CO_2 Transport via Pipelines: Design of CO_2 networks using an Optimal Power Flow approach

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ABSTRACT

The successful implementation of CCU and CCS measures requires the development of a CO_2 infrastructure connecting CO_2 sources and sinks. From an economic standpoint, pipelines are the only way to transport large quantities of CO_2 over land. In this work techno-economic optimization approaches for CO_2 pipeline networks are evaluated by comparing Network Flow and Optimal Power Flow models. The study presents a methodology incorporating power flow calculations, focusing on pressure and temperature effects in gaseous, supercritical and dense-phase CO_2 transport. A designed case study demonstrates the application to determine cost-optimal network topology and sizing, without and with considering physical constraints such as pressure losses. The findings reveal significant differences in investment decisions between Network Flow and Optimal Power Flow models, emphasizing the importance of incorporating physical constraints into optimization processes.

KEYWORDS

Carbon Capture and Storage, Carbon Capture and Utilization, CO_2 transport, Network Optimization, Optimal Power Flow

INTRODUCTION

Meeting the global climate targets according to the Paris Agreement [1] presents a critical challenge for the coming decades. Certain emissions from industry, energy generation and diffuse sources such as from agriculture cannot be completely avoided. Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS) are therefore considered essential components for achieving the climate targets [2]. The successful implementation of CCU and CCS measures require the development of a CO_2 infrastructure connecting CO_2 sources and sinks.

CO_2 transport

Pipeline transport is the most economical way for over-land transports of large quantities of CO_2 [3,4]. CO_2 can be transported in a gaseous, liquid, dense or supercritical state, therefore its transportation is significantly affected by temperature, pressure and impurities. The most effective method for pipeline-transport of CO_2 is in supercritical or dense phase, with pressures from 83 to 152 bar, possibly up to 193 bar. CO_2 is in a supercritical state when its pressure is above the critical pressure of 73.8 bar and the temperature is above the critical temperature of

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31.1 °C. With pressures above the critical pressure but temperatures below the critical temperature, it is considered dense phase. Due to safety reasons, in densely populated areas often gaseous transport is preferred but should only be considered for short-distances [3,5].
During the transportation no phase changes are allowed, therefore special attention must be paid to pressure and heat losses. Because of the high density of the CO_2 in supercritical and dense phase pressure losses due to elevation changes are of particular importance.

Optimization models

There are several optimization approaches for CO_2 pipeline networks up to now. Generally, optimization models can be categorized into Network Flow and Optimal Power Flow models. The former consider no or little physics in CO_2-transportation, the latter do. In Figure 1 a comparison between these models is shown.

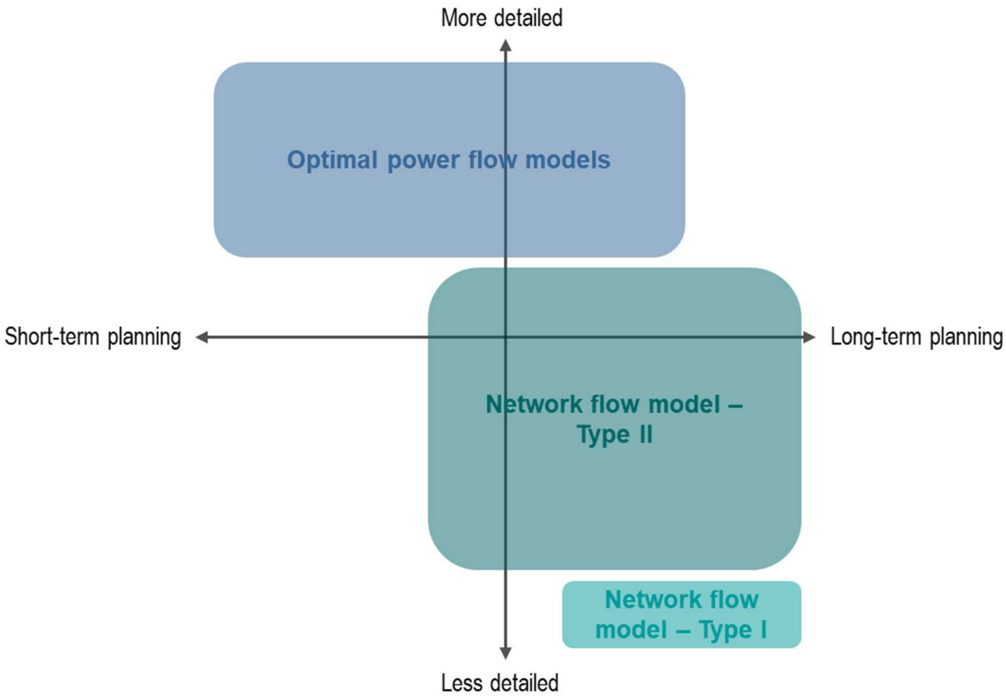

Figure 1: Comparison between Network Flow and Optimal Power Flow models

Network Flow models are typically less detailed and are classified into type I (without losses) and type II (with losses modeled as transmission efficiency). Optimal Power Flow models are based on physical constraints linking pressure and mass flow [6]. Optimal Power Flow (OPF) models are based on physical principles that combine time- and location-dependent pressure and mass flows with techno-economic optimization [6]. The detail of modeling varies depending on its application: Long-term planning models typically use coarse system models compared to short-term operational models [7].
Morbee et al. [8] developed the optimization tool *InfraCCS* that determines the optimal pipeline-based CO_2 network for a given set of sources and sinks. The tool aims to design the optimal CO_2 transport network, focusing on minimizing costs. The process involves clustering sources and sinks, forecasting CO_2 capture and storage evolution, routing potential pipelines while using a mixed-integer linear programming (MILP) Network Flow model to select the most cost-effective network configuration. Middleton et al. [9] introduced several key innovations for modelling CO_2 infrastructure, including realistic pipeline networks that leverage economies of scale, the ability to route pipelines in regions without pre-defined routes, and handling geologic uncertainty in reservoir performance. In this work as well a Network

Flow MILP optimization problem is formulated to minimize costs. The developed open-source optimization tool is called *SimCCS*. Knoope et al. [10] developed a Network Flow optimization model for CO_2 pipelines that integrates economic risks and uncertainties such as commodity cost, time and transport cost, using MILP. Qiu et al. [11] introduced a new formulation for clustered CO_2 transport networks using a Markov Decision Process, which enables more detailed modelling of non-linear transport costs and finer geographical resolution.

Research Objective

Existing optimization models for CO_2 pipeline networks do not account for the physical constraints of CO_2 transport comprehensively. CO_2 network design typically uses Network Flow models that optimize the routing or sizing but are not able to accurately capture physical constraints. Power Flow calculations can simulate existing designs with physical precision but do not offer optimization capabilities. Currently, there are no models that combine optimization with physical accuracy, known as Optimal Power Flow models.
Optimal Power Flow models are based on physical principles that combine time- and location-dependent pressure and mass flows with techno-economic optimization. Thus, they allow to determine cost-optimal topology and sizing of a transport network with an assumed higher degree of accuracy compared to Network Flow-based optimization. The development of an OPF model requires linking a detailed power flow calculation with an optimization approach. Therefore, designing optimal CO_2 pipeline networks, the following research question need to be addressed:

- What is the impact of different optimization models (Network Flow vs. Optimal Power Flow) on real-life CO_2 transport network routing problems?

To answer this question a techno-economic optimization approach is combined with power flow calculations.

METHODOLOGY

In this work cost-minimizations together with Network and Optimal Power Flow calculations to determine optimal design of CO_2 networks is used. A possible topology of the CO_2 network is given comprising different pipeline routes. The cost-optimal pipeline routing should be determined through the optimization process. The optimal system design is reached when the costs reach a minimum. A linear Network Flow formulation is compared to a MILP Optimal Power Flow formulation. The MILP formulation is used to piecewise linearize the non-linear pressure loss in CO_2 pipes.

Power flow calculations

Pipeline network power flow calculations are used to assess flow parameters like pressure drops, pressure distributions or temperature distributions. The pressure drop through a pipeline is described by a quadratic dependency of the volume flow $\dot{V}$ or mass flow $\dot{m}$ according to Darcy's law (Eq. (1)), with the Darcy friction factor λ, pipe length l, diameter d and fluid density ρ [12]. The total pressure drop is the sum of the pressure drop due to friction (Darcy's law) and due to the change of elevation Δh.

$$\Delta p = \frac{\lambda \cdot l \cdot \rho \cdot 8}{d^5 \cdot \pi^2} \dot{V}^2 + \rho \cdot g \cdot \Delta h = \frac{\lambda \cdot l \cdot \rho \cdot 8}{d^5 \cdot \pi^2} \left(\frac{\dot{m}}{\rho}\right)^2 + \rho \cdot g \cdot \Delta h \tag{1}$$

In HyFlow [13,14], a power flow simulation tool developed at the Montanuniverstät Leoben, a node potential algorithm for CH_4-, H_2- and heat networks was established, that allows for the calculation of mass flow and pressure drop in the branches of the networks. This methodology is being further developed to determine the pressure distribution in CO_2 networks depending on feed in pressures and temperatures. To determine the thermodynamic properties of CO_2, the equation of state (EOS) from Span and Wagner [15] is used. The developed tool enables power flow simulation for networks with varying pressure levels that are interconnected, allowing for gaseous CO_2 transport and CO_2 transport in the dense as well as supercritical phase. The power flow calculations are conducted with high spatial and temporal resolution, considering mass flow-dependent pressure differences due to friction, elevation and heat transfer along the pipeline.

Optimization approach

The goal of the techno-economic optimization approach is to identify the most cost-effective CO_2 network. This involves determining the optimal network routing and sizing. This paper aims to compare the Network Flow Optimization approach with Optimal Power Flow, thus both approaches are explained.

Network Flow Optimization model (type I)

The CO_2 mass flow of the sources, maximal injection rates of the sinks, possible pipeline routes as well as cost-functions of the pipes are given. The source mass flows are specified through individual time series. The optimization problem is to determine the routing of the pipeline system to minimize overall costs. The modeling is implemented in Python using the open-source package oemof.solph [16] which relies on pyomo [17] for creating the mixed-integer linear optimization problem. The CO_2 pipelines are modelled with a MILP model based on [18]. A scheme of the modelled pipeline for the Network Flow Model is shown in Figure 2.

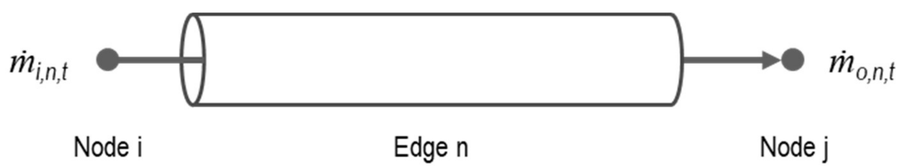

Figure 2: Scheme of the modelled CO_2 pipeline for the Network Flow model

The Network Flow model type I (without losses) is described by a simple mass balance (Equ. (2)):

$$\dot{m}_{i,n,t} = \dot{m}_{o,n,t} \tag{2}$$

The investment decision is made by considering maximum mass flows at the sources. Following constraints result for a non-convex investment optimization:

$$min! \sum_{n} C_n \tag{3}$$

$$C_n = \dot{m}_{invest} \cdot c_{invest} \cdot l + c_{investfix} \cdot y_n \tag{4}$$

$$\dot{m}_{n,invest,min} \cdot y_n \leq \dot{m}_{n,invest} \leq \dot{m}_{n,invest,max} \cdot y_n \tag{5}$$

$$\dot{m}_{i,n,invest} = \dot{m}_{o,n,invest} \tag{6}$$

with following decision variables and parameters:

$\dot{m}_{i,n,t}$	Mass flow at the inlet of the CO_2 pipe n at time step t [kg CO_2/s]
$\dot{m}_{o,n,t}$	Mass flow at the outlet of the CO_2 pipe n at time step t [kg CO_2/s]
C_n	Investment costs of the CO_2 pipe n [€]
$\dot{m}_{n,invest}$	Transport capacity of CO_2 pipe n [kg CO_2/s]
c_{invest}	Capacity dependent investment costs [€/(km*kg CO_2/s)]
$c_{invest,fix}$	Fix investment costs [€]
y_n	Investment decision variable of the pipe n [-] (0 = no investment, 1= investment)

Optimal Power Flow model

For the Optimal Power Flow model pressure restrictions are considered through a piecewise linearized function of pressure losses depending on the mass flows through the pipes at certain grid points. The developed scheme is shown in Figure 3.

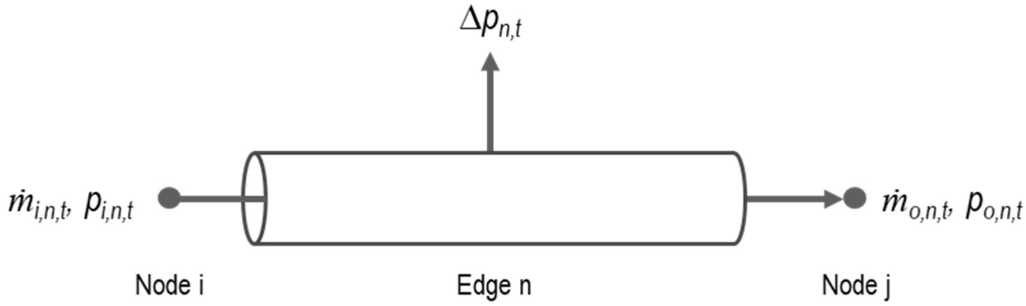

Figure 3: Scheme of the modelled CO_2 pipeline for the Optimal Power Flow model

This is done by determining the values of Equ. (1) for certain grid points with the power flow simulation tool HyFlow. Therefore, the mass flow is stepwise increased from 0 to the maximum mass flow. For each step, the corresponding pressure drop is calculated. This allows a mixed-integer linear problem to be formulated. The constraints of Optimal Power Flow model are described by the following equations:

$$\dot{m}_{i,n,t} = \dot{m}_{o,n,t} \tag{7}$$

$$p_{o,n,t} = p_{i,n,t} - \Delta p_{n,t} \tag{8}$$

$$\Delta p_{n,t} = lf_n \cdot \dot{m}_{i,n,t} \tag{9}$$

$$p_{i,n,t}, p_{o,n,t} \geq p_{min} \quad (10)$$

$$p_{i,n,t}, p_{o,n,t} \leq p_{max} \quad (11)$$

The investment decision is made by considering maximum mass flows at the sources. Following constraints result for a convex investment optimization:

$$min! \sum_{n} C_n \quad (12)$$

$$C_n = \dot{m}_{invest} \cdot c_{invest} \cdot l + c_{investfix} \cdot y_n \quad (13)$$

$$\dot{m}_{n,invest,min} \cdot y_n \leq \dot{m}_{n,invest} \leq \dot{m}_{n,invest,max} \cdot y_n \quad (14)$$

$$\dot{m}_{i,n,invest} = \dot{m}_{o,n,invest} \quad (15)$$

$$p_{o,n} = p_{i,n} - \Delta p_n \cdot \dot{m}_{i,n,invest} \quad (16)$$

$$p_b \geq p_{min} \quad (17)$$

$$p_b \leq p_{max} \quad (18)$$

with following decision variables and parameters:

$\dot{m}_{i,n,t}$	Mass flow at the inlet of the CO_2 pipe n at time step t [kg CO_2/s]
$\dot{m}_{o,n,t}$	Mass flow at the outlet of the CO_2 pipe n at time step t [kg CO_2/s]
$p_{o,n,t}$	Pressure at the outlet of the CO_2 pipe n at time step t [bar]
$p_{i,n,t}$	Pressure at the inlet of the CO_2 pipe n at time step t [bar]
p_{min}	Pressure minimum [bar]
p_{max}	Pressure maximum [bar]
$\Delta p_{n,t}$	Pressure loss of the CO_2 pipe n at time step t [bar]
lf_n	Pressure loss factor of the CO_2 pipe n [bar/(kg CO_2/s)]
C_n	Investment costs of the CO_2 pipe n [€]
$\dot{m}_{n,invest}$	Transport capacity of CO_2 pipe n [kg CO_2/s]

c_{invest} Capacity dependent investment costs [€/(km*kg CO_2/s)]

$c_{invest,fix}$ Fix investment costs [€]

y_n Investment decision variable of the pipe n [-] (0 = no investment, 1= investment)

CASE STUDY

To answer the research questions and verify the approach a case study is designed. The system consists of four sources with fixed CO_2 mass flows and two sinks, that represent geological CO_2 storages with given maximum injection rates. For the OPF model reservoir pressures that must be ensured are additional parameters. Points in the grid where two or more pipelines meet are called forks. The topology of the given network is shown in Figure 4.

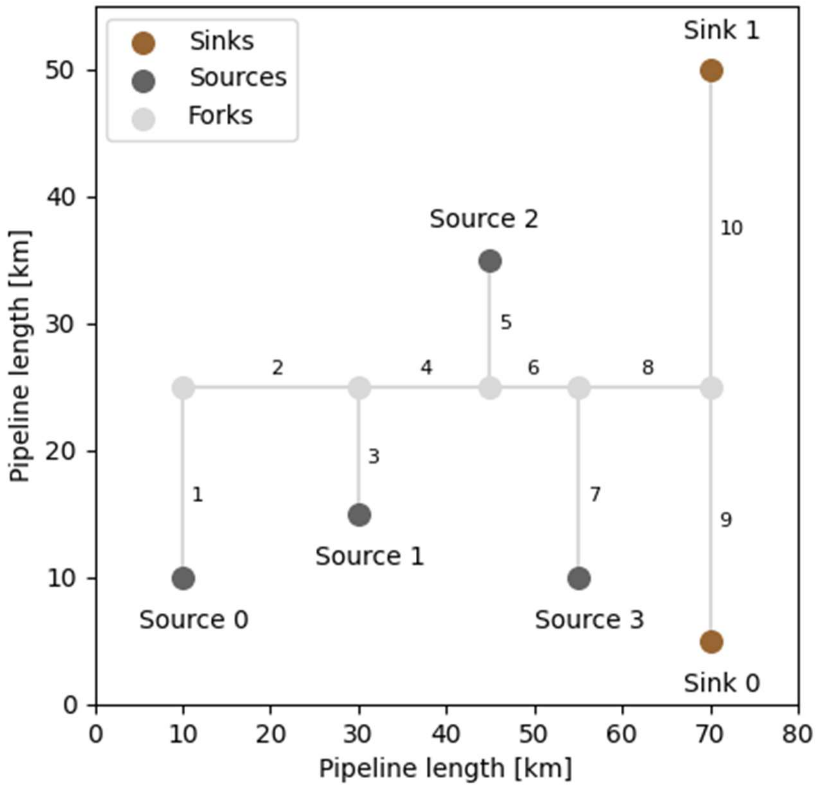

Figure 4: Given network topology of the modelled system

The input data of the nodes and pipes is given in Table 1 and Table 2. The maximum injection rate of each sink is sufficient to store the quantities fed into the network, therefore it is not necessary to use both sinks.

Table 1: Node input data of the modelled system

Node ID	Nodes	Max. mass flow [kg/s]	Given node pressure [bar]	Altitude [m]
1	Source 0	2	≤110	390
2	Source 1	2	≤110	395
3	Source 2	2	≤110	390

4	Source 3	2	≤110	400
5	Fork 0	-	-	400
6	Fork 1	-	-	400
7	Fork 2	-	-	400
8	Fork 3	-	-	400
9	Fork 4	-	-	410
10	Sink 0	-10	≥ 105	510
11	Sink 1	-10	≥ 105	410

The feed in temperature of the sources is 25 °C (dense liquid phase) to make sure that ground temperatures are not strongly affected. The average ground temperature is 12 °C and the pipes are installed at a depth of 2 m. For this case study it is assumed that the CO_2 stream is pure. Pipes with a roughness of 50 µm [19] and a wall thickness of 11 mm are installed.
Sink 0 is located at an altitude of 510 m above sea level, while Sink 1 is at an altitude of 410 m. While the distance of Sink 0 to the connecting pipe is 20 km, the distance of Sink 1 is 25 km.

Table 2: Pipe input data of the modelled system

Pipe ID	From node [-]	To node [-]	Length [km]	Diameter [m]	Elevation change [m]
1	Source 0	Fork 0	15	0.25	10
2	Fork 0	Fork 1	20	0.25	0
3	Source 1	Fork 1	10	0.25	5
4	Fork 1	Fork 2	10	0.30	0
5	Source 2	Fork 2	10	0.25	10
6	Fork 2	Fork 3	10	0.35	0
7	Source 3	Fork 3	15	0.25	0
8	Fork 3	Fork 4	15	0.4	10
9	Fork 4	Sink 0	20	0.4	100
10	Fork 4	Sink 1	25	0.4	0

The capacity dependent investment costs are assumed to be 1 394 €/(km*(kg CO_2/s) with fix costs of 780 900 € [20].

RESULTS

The results show two very different findings for the Network Flow and Optimal Power Flow model.

Network Flow model

In the Network Flow model losses are not considered. Therefore, the investment decision is solely influenced by costs and depends on the installed capacity as well as length of the pipeline, what results in the network topology shown in Figure 5 .

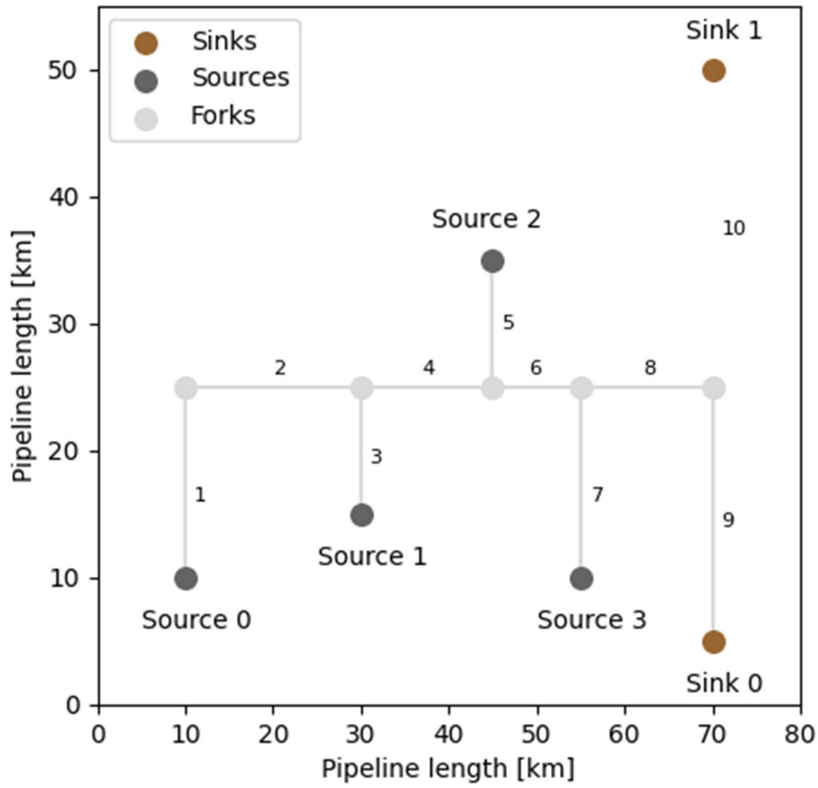

Figure 5: Resulting network topology for the Network Flow model

The invested capacities and resulting costs are shown in Table 3.

Table 3: Resulting costs and invested capacities for the Network Flow model

Pipe ID	From node	To node	Invested capacity [kg/s]	Costs [€]
1	Source 0	Fork 0	2	11 755 320
2	Fork 0	Fork 1	2	15 673 760
3	Source 1	Fork 1	2	7 836 880
4	Fork 1	Fork 2	4	11 797 140
5	Source 2	Fork 2	2	7 836 880
6	Fork 2	Fork 3	6	7 892 640
7	Source 3	Fork 3	2	11 755 320
8	Fork 3	Fork 4	8	11 880 780
9	Fork 4	Sink 0	8	15 841 040
10	Fork 4	Sink 1	0	0

Since Pipe 9 incurs lower costs due to its length, the investment decision in the Network Flow is to invest in Pipe 9.

Optimal Power Flow model

Compared to the Network Flow model the Optimal Power Flow model considers pressure losses along the pipe. Due to the elevation change between Node 9 and Node 11, Pipe 9 experiences a higher pressure loss compared to Pipe 10. Maximal pressure losses over the pipes, invested capacities and the resulting costs are given in Table 4.

Table 4: Resulting costs, invested capacities and pressure losses for maximal flow rates for the Optimal Power Flow model

Pipe ID	From node	To node	Δp_{max} [bar]	Invested capacity [kg/s]	Costs [€]
1	Source 0	Fork 0	0.830	2	11 755 320
2	Fork 0	Fork 1	0.018	2	15 673 760
3	Source 1	Fork 1	0.417	2	7 836 880
4	Fork 1	Fork 2	0.013	4	11 797 140
5	Source 2	Fork 2	0.826	2	7 836 880
6	Fork 2	Fork 3	0.013	6	7 892 640
7	Source 3	Fork 3	0.013	2	11 755 320
8	Fork 3	Fork 4	0.835	8	11 880 780
9	Fork 4	Sink 0	8.197	0	0
10	Fork 4	Sink 1	0.003	8	19 801 300

The resulting network topology of the modelled system is shown in Figure 6.

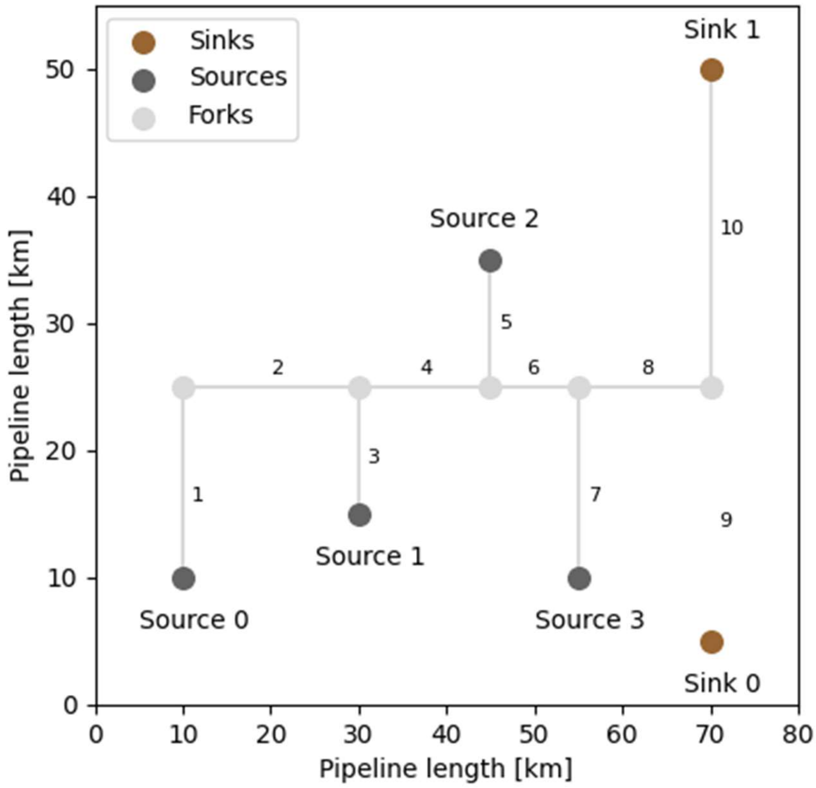

Figure 6: Resulting network topology for the Optimal Power Flow model

Because of the pressure loss from Pipe 9 the required pressure at the sink of 105 bar cannot be ensured. Consequently, the OPF model does not make an investment decision for Pipe 9, although Pipe 10 should be preferred due to its lower costs resulting from its shorter length.

DISCUSSION

The results highlight the importance of integrating physical constraints into CO_2 pipeline network optimization. The Network Flow model, which neglects pressure losses, suggests investing in Pipe 9 due to lower costs associated with its length. In contrast, the Optimal Power Flow model, which accounts for pressure losses, reveals that Pipe 9 cannot meet the required pressure at the sink, leading to a preference for Pipe 10 despite its higher costs. This discrepancy underscores the necessity of including detailed physical constraints in optimization models to ensure operational feasibility.

The case study illustrates that while Network Flow models offer a simplified approach with lower computational requirements, they may lead to suboptimal network designs while physical restrictions are not considered. Optimal Power flow models, though more complex, provide a more accurate representation of real-world conditions, including pressure losses and temperature effects, resulting in more reliable investment decisions. Future research should focus on refining Optimal Power Flow models to enhance their efficiency.

CONCLUSION

This study demonstrates the critical role of incorporating physical constraints into CO_2 pipeline network optimization. The comparison between Network Flow and Optimal Power Flow models reveals that while Network Flow models are useful for preliminary cost estimates, they may not capture essential operational constraints. The consideration of pressure and temperature effects of Optimal Power Flow models offers a more accurate assessment of network feasibility and investment decisions. For future CO_2 transport infrastructure development integrating detailed physical modeling into optimization processes is essential for designing cost-effective and operationally viable networks.

REFERENCES

[1] United Nations Framework Convention on Climate Change. Paris Agreement; 2016.

[2] Hochmeister S, Kühberger L, Kulich J, Ott H, Kienberger T. A methodology for the determination of future Carbon Management Strategies: A case study of Austria. IJSEPM 2024;41:108–24. https://doi.org/10.54337/ijsepm.8280.

[3] McKaskle R, Beitler C, Dombrowski K, Fisher K. The Engineer's Guide to CO2 Transportation Options. SSRN Journal 2022. https://doi.org/10.2139/ssrn.4278858.

[4] Lu H, Ma X, Huang K, Fu L, Azimi M. Carbon dioxide transport via pipelines: A systematic review. Journal of Cleaner Production 2020;266:121994. https://doi.org/10.1016/j.jclepro.2020.121994.

[5] Wang D, Zhang Y, Adu E, Yang J, Shen Q, Tian L et al. Influence of Dense Phase CO2 Pipeline Transportation Parameters. IJHT 2016;34(3):479–84. https://doi.org/10.18280/ijht.340318.

[6] Kriechbaum L, Gradl P, Reichenhauser R, Kienberger T. Modelling Grid Constraints in a Multi-Energy Municipal Energy System Using Cumulative Exergy Consumption Minimisation. Energies 2020;13(15):3900. https://doi.org/10.3390/en13153900.

[7] Frank S, Rebennack S. An introduction to optimal power flow: Theory, formulation, and examples. IIE Transactions 2016;48(12):1172–97. https://doi.org/10.1080/0740817X.2016.1189626.

[8] Morbee J, Serpa J, Tzimas E. Optimised deployment of a European CO2 transport network. International Journal of Greenhouse Gas Control 2012;7:48–61. https://doi.org/10.1016/j.ijggc.2011.11.011.

[9] Middleton RS, Yaw SP, Hoover BA, Ellett KM. SimCCS: An open-source tool for optimizing CO2 capture, transport, and storage infrastructure. Environmental Modelling & Software 2020;124:104560. https://doi.org/10.1016/j.envsoft.2019.104560.

[10] Knoope M, Ramírez A, Faaij A. The influence of uncertainty in the development of a CO2 infrastructure network. Applied Energy 2015;158:332–47. https://doi.org/10.1016/j.apenergy.2015.08.024.

[11] Optimal Clustered, Multi-modal CO2 Transport Considering Non-linear Costs - a Path-planning Approach. PSE Press; 2024.

[12] Rüdiger J. Enhancements of the numerical simulation algorithm for natural gas networks based on node potential analysis. IFAC-PapersOnLine 2020;53(2):13119–24. https://doi.org/10.1016/j.ifacol.2020.12.2282.

[13] Greiml M, Fritz F, Steinegger J, Schlömicher T, Wolf Williams N, Zaghi N et al. Modelling and Simulation/Optimization of Austria's National Multi-Energy System with a High Degree of Spatial and Temporal Resolution. Energies 2022;15(10):3581. https://doi.org/10.3390/en15103581.

[14] Kienberger T, Traupmann A, Sejkora C, Kriechbaum L, Greiml M, Böckl B. Modelling, designing and operation of grid-based multi-energy systems. 7-24 Pages / International Journal of Sustainable Energy Planning and Management, Vol. 29 (2020) 2020. https://doi.org/10.5278/IJSEPM.3598.

[15] Span R, Wagner W. A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100 K at Pressures up to 800 MPa. Journal of Physical and Chemical Reference Data 1996;25(6):1509–96. https://doi.org/10.1063/1.555991.

[16] Krien U, Schönfeldt P, Launer J, Hilpert S, Kaldemeyer C, Pleßmann G. oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems. Software Impacts 2020;6:100028. https://doi.org/10.1016/j.simpa.2020.100028.

[17] Pyomo-optimization modeling in python; 2017.

[18] Johannes Röder, jnnr, MaGering, rbv83, Joris Zimmermann, Uwe Krien et al. oemof/DHNx: Short update. Zenodo; 2023.
[19] Knoope M, Ramírez A, Faaij A. A state-of-the-art review of techno-economic models predicting the costs of CO2 pipeline transport. International Journal of Greenhouse Gas Control 2013;16:241–70. https://doi.org/10.1016/j.ijggc.2013.01.005.
[20] European Commission, Joint Research Centre, Drazen T, Uihlein A, Hidalgo González I. Shaping the future CO2 transport network for Europe. Publications Office of the European Union; 2024.