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Economic optimization of CO_2 pipeline configurations.

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Abstract

In this article, an economic optimization tool is developed taking into account different steel grades, inlet pressure, diameter and booster stations for point-to-point pipelines as well as for simple networks. Preliminary results show that gaseous CO_2 transport is cost effective for relatively small mass flows and short (trunk) pipelines. For instance, for a pipeline transporting 5 Mt/y over 100 km of agricultural terrain, gaseous transport would cost 10.2 €/t and liquid transport 12.1 €/t (including initial compression). In terms of materials, the results indicate that higher steel grades (X70) are the most cost effective for onshore pipelines transporting liquid CO_2 while for gaseous CO_2 lower steel grades (X42) are more cost effective.

Keywords: Economic optimization; CO_2 pipeline transport; gaseous; booster stations; steel grades

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1. Introduction

Carbon capture and storage (CCS) is a CO_2 abatement option that can contribute significantly to the reduction of CO_2 emissions to limit temperature increase [1, 2]. Projections show that more than 20% of the required CO_2 emission reductions could be realized with CCS in the period 2015-2050 [3]. For this, about 2.4 and 7.8 Gt CO_2/y have to be transported to storage fields in 2030 and 2050, respectively [3]. First estimations indicate that worldwide CO_2 pipeline networks would be required of approximately 100.000 km in 2030 and between 200.000 and 550.000 km in 2050, depending on the level of integration [4]. Building a CO_2 infrastructure of such a scale would require a significant effort and would represent a massive investment.

To estimate the costs of a CO_2 pipeline for a given diameter and length, several different types of models exist in literature, namely linear models [5-7]; models based on the weight of the pipeline [8, 9];

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quadratic equations [10, 11] and the so-called CMU model [12]. In a previous study, these cost models are reviewed and compared [13]. This comparison shows that there is a large cost variation for a given diameter on flat agricultural land. For instance, for a diameter of 0.4 m the costs varied between 0.3 and 1.7 M€$_{2010}$/km, see Fig. 1.

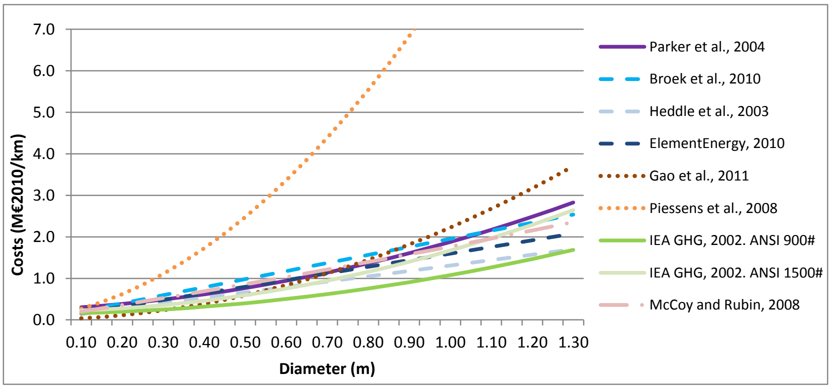

Fig. 1: Comparison of capital costs for nine different models for onshore CO_2 pipelines on flat agricultural terrain for 25 km (adapted from [13]).

Besides the large costs range, a number of major limitations were found [13]:

- Almost all models use existing natural gas pipelines as the basis for their cost estimation. Thereby the models, with exception of the weight base models, ignore the higher operation pressure required for CO_2 transport, which will require a larger wall thickness and pose higher costs.
- Most models are based on onshore natural gas pipelines constructed in the 1990s and early 2000s in the United States. Thereby, ignoring the large increase in material and construction prices of the last several years.
- Most cost models do not indicate the steel grade their cost equation is based on, while others base their cost equation on only one steel grade. However, steel grades determine for a large part the material costs and substantial cost reductions can be realized by using higher steel grades for pipelines operating on high pressures [14-17].
- All models are based on dense liquid CO_2 transport, while in certain conditions gaseous CO_2 transport may be more cost effective. Gaseous CO_2 transport requires a large pipeline diameter, which would increase the investment costs, but would require less compression capacity, which would decrease the capital and energy costs at the capture site. A similar economic decision has to be made between diameter, inlet pressure and the installation of booster stations for liquid CO_2 transport.

To overcome these limitations, an economic optimization tool for CO_2 pipeline transport has been developed. This tool include inlet pressure, diameter, different steel grades and the possibility of booster stations to evaluate under which conditions gaseous transport is more cost effective than liquid CO_2 pipeline transport and investigate when booster stations have to be installed. The economic tool is based on a new developed pipeline cost model, which is related to the weight of the pipeline and used up-to-date steel prices and construction costs.

2. Methodology

2.1 Optimization tool of a point-to-point pipeline

In this study, both gaseous as well as dense liquid transport is included in the optimization process. For liquid cases, the inlet pressures range from 9 to 24 MPa, in steps of 1 MPa, and with 0 to 10 booster stations. For gaseous CO_2 transport, inlet pressures range from 1.6 to 3 MPa, in steps of 0.1 MPa, and the outlet pressure is fixed on 1.5 MPa. The possibility of recompressing is not included for gaseous transport, due to the high energy consumption and recompression costs. Overall, 191 cases are analyzed.

For each case, the specific pressure drop is calculated (see equation 1) which is used to calculate the diameter. However, not all diameters are commonly available in the market, and hence the diameter is increased to the next available nominal pipe size (NPS). If the calculated diameter is larger than the largest available NPS, the case is not taken into account further. At this moment, the possibility of placing multiple pipelines next to each other is not considered.

$$\Delta P_{design} = \frac{(P_{inlet} - P_{outlet}) * (n_{booster} + 1)}{L} + \frac{g * \rho * \Delta z}{L} \tag{1}$$

where ΔP_{design} is the design pressure drop (Pa/m); P_{inlet} and P_{outlet} are the pressure inlet and outlet, respectively (Pa); $n_{booster}$ is the number of booster stations; L is the length of the pipeline (m); G is the gravity constant (9.81 m/s^2); ρ is the density (kg/m^3) and Δz is the height difference (m).

The thickness is calculated for each case, since this should be a main input in the cost determination of the pipeline for a system analysis [13]. The thickness is related to the inlet pressure, a safety factor depending on the terrain, the NPS and the yield stress of the lowest steel grade. Subsequently, the material costs of the pipeline are calculated based on the thickness, steel costs for the specific steel grade and the NPS. This process is repeated for each steel grade, and the combination of steel grade, NPS and thickness resulting in the lowest capital costs is selected.

To ensure that the combination between inlet pressure, diameter and number of booster stations is feasible, the velocity is calculated. A limit of 6 m/s for liquid CO_2 has been set to avoid erosion, vibrations and damaging of the pipeline [18] and above 0.5 m/s to ensure that the CO_2 flows. For gaseous CO_2 transport, a velocity range of 5-20 m/s is assumed. If a specific case results in a velocity outside the identified range, the case is ignored.

For each combination of booster stations, inlet pressure and pipeline diameter, the energy costs are calculated with an electricity price of 100 €/MWh and the operation and maintenance (O&M) costs are assumed to be a fixed percentage of the investment costs. Subsequently, the levelized costs of CO_2 transport are calculated, see equation 2. The combination with the lowest levelized costs is considered the optimal combination of inlet pressure, diameter and number of booster stations. For an overview of the optimization process, see Fig. 2.

$$\mathrm{LC} = \frac{\mathrm{CRF}*(\mathrm{I_{boost}}+\mathrm{I_{comp}})+\mathrm{CRF}*\mathrm{I_{pipe}}+\mathrm{OM_{boost}}+\mathrm{OM_{pipe}}+\mathrm{OM_{comp}}+\mathrm{E_{boost}}+\mathrm{E_{comp}}}{\mathrm{m}*\mathrm{OH}*3.6} \tag{2}$$

where LC are the levelized cost of CO_2 transport (€/t CO_2); CRF is the capital recovery factor, which is calculated with $\frac{r}{1-(1+r)^{-L}}$; r is the discount rate (%); L is the lifetime (years); I are the investment costs (€); OM are the O&M costs (€/y); E are the energy costs (€/y); m is the CO_2 mass flow (kg/s); OH are the number of operation hours (hr); and the subscripts boost, comp and pipe refer to booster stations, pipeline and compressors, respectively.

2.2. Optimization of simple networks

In the future, it is expected that not only point-to-point pipelines will be constructed but also trunklines will arise which transport CO_2 from multiple sources to one or more sinks [7, 19, 20]. Four different networks options are examined, namely:

I. Gaseous transport in the feeders as well as in the trunk line and spin-offs.
II. Gaseous transport in the feeders and liquid transport at the trunk line and spin-offs.
III. Liquid transport in the entire network, where the CO_2 is compressed at the capture sites.
IV. Liquid transport in the entire network, where a booster is installed before the trunk line.

The trunkline is optimized with respect to diameter, inlet pressure, number of booster stations and steel grade with the methodology described in 2.1. For the feeders transporting the CO_2 to the trunkline and for the spin-offs transporting the CO_2 from the trunkline to the sink, a more simple approach is taken to limit the calculation time. For these relatively short pipelines, a constant maximum design pressure drop is assumed and the possibility of installing booster stations is not considered. Furthermore, all feeders and spin-offs are assumed to be constructed from X70 for liquid CO_2 transport and of X42 for gaseous transport despite that the optimal steel grade for the trunkline may be different. These simplifications have a minor influence on the total levelized costs because compared to the trunk line, the feeders and spin-offs are limited in length.

The levelized costs of the four different network options are compared with each other, and the one resulting in the lowest levelized costs is selected.

3. Results

3.1 Preliminary results of the optimization process for point-to-point pipelines

Preliminary results of the optimization process for point-to-point pipelines over three kinds of terrains are given in Table 1. The results show that for onshore pipelines transporting liquid CO_2, the specific pressure drop is about 15-45 Pa/m, inlet pressures are 9-12 MPa and booster stations are placed roughly every 100 km.

For offshore pipelines, the installation of booster stations was excluded in the model because a platform should be installed which is very expensive. Consequently, for long offshore CO_2 pipelines the inlet pressure is increased at the capture plant to 12-19 MPa. For long offshore pipelines of 500 km or more, also the diameter is increased to lower the specific pressure drop.

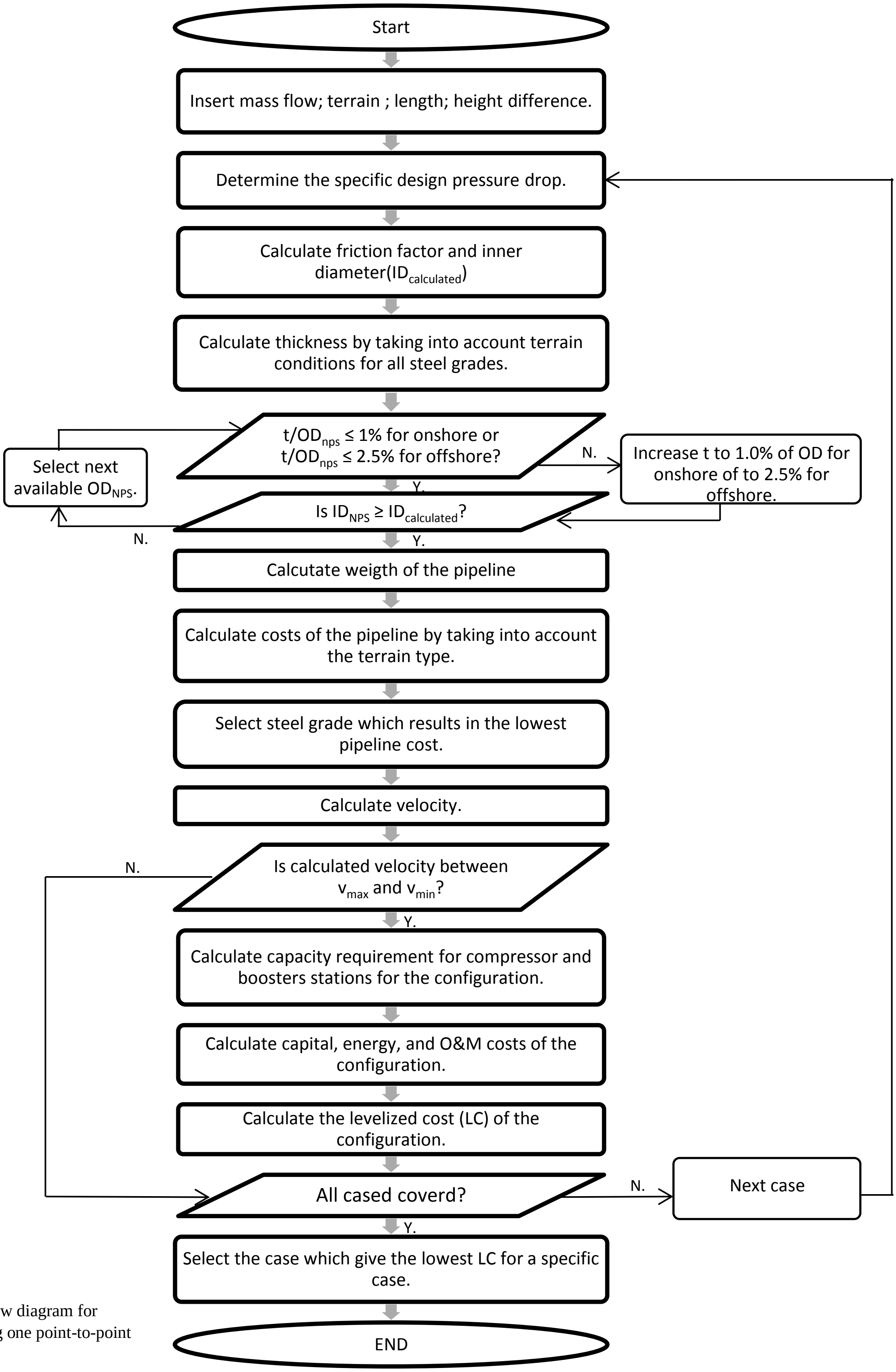

Fig. 2: Flow diagram for optimizing one point-to-point pipeline.

Table 1: Selection of preliminary results of the optimization process for point-to-point pipelines for several cases.

Terrain	Mass flow (Mt/y)	Length (km)	OD (m)	P_{inlet} (MPa)	$N_{booster}$	$L_{boosters}$ (km)	LC (€$_{2010}$/t)	ΔP_{act} (Pa/m)	Steel grade	Phase
Agricultural	10	100	0.61	10	0	127	12.3	16	X70	Liquid
Populated	10	100	0.51	10	2	46	12.3	43	X70	Liquid
Offshore	10	100	0.51	13	n.a.	n.a.	11.8	41	X65	Liquid
Offshore	10	300	0.61	13	n.a.	n.a.	14.0	16	X65	Liquid
Offshore	10	500	0.61	17	n.a.	n.a.	16.5	16	X65	Liquid
Offshore	5.0	100	0.41	12	n.a.	n.a.	12.4	33	X65	Liquid
Offshore	5.0	300	0.41	19	n.a.	n.a.	15.4	35	X65	Liquid
Offshore	5.0	500	0.51	14	n.a.	n.a.	19.3	10	X65	Liquid
Offshore	15.5	100	0.61	12	n.a.	n.a.	11.5	38	X65	Liquid
Agricultural	1.0	100	0.22	12	0	115	14.1	35	X70	Liquid
Agricultural	2.5	100	0.32	11	1	109	12.6	28	X65	Liquid
Agricultural	5.0	100	0.41	10	1	62	12.1	32	X65	Liquid
Agricultural	20	100	0.76	10	0	102	11.2	20	X65	Liquid
Agricultural	20	300	0.76	10	2	102	12.4	20	X65	Liquid
Agricultural	20	500	0.76	10	4	102	13.5	20	X65	Liquid
Agricultural	16.5	100	0.76	9.0	1	76	11.3	13	X65	Liquid
Agricultural	1.0	100	0.51	2.7	n.a.	n.a.	14.0	11	X42	Gaseous
Agricultural	2.5	100	0.76	2.4	n.a.	n.a.	11.4	8.6	X42	Gaseous
Agricultural	5.0	100	1.07	2.2	n.a.	n.a.	10.2	6.0	X42	Gaseous
Agricultural	10	100	1.42	2.1	n.a.	n.a.	9.4	5.4	X42	Gaseous
Agricultural	16.5	100	1.42	3.0	n.a.	n.a.	9.5	15	X52	Gaseous
Offshore	5.0	100	0.91	3.0	n.a.	n.a.	11.9	15	X42	Gaseous
Offshore	15.5	100	1.42	3.0	n.a.	n.a.	10.5	14	X42	Gaseous

Gaseous CO_2 transport is cost-effective compared to liquid CO_2 transport for mass flows up to 16.5 Mt/y and 100 km over agricultural terrain and for mass flows up to 15.5 Mt/y and 100 km for offshore pipelines. Savings in compression energy compensate the higher construction costs for a larger diameter pipeline. Nevertheless, if a pressure of 8 MPa or higher is required to inject the CO_2 in the storage field, then compression at the capture plant and transporting it as a liquid is more cost-effective than transporting it as a gas and compress it from 1.5 MPa to a liquid at the storage location.

Furthermore, the results show that for onshore pipelines transporting liquid CO_2 steel grades X65 and X70 are used while for pipelines transporting gaseous CO_2 steel grades X42 and X52 are used. This is due to the minimal thickness requirement of 1% of the outer diameter.

3.2 Preliminary results of the optimization process for simple networks

Preliminary results of the optimization process for simple networks are given in Table 2. Compression and pumping at the capture side (network option III) is the best option if the network consists of short feeders and a long trunkline. If the distance of the feeders is increasing, network option IV, where a booster stations is installed just before the trunkline, becomes more cost effective.

For networks with short trunklines and small mass flows, gaseous CO_2 transport in whole the network (option I) can be the most cost-effective option. For instance, for two mass flows of 5 Mt/y, an onshore trunkline of 100 km, feeders and spin-offs of 10 km, gaseous transport is cheaper (10 $€_{2010}$/t) than liquid transport (12.0 $€_{2010}$/t and 12.1 $€_{2010}$/t for option III and IV, respectively). Gaseous transport in the feeders and compression before the trunkline (option II) become economically not the best alternative if the CO_2 is released at atmospheric pressure regardless the length of, and mass flows through the feeders and trunkline.

Table 2: Selection of preliminary results of the optimization process for simple networks.

Location trunk line and spin-offs	Mass flow (Mt/y)	Length trunkline (km)	Location feeders	Length feeders (km)	Length spin-offs (km)	Network option	Levelized costs ($€_{2010}$/t)
Offshore	2 * 10	500	Populated	2*10	2*10	III	15.3
Offshore	2 * 10	500	Populated	2*50	2*10	III	16.1
Offshore	2 * 10	500	Populated	2*75	2*10	IV	16.6
Offshore	2 * 10	500	Agricultural	2*10	2*10	III	15.2
Offshore	2 * 10	500	Agricultural	2*50	2*10	III	15.7
Offshore	2 * 10	500	Agricultural	2*75	2*10	IV	16.0
Offshore	2 * 5.0	100	Agricultural	2 *25	2*10	I	10.9
Agricultural	2 * 5.0	100	Agricultural	2 *10	2*10	I	10.0
Agricultural	2 * 5.0	100	Agricultural	2 *50	2*10	I	11.0
Agricultural	2 * 10	250	Agricultural	2*10	2*10	III	12.4
Agricultural	2 * 10	250	Agricultural	2*25	2*10	IV	12.5

4. Conclusions

In this study, an economic optimization model was developed including inlet pressure, diameter, booster stations and different steel grades to evaluate the most cost effective way to design CO_2 pipeline transport. Several conclusions can be drawn from the preliminary results:

- Higher steel grades, like X70, result on average in lower transportation costs for onshore pipelines transporting liquid CO_2 than lower steel grades, like X42.
- Inlet pressures for onshore pipelines transporting liquid CO_2 are about 10 MPa and booster stations are installed roughly every 100 km. For offshore pipelines, higher inlet pressures are selected because booster stations are not an option.
- Pipelines transporting CO_2 as a gas is in specific cases better than transporting CO_2 as a liquid for point-to-point as well as for simple networks.

- When the distance between the capture plant and the trunkline is small, the CO_2 is compressed to the required pressure at the capture plant. However, for longer distances, a booster stations is installed just before the trunk line to increase the pressure to the required inlet pressure.

The economic optimization model is currently being extended to include time-aspects, the effect of impurities in the CO_2 flow and to make it more spatial explicit. The results will be reported in a forthcoming article.

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References

[1] Moomaw W, Yamba F, Kamimoto M, Maurice L, Nyboer J, Urama K, et al. Renewable energy and climate change. In: *IPCC special report on renewable energy sources and climate change mitigation.* Cambridge, United Kingdom and New York, USA: Cambridge University Press; p. 1-68. 2011

[2] IEA. *World energy outlook 2010*. Organisation for Economic Co-operation and Development (OECD) / International Energy Agency (IEA); 2010.

[3] IEA. *Energy technology perspective 2012. Pathways to a clean energy system*. Paris, France: Organisation for Economic Co-operation and Development (OECD) / International Energy Agency (IEA); 2012.

[4] IEA. *Energy technology perspectives 2010: Scenarios and strategies to 2050*. Paris, France: Organisation for Economic Co-operation and Development (OECD) / International Energy Agency (IEA). 2010.

[5] Heddle G, Herzog H, Klett M. *The economics of CO_2 storage*. Massachusetts Institute of Technology. 2003.

[6] Van den Broek M, Brederode E, Ramírez A, Kramers L, van der Kuip M, Wildenborg T, et al. Designing a cost-effective CO_2 storage infrastructure using a GIS based linear optimization energy model. *Environ Modell Softw*. 2010;25(12):1754-68.

[7] ElementEnergy. *CO_2 pipeline infrastructure: An analysis of global challenges and opportunities.* Final report for International Energy Agency Greenhouse Gas Programme. 2010.

[8] Gao L, Fang M, Li H, Hetland J. Cost analysis of CO_2 transportation: Case study in China. *Energy Procedia*. 2011;4:5974-81.

[9] Piessens K, Laenen B, Nijs W, Mathieu P, Baele JM, Hendriks C, et al. *Policy support system for carbon capture and storage. Science for a sustainable development*. Report No.: SD/CP/04A. 2008.

[10] Parker N. *Using natural gas transmission pipeline costs to estimate hydrogen pipeline costs.* Report No.: UCD-ITS-RR-04-35. 2004

[11] IEA GHG. *Pipeline transmission of CO_2 and energy*. Transmission study report. Prepared by Woodhill Engineering Consultants; IEA GHG. Report No.: PH4/6. 2002

[12] McCoy ST, Rubin ES. An engineering-economic model for pipeline transport of CO_2 with application to carbon capture and storage. *Int J Greenh Gas Con*. 2008;2:219-229.

[13] Knoope MMJ, Ramírez A, Faaij APC. A state-of-the-art review of techno-economic models predicting the costs of CO_2 pipeline transport. *Submitted for publication*. 2012.

[14] Gräf MK, Hillenbrand HG, Heckmann CJ, Niederhoff KA. High-strength large-diameter pipe for long-distance high pressure gas pipelines. *Proc Int Offshore Polar Eng Conf*. 2003:2347-54

[15] Cayrade P. *Investment in gas pipelines and liquefied natural gas infrastructure. What is the impact on the security of supply?* INDES Working paper no.3. 2004

[16] Sanderson N, Ohm R, Jacobs M. Study of X-100 line pipe costs point to potential savings. *Oil and Gas J*. 1999;97(11):54.

[17] Felber S, Loibnegger F. The pipeline steels X100 and X120. *XI-929-09*. 2009:1-24.

[18] NORSOK. *NORSOK standard process design*. Report No.: P-001. 2006.

[19] ZEP. CO_2 transport costs. *Zero emission platform*. 2010.

[20] Chandel MK, Pratson LF, Williams E. Potential economies of scale in CO_2 transport through use of a trunk pipeline. *Energ Conver Manage*. 2010;51(12):2825-34.