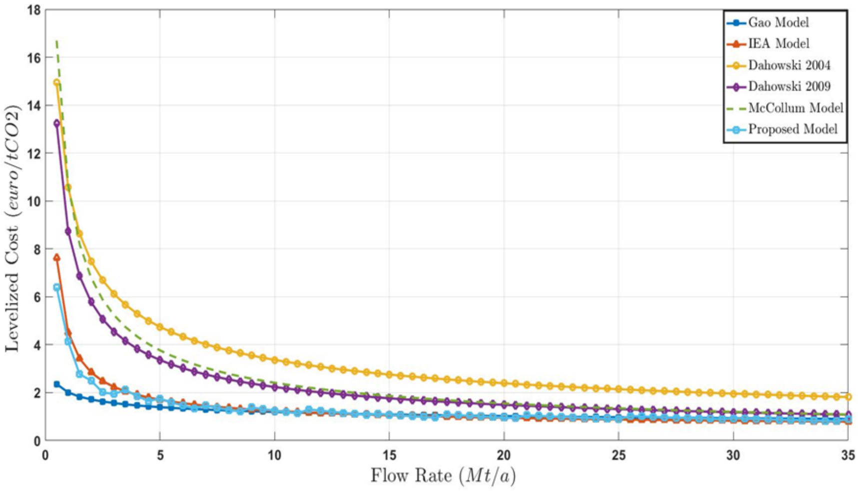

Figure 7. Comparing the levelized costs of different techno-economic models (for a pipeline length of 150 km)

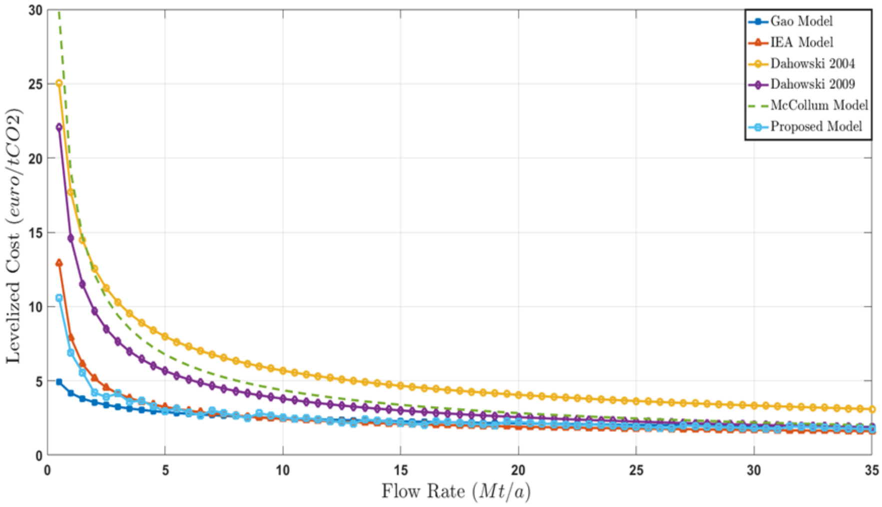

Figure 8. Comparing the levelized costs of different techno-economic models (for a pipeline length of 250 km)

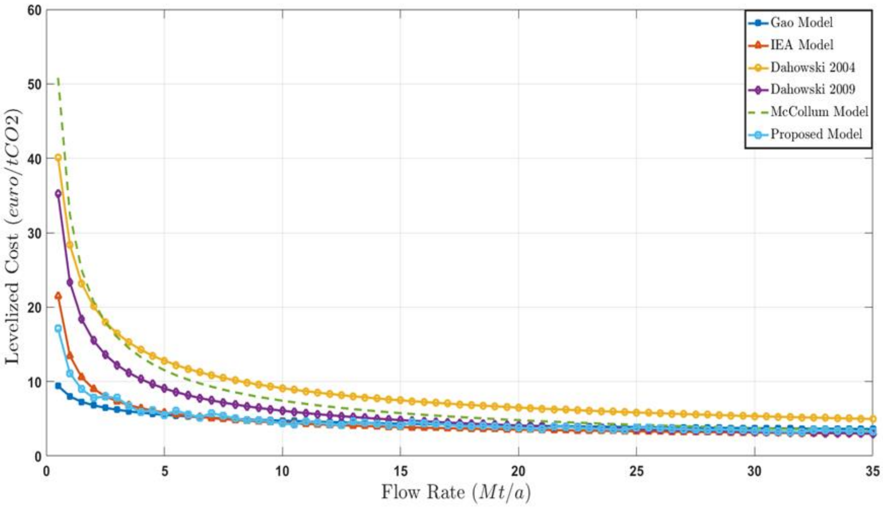

Figure 9. Comparing the levelized costs of different techno-economic models (for a pipeline length of 450 km)

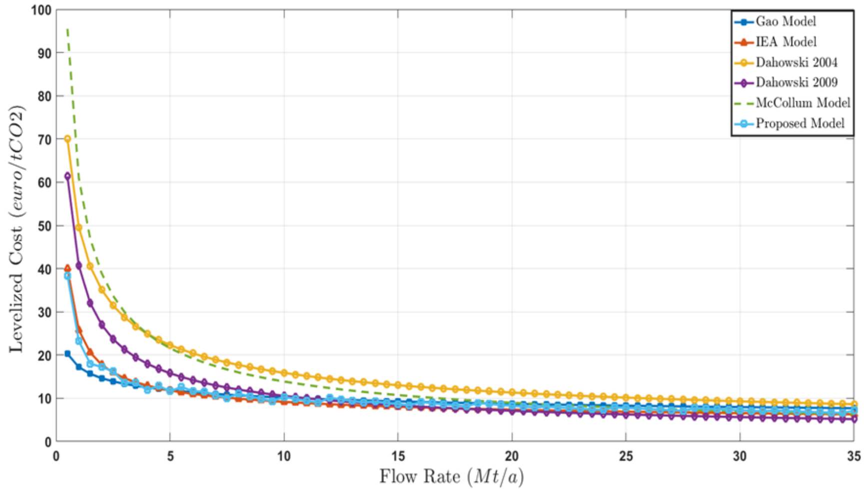

Figure 10. Comparing the levelized costs of different techno-economic models (for a pipeline length of 700 km)

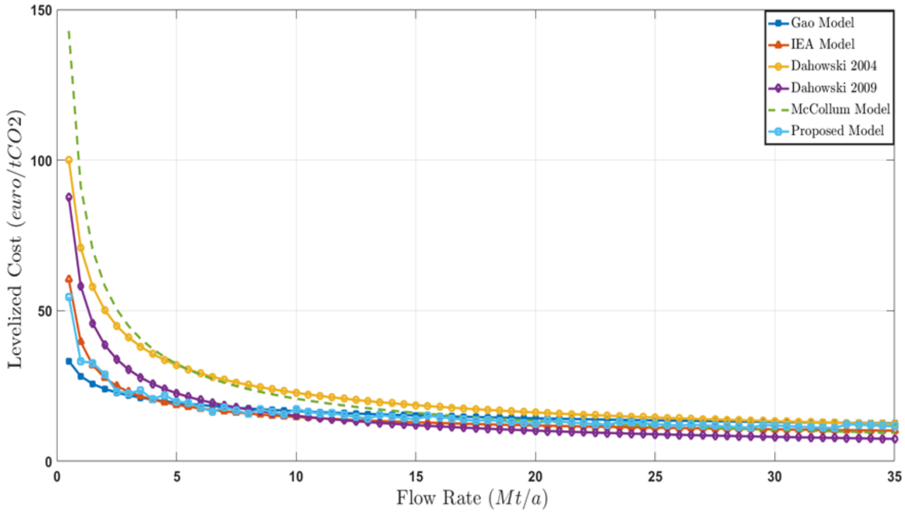

Figure 11. Comparing the levelized costs of different techno-economic models (for a pipeline length of 1000 km)

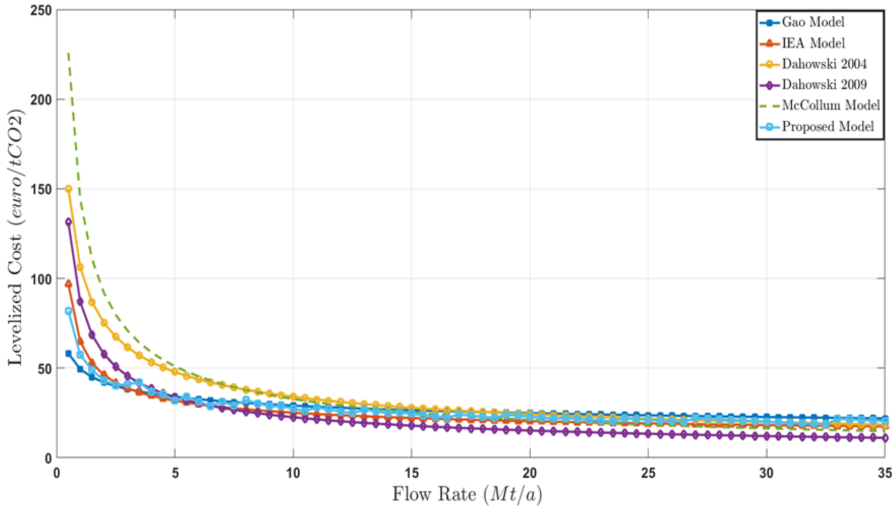

Figure 12. Comparing the levelized costs of different techno-economic models (for a pipeline length of 1500 km)

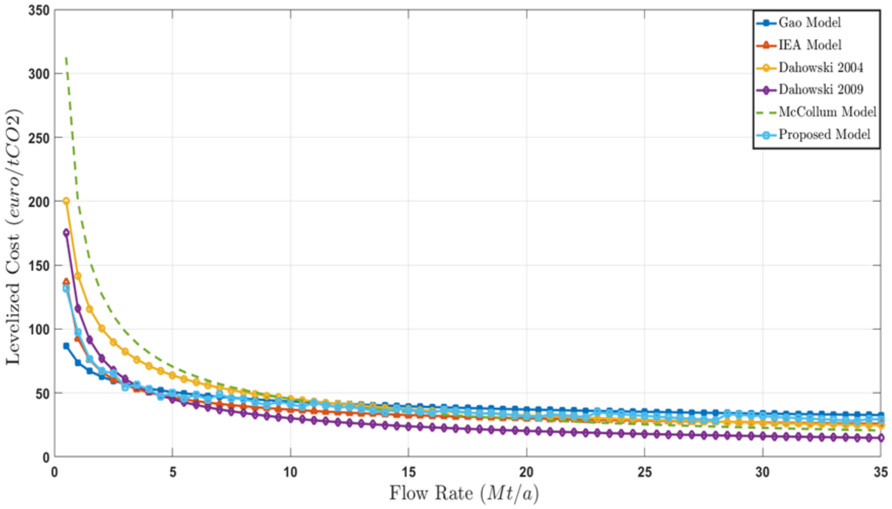

Figure 13. Comparing the levelized costs of different techno-economic models (for a pipeline length of 2000 km)

Reasons for the wide range of the levelized cost per ton of CO_2 transport in the studied models are:

- Topographic conditions:

One reason could be different topographic and geographical conditions and terrain smoothness and unevenness as model assumptions. For example, locating in flat surfaces, forestlands, or desert lands, as well as onshore or off-shore types all, are among the modeling assumptions affecting the levelized cost per ton of CO_2 transport in different projects.

- Project location:

The location of projects is one of the important assumptions that play a key role in modeling parameters such as labor costs and right of way and consequently, in the cost of investment and operation. For example, labor costs vary significantly between China and the United States.

- Different assumptions in cases such as project life, interest rate, and final capacity of the pipeline
- Type of steel, coating, and insulation used in the pipeline
- Details of the parameters involved in the economic modeling of CO_2 pipelines

3.2.6. Stochastic analysis

The budget-type techno-economic model has uncertainties due to various technical and economic parameters involved in the modeling. The specifications of the CO_2 pipeline projects such as the project life span, interest rates, raw materials and equipment, land ownership, labor, pipeline construction operations, parameters related to investment costs, tax policies, etc. all affect the final cost of the pipeline. For this purpose, a stochastic analysis was performed for the economic model.

Table 7 lists the stochastic parameters that the analysis was done based on their changes. Stochastic analysis on different parameters requires determining the variable costs of technical-economic parameters. To generate indeterminate numbers, the normal and uniform distribution of key parameters was used and the test was performed 1000 times. Finally, with the results of normal distribution of data, a cumulative probability function was created for the levelized cost. Figures 14-21 give a probability of 90 and 10% for the levelized cost per different lengths and flow rates. The analysis results can be seen in the following diagrams. The non-use of other complex distributions is due to their inefficiency in analyzing the statistical data.

Table 7. Effective parameters in the stochastic analysis

Parameter	stochastic parameters variation range	Unit
Mass flow	1-35	$Mt.a^{-1}$
Distance	50-2000	km
Input Pressure	Normal distribution (13-15)	MPa
Output pressure	Normal distribution (9-11)	MPa
Mean Temperature	Normal distribution (20-26)	°C
Average distance between pressure boosting stations	Normal distribution (150-250)	km
Type of pipeline used based on API 5L Standard	X70	-
Steel yield stress	483	MPa
Density of steel	7.9	$g.cm^{-3}$
Correction factor of civil operations	Uniform distribution (1-1.05)	-
Correction factor of manpower	Uniform distribution (1.2-1.35)	-
Correction factor of equipment transportation	Uniform distribution (1-5)	-
Pipeline lifetime	Uniform distribution (20-30)	Year
Inflation rate	Normal distribution (0.05-0.15)	%
Electricity price	Uniform distribution (0.02-0.04)	€
Capacity factor	Normal distribution (0.7-0.9)	-

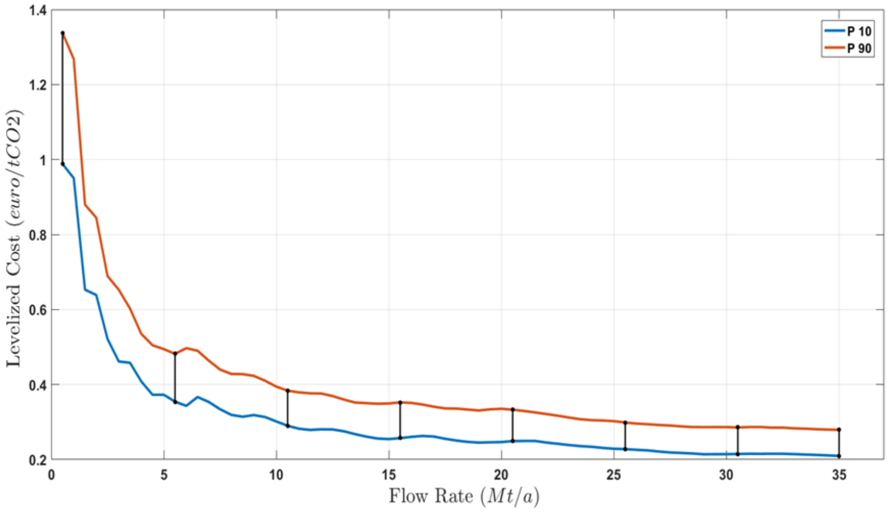

Figure 14. Levelized cost range at different flow rates for a 50-km pipeline (at probabilities of 10% and 90%)

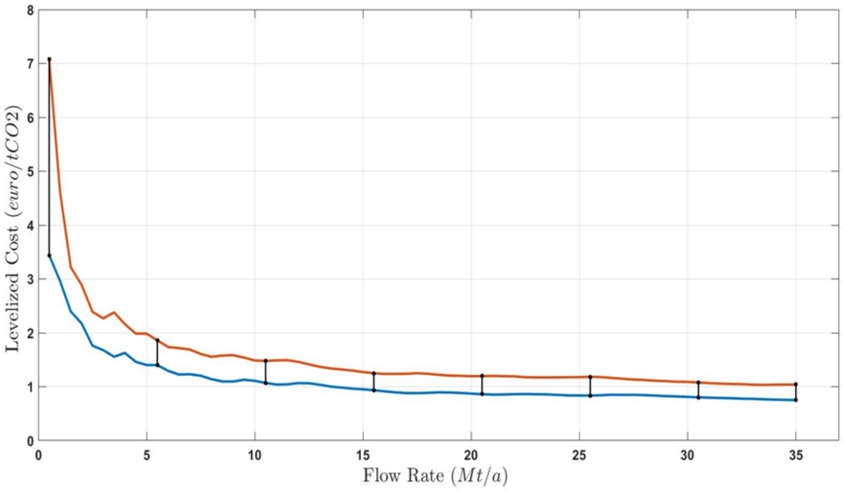

Figure 15. Levelized cost range at different flow rates for a 150-km pipeline (at probabilities of 10% and 90%)

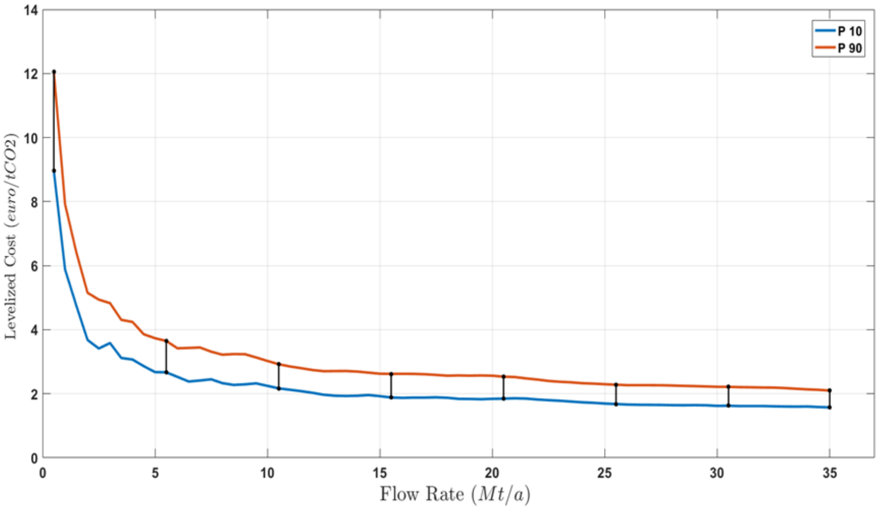

Figure 16. Levelized cost range at different flow rates for a 250-km pipeline (at probabilities of 10% and 90%)

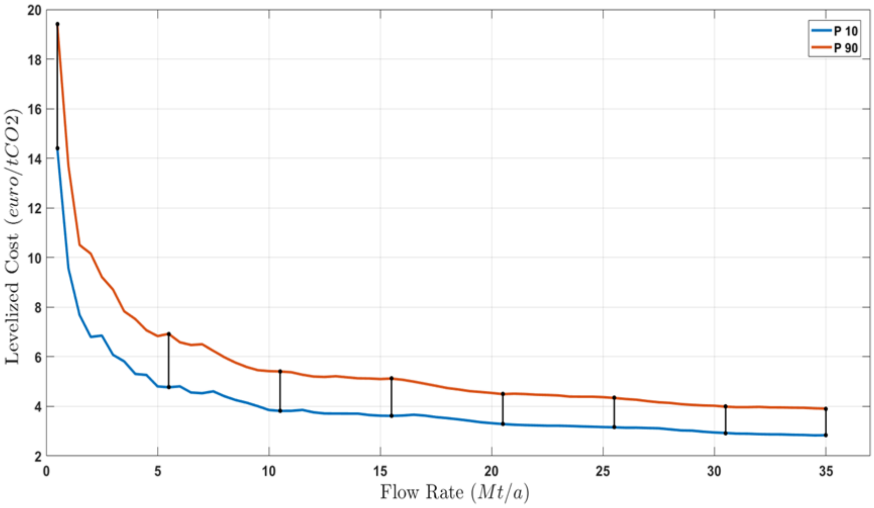

Figure 17. Levelized cost range at different flow rates for a 400-km pipeline (at probabilities of 10% and 90%)

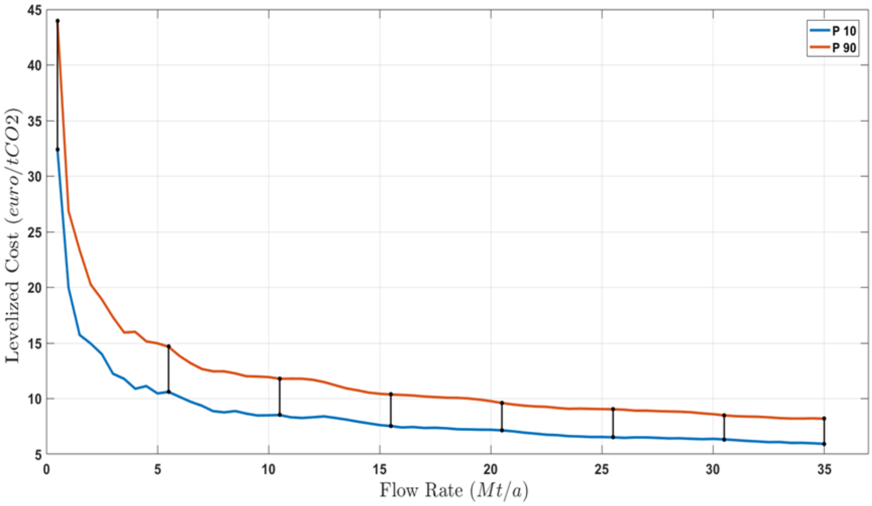

Figure 18. Levelized cost range at different flow rates for a 700-km pipeline (at probabilities of 10% and 90%)

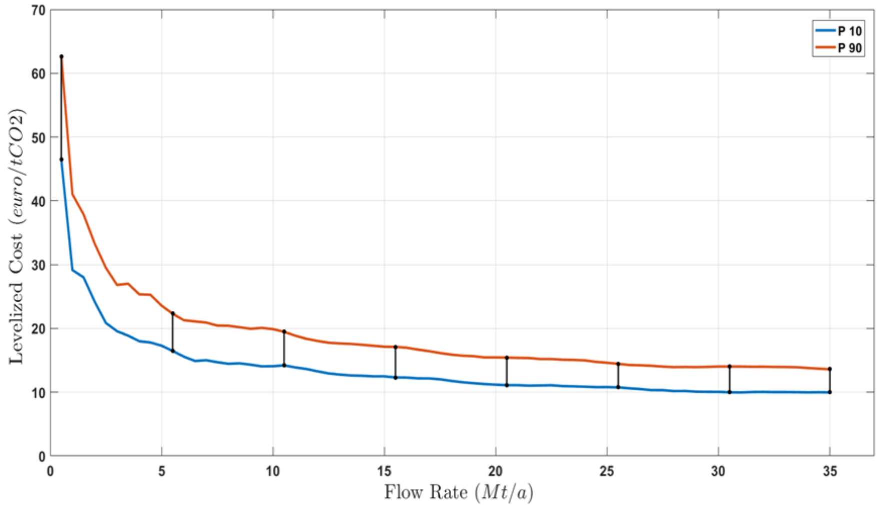

Figure 19. Levelized cost range at different flow rates for a 1000-km pipeline (at probabilities of 10% and 90%)

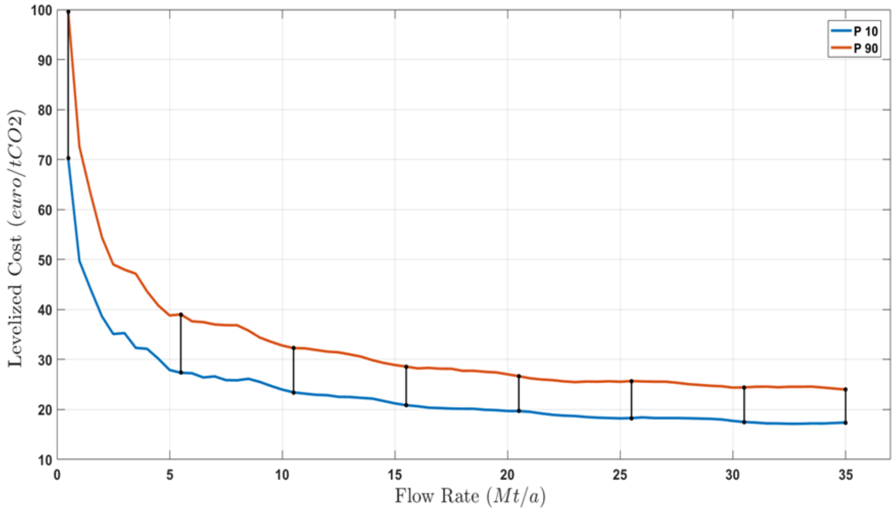

Figure 20. Levelized cost range at different flow rates for a 1500-km pipeline (at probabilities of 10% and 90%)

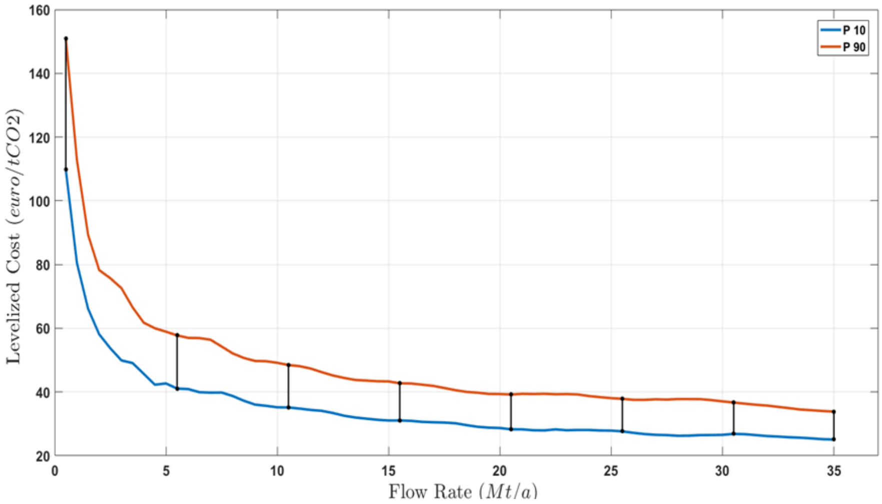

Figure 21. Levelized cost range at different flow rates for a 2000-km pipeline (at probabilities of 10% and 90%)

3.2.7. Case study

As mentioned earlier, the developed model can be generalized to other CO_2 pipeline transport with different flow rates, pipeline diameter, inlet, and outlet pressure, ambient temperature, and other influential parameters, as well as from any emission sources to the place of CO_2 operation sites. However, in this section, due to the significant amount of CO_2 emissions from Ramin Power Plant (about 7 million tons per year), the economic analysis was done for the CO_2 transmission pipeline from Ramin Power Plant to Ramshir Oil Field. Ramin Power Plant is one of the largest power plants in Iran, which has been built to supply electricity to Khuzestan Province and the national grid. The power plant, with a production capacity of 1850 MW, is one of the major emission sources in the southern part of the country. Ramshir Oil Field is located in Ramshir City, 15 km southwest of Omidieh City in Khuzestan Province. The oil field is adjacent to Shadegan, Ragesefid, and Aghajari Fields. The geographical location of the Ramin Power Plant and Ramshir Oil Field is shown in Figure 22. The key modeling parameters and modeling results are given in Table 8. According to the capacity of the emission source, the stochastic analysis of the levelized cost up to the capacity of 4 million tons per year is shown in Figure 23. It is worth mentioning that the assumptions for the economic analysis of the CO_2 pipeline from Ramin Power Plant to Ramshir Oil Field are the same as the basic model, which is not listed in Table 8 to avoid duplication.

Figure 22. Schematic of CO2 transmission pipeline from the emission source (Ramin Power Plant) to the place of CO2 operation (Ramshir Oil Field)

Table 8. Key Parameters and results of economic modeling of Ramin Power Plant-Ramshir Oil Field CO2 transmission pipeline

Parameter	Amount	Unit
Pipeline length	110	Km
Mass flow	2	$Mt.a^{-1}$
Pipeline lifetime	25	Year
Inflation rate	9.6	%
Capacity factor	0.8	-
Input pressure	14	MPa
Minimum outlet pressure	10	MPa
Calculated diameter of pipe	0.273	m
Material and equipment cost	8.36	M€
Manpower cost	5.05	M€
Capital cost of pipeline	18.37	€M
Levelized cost	1.55	€/ton
Levelized cost (Cumulative probability of 10%)	1.37	€/ton
Levelized cost (Cumulative probability of 90%)	2.07	€/ton

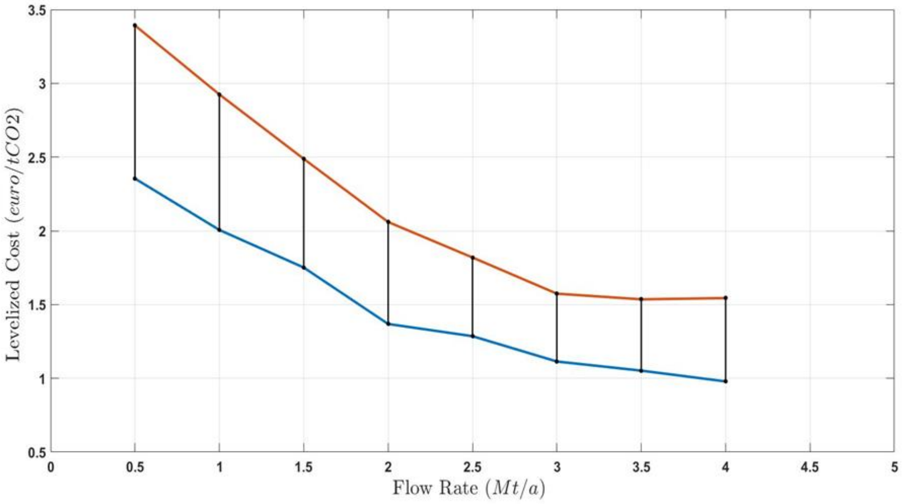

Figure 23. levelized cost range of Ramin Power Plant-Ramshir Oil Field CO2 transmission pipeline

4. Conclusion

After presenting the modeling results, the main purpose of this section is a comparison and systematic assessment of the techno-economic model in terms of the costs of investment, repair and maintenance, and pressure boosting stations of CO_2 pipelines. According to the model, it is concluded that:

Due to the high levels of CO_2 emissions in the southern part of the country and the shortcomings in the increase of oil extraction, which has led to the waste of oil in recent years, increasing oil extraction by injecting CO_2 is a very good option to solve this problem. It is worth mentioning that Iran has a capacity of 10 Gt CO_2 storage. This potential for the exploitation and storage of CO_2 highlights the need to address this issue. Comparing the developed model with other models revealed that the range of levelized cost in different flow rates is wider, which may be due to the following reasons:

- Topographic conditions
- Project location
- Different assumptions in cases such as project life span, interest rate, and final capacity of the pipeline
- Type of steel, coating, and insulation used in the pipeline
- detail of the parameters involved in the economic modeling of the CO_2 pipeline

First, it should be noted that this model could be used for different lengths and flow rates of a carbon grid. In the developed budget-type model, attempts were made to include the necessary techno-economic details, so the results could be a good criterion for the cost estimate of a CO_2 pipeline. The main findings of this study are:

- Increasing the length of the pipeline in a given flow rate will increase the costs.
- Increasing the discharge over a certain length, while increasing the cost of investment, reduces the levelized cost of CO_2 transport. This means that in a given length, although increasing the flow rate increases the diameter and this has technical-economic consequences, due to the reduced levelized cost, in the fixed-length, priority is given to increasing the flow rate. However, it should be noted that with a further increase of the flow rate from a certain range, the decreasing slope of the levelized cost decreases. This means that the increase in flow rate at a certain length should be controlled and evaluated by analyzing the parameters, such as the project location, amount of emissions, optimal flow point, and available CO_2 exploitation opportunities in a CCS project.

By comparing the developed budget-type techno-economic model with other available models, it was found that the cost of CO_2 pipeline in Iran is lower than that in other countries, which may be to the particular conditions of Iran, such as lower labor costs. This can increase the attractiveness of CCS projects for Iran. Considering the uncertainties in CO_2 pipeline projects resulting from changes in technical-economic parameters in different conditions, the statistical analysis of the budget-type model is very important. According to the results of this analysis, from an economic point of view, a better understanding may be obtained of the CCS chain, especially the CO_2 pipeline, which acts as a connector in this chain.

In the final part of the research, the cost of transferring 2 million tons of CO_2 from Ramin Power Plant to Ramshir Oil Field was calculated according to the basic model. The model results are as follows:

The pipeline diameter=0.273 m, the investment cost for the 110-km pipeline= 18.37

million €, the levelized cost = 1.55 €/ton, the levelized cost with a cumulative probability of 10% = 1.37 €/ton, and the levelized cost with a cumulative probability of 90% = 2.07 €/ton.

Based on the results of the previous section, two suggestions are presented to continue the present study:

1) Investigating the CO_2 exploitation potentials in Iran and using decision-making algorithms to rank emission priorities for CO_2 capture and operation sites

2) Developing a techno-economic model for a comprehensive system of CO_2 capture, transmission, and storage

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