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Conceptual design of multi-source CCS pipeline transportation network for Polish energy sector

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Abstract. The aim of this study was to identify an optimal CCS transport infrastructure for Polish energy sector in regards of selected European Commission Energy Roadmap 2050 scenario. The work covers identification of the offshore storage site location, CO_2 pipeline network design and sizing for deployment at a national scale along with CAPEX analysis. It was conducted for the worst-case scenario, wherein the power plants operate under full-load conditions. The input data for the evaluation of CO_2 flow rates (flue gas composition) were taken from the selected cogeneration plant with the maximum electric capacity of 620 MW and the results were extrapolated from these data given the power outputs of the remaining units. A graph search algorithm was employed to estimate pipeline infrastructure costs to transport 95 MT of CO_2 annually, which amount to about 612.6 M€. Additional pipeline infrastructure costs will have to be incurred after 9 years of operation of the system due to limited storage site capacity. The results show that CAPEX estimates for CO_2 pipeline infrastructure cannot be relied on natural gas infrastructure data, since both systems exhibit differences in pipe wall thickness that affects material cost.

1 Introduction

The long-term warming of the climate system is mainly driven by CO_2 emissions, therefore the internationally agreed objective of limiting the increase in global average temperatures to well below 2°C above pre-industrial levels requires significant reductions in CO_2 emissions. In the context of necessary reductions by developed countries as a group, the European Union member states are committed to reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050 [1]. The reductions of greenhouse gas emissions will put particular pressure on energy systems, which need to be almost emission-free despite higher demand. The European Commission proposed several scenarios of energy system transformation for achieving its 2050 emissions target. In a low nuclear energy scenario, assuming that no new nuclear reactors are being built (besides reactors currently under construction), around 32% penetration of CCS in power generation has been predicted. In the case of industrial applications carbon capture and storage is expected to account even for half of the global emissions cuts required by 2050. Indeed, CCS is the only technology

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that can significantly reduce CO_2 emissions from coal- and gas-fired power plants as well as from energy intensive-industries.

Until recently research objectives on CCS transport were mostly focused on predicting the cost of pipeline transport [2], while route planning received relatively less attention. Chandel et al. [3] describe the economies of scale that can be achieved for CO_2 transport by collecting CO_2 emissions from multiple power plants into a trunkline that pipes the emissions to a single storage site. As the CO_2 flow rate that can be handled by a trunkline is increased, the levelized cost of transporting it declines exponentially. They conclude that low transportation costs over long distances open up the possibility for developing CCS systems that connect CO_2 sources to far away storage sites where storage costs are relatively low. Weiths and Wiley [4] employ genetic algorithm for designing the spanning tree type CCS network. Optimal CCS network transporting CO_2 from each source to at least one sink should not have loops, since recirculation would increase the pumping power required by the network, unless there is the advantage due to redundancy in parallel configuration of the pipelines. Different transport and storage options resulting in different network topology were discussed in the study of offshore CO_2 transportation cases for South Korea by Zahid et al. [5] and Jung et al. [6]. CO_2 transport options from coal-fired power plant to offshore storage sites near Japan‘s coastline, including liquefied CO_2 by ship, CO_2 hydrate by ship and pipeline, were studied by Suzuki et al. [7]. In the study by Jain et al. [8] greedy algorithm was used to calculate the optimal distance between the source and the sink for CCS infrastructure in eastern India. It was assumed that future pipelines for transportation of CO_2 would be built along the railway network. Least cost optimisation model of an integrated CO_2 capture, transportation and storage infrastructure for the UK over four time periods up to year 2050 was presented in the study by Elahi et al. [9]. The physical characteristics of a potential pipeline network for CO_2 transportation in the Humber Region in the UK area have been discussed by Luo et al. [10]. Hetland et al. [11] present the status of the large European CCS demonstration projects with particular emphasis on transport systems development. The costs of 15 transport scenarios involving the use of 3 pipelines and 5 offshore storage sites in Guangdong province, China were evaluated by Bai et al. [12]. It has been concluded that cost assessment methodology during the design-price evaluation should integrate local prices. Some key design issues that must be considered for the development of large scale CO_2 transportation network are reviewed in the study by Han et al. [13]. They conclude that to ensure the safe and cost-effective transportation, the concentrations of impurities in CO_2 stream should be restricted in an appropriate range. Similar conclusions were drawn in the studies by Chaczykowski and Osiadacz [14] and Wetenhall et al. [15], where the effect of impurities on pumping power and transport costs was observed, regardless of the assumed network structure and geometry.

The main objective of this study is to identify an optimal group selection of power plants, which contribute 32% to national power generation capacity for achieving European Commission 2050 emissions target. The optimal selection of power plants has been made based on a tree branched pipeline network design and a capital expenditures analysis for each unit. The design-price evaluation integrates local prices. Finally, the comparison to the current natural gas infrastructure capital expenditures is made.

2 Basic assumptions and input data

CO_2 streams for power plants have been calculated based on the analysis carried out for “Siekierki” power plant, located in Warsaw, whose flue gas composition was obtained from plant operator. A basic post combustion installation based on MEA absorption process was assumed and with the use of process simulator, taking the overall efficiency of

90%, the flow rate of 951 m^3/h of captured CO_2 was predicted. The volume stream from the above plant was considered as a reference case, by looking at we have extrapolated the numbers for the other power plants. The results are presented in table 2.1

The operating pressure range of the pipeline infrastructure was set to (8–15) MPa in order to maintain the post combustion CO_2-rich mixture in supercritical phase. As a result the pipeline wall thickness for the whole network was chosen equal to 25 mm. X70 steel has been selected for pipe material with the density of 7850 kg/m^3.

Material costs are calculated based on pipeline mass [16], with the assumption of unit price of 1000 € per 1 tonne of X70 steel. These costs were assumed to represent 30% of total costs including assembly works.

2.1 Power plants in Polish energy sector

The basic parameters of major fossil fuel based power plants in Polish energy sector are presented in Table 2.1. Predicted CO_2 streams are extrapolated values based upon the reference case calculations for the Siekierki power plant input data.

Table 2.1. Technical data of power plants.

No.	Power plant	Fuel	Power MW	CO_2 stream m^3/h	Latitude	Longitude
1	Rogowiec	Lignite	5 298	8 127	51°16'36"N	19°18'11"E
2	Kozienice	Black coal	2 820	4 326	51°35'08"N	21°33'04"E
3	N. Czarnowo	Black coal	1 984	3 044	53°11'42"N	14°29'06"E
4	Połaniec	Black coal, Biomass	1 811	2 778	50°25'57"N	21°16'50"E
5	Rybnik	Black coal	1 775	2 723	50°05'55"N	18°32'42"E
6	Jaworzno	Black coal, Biomass	1 535	2 355	50°12'16"N	19°16'12"E
7	Bogatynia	Lignite	1 499	2 300	50°54'27"N	14°57'14"E
8	Brzezie	Black coal	1 492	2 289	50°45'39"N	17°52'30"E
9	Pątnów	Lignite	1 200	1 841	52°18'27"N	18°15'29"E
10	Łaziska Górne	Black coal	1 155	1 772	50°09'17"N	18°50'37"E
11	Będzin	Black coal	820	1 258	50°19'26"N	19°07'45"E
12	Trzebinia	Black coal	666	1 022	50°09'35"N	19°28'14"E
13	Ostrołęka	Black coal, Biomass	647	993	53°04'58"N	21°34'21"E
14	Warszawa	Black coal, Biomass	620	951	52°13'56"N	21°00'30"E
15	Pątnów	Lignite	474	727	52°18'27"N	18°15'29"E
16	Skawina	Black coal, Biomass	440	675	49°58'30"N	19°49'42"E
17	Stalowa Wola	Black coal	330	506	50°34'34"N	22°03'40"E
18	Konin	Lignite	198	304	52°13'39"N	18°15'41"E

2.2 Identification of storage site

The selected geological structure is located in northwest area of the Baltic Sea. Based on the Polish Geological Institute report [17], there are four wells in the sea that satisfy the CO_2 storage criteria with total capacity of 0.9 Gt. Storage depth of the structure is 800–2800 m and its porosity is higher than 9%.

3 CO_2 transmission system design

It has been assumed that pipeline system would be used to transport dense-phase, CO_2-rich mixtures from capture plants to the offshore storage site. Pipeline transportation has the

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advantages of being cost-effective and readily expandable. The CO_2 pipe network, except from pipeline interconnector to the storage site, consists of tree branches running parallel to the existing natural gas transmission system infrastructure. The advantages arising from such arrangement are threefold:

1. The existing natural gas pipeline safe separation distances, i.e. the distances at which natural gas pipelines can be safely sited near a community, could be considered as beneficial in terms of CO_2 pipeline risk analysis. These distances are defined in terms of the distances needed to protect against a specified heat flux from the fire. There have been limited studies to date concerning the determination of safety separation distances for CO_2 pipelines. Mahgerefteh et al. [18] performed the modelling of product loss during a pipeline rupture, which is an important factor related to the establishment of a safe separation distance therefrom. Comparison of CO_2 outflow data with those for the rupture of the same pipeline containing natural gas indicates a significantly greater amount of CO_2 released.
2. The pumps installed in booster stations along the pipelines to compensate for the pressure losses and elevation changes and to ensure a required flow of CO_2 would be able to be driven by gas turbines fuelled with natural gas, which would not require significant additional investments in gas pipeline or electricity infrastructure.
3. Linear infrastructure investment projects, such as roads, railway lines, telecommunication lines, electric power lines and pipelines for transmission of gas and petroleum products have a negative ecological effects in terrestrial and aquatic ecosystems. It is clear that the impacts associated with the use of existing infrastructure corridor would be quite different compared to those posed by newly built infrastructure.

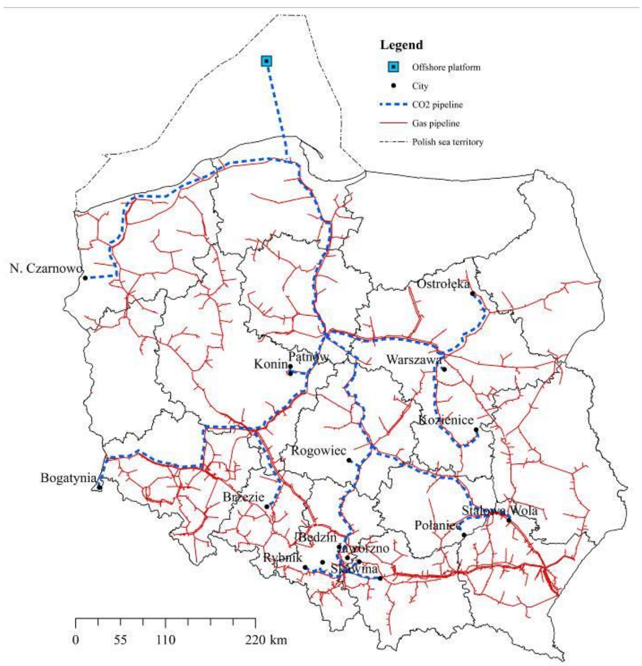

Fig. 3.1. Optimal infrastructure design including all power plants.

The capital cost of a pipeline project is largely a function of its diameter and length, although other factors, such as operating pressure, and various risk factors, are also significant. One of the challenging problems in pipeline infrastructure design calculations is the shortest path problem minimizing transport costs. Shortest path programming is a well-established subject in mathematics and computer science. Dijkstra's algorithm solves the single-source shortest-path problem on directed graph with a nonnegative edge weights. This algorithm was used as a subroutine in this work. However, Dijkstra's algorithm fails to form a tree that includes every specific vertex. Furthermore, optimal CO_2 pipeline infrastructure parallel to the natural gas transmission system do not necessarily should have shortest paths to the storage site due to the overlapped paths that could be used as trunk lines with reduced pipe material coverage. In fact, the priority level of this requirement can be very high as in the case of data transmission applications [19]. In this study we propose the following algorithmic approach to the preliminary design of CO_2 transmission system infrastructure running parallel to an existing natural gas pipeline infrastructure:

1. Determine shortest paths along existing natural gas pipelines from power plants to storage site and mark all power plants as unexamined.
2. Set the unexamined plant with the longest path as current plant, mark it as examined and save its value in a matrix of distances.
3. Find the first/next unexamined plant to the current plant by shortest path routing.
4. Shortest path from the unexamined plant to the storage site forms a subtree of the currently registered tree in a matrix of distances? Yes: Set it as current plant, mark examined and fulfil its value in a distance matrix; No: Mark the plant as examined and go to pt. 3
5. Are all the plants examined? Yes: Go to pt. 6., No: Go to pt. 3.
6. Matrix of distances completed? Yes: End; No: Mark all power plants with missing routes as unexamined and go to pt. 2. to continue with the new start point.

The results of optimal infrastructure design calculations for all power plants based on the above procedure are presented in Fig. 3.1. Given the topology of the network, appropriate diameter sizing calculations were performed using the steady state pipeline flow model from [20] with maximum flow velocity criterion of 20 m/s. The results are shown in Table 3.1 in the form of the corresponding flow weighted unit costs of the CO_2 transport infrastructure for each power plant. The total transportation distance and total CAPEX for this case scenario were 2544 km and 2 167.8 M€, respectively.

Table 3.1. Transport infrastructure CAPEX for individual power plants.

Power Plant	Total cost (M€)	Flow weighted unit cost EUR/(m^3/h)
Będzin	59.3	45 615
Bogatynia	230.4	100 193
Brzezie	149.9	65 514
Jaworzno	116.2	45 615
Konin	9.6	31 701
Kozienice	274.4	63 434
Łaziska Górne	103.2	45 615
N. Czarnowo	232.9	76 508
Ostrołęka	82.6	83 247
Pątnów I Pątnów II	78.6	30 578
Połaniec	207.5	74 679
Rogowiec	277.0	34 091
Rybnik	158.9	45 615
Skawina	45.6	45 615
Stalowa Wola	40.0	79 195
Trzebinia	59.1	45 615
Warszawa	42.3	44 489

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4 Optimal CO_2 transportation network for selected 2050 EC roadmap scenario

Mechleri et al. [21] presented an approach for the optimal design of CO_2 transport pipeline. They demonstrate that where CCS plants are deployed in an energy system characterised by high share of intermittent renewable energy, the resulting displacement of CCS power plant generation by renewable energy generation leads to a decade-on-decade declining flow of CO_2 through the transport infrastructure. This means that the right-sizing of CO_2 transport infrastructure requires the assumption of a reduced penetration of CCS in power generation without compromising the ability to accommodate future capacity. Therefore, the realistic scenarios should assume reduced penetration of CCS in power generation sector. In this study 32% penetration of CCS in power generation as predicted in [1] is considered.

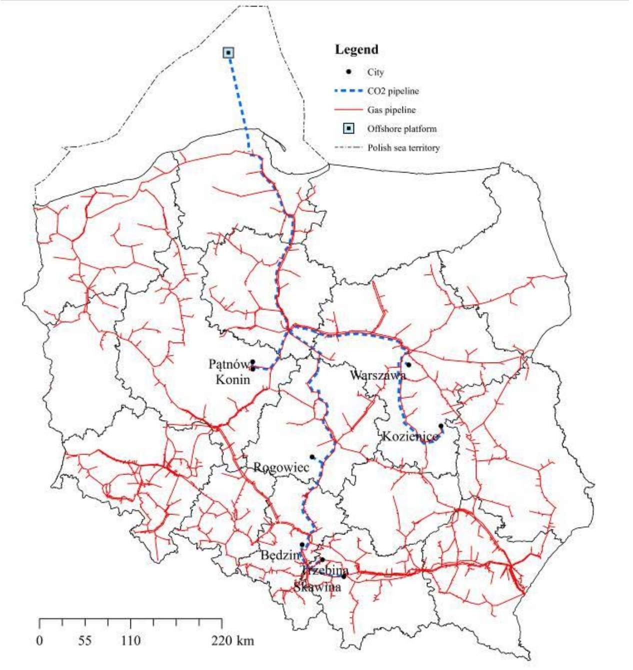

Fig. 4.1. Optimal CO_2 transport route regarding infrastructure CAPEX.

The selection of CO_2 sources was made by taking into account the flow weighted unit cost of transport infrastructure (per m^3/h) required for each power plant. Power plants with high costs were discarded and the choice was made among the ones with low values, having in mind that total power output of the selected units should contribute towards 32% in total national power generation capacity. Infrastructure design procedure described above was again employed for this scenario followed by diameter sizing calculations resulting in technical specification of the infrastructure as presented in Tables 4.1 and 4.2.

Annual amount of transported CO_2 is 168 460 305 m^3 which is 95 MT. Storage site capacity is ~900 MT [17] which gives for this case scenario 9 years of operational time under full load conditions of power plants. Total CAPEX is 612.6 M€.

Table 4.1. Infrastructure costs for specific branches.

Main branch					
Power Plant No.	**CO_2 stream (m^3/h)**	**Length (km)**	**DN**	**Pipeline cost (M€)**	**Cost incl. assembly works (M€)**
(16+12+11+1)+(9+15+18)+(2+14)	19 231	252	650	98.7	328.9
Skawina - Rogowiec branch					
16	675	41	150	3.6	12.1
12	1 022	21	200	2.5	8.4
12+16	1 697	2	250	0.3	1.0
11	1 258	5	200	0.6	2.0
16+12+11	2 955	130	300	24.0	79.9
1	8 127	15	450	4.0	13.3
16+12+11+1	11 082	31	500	9.2	30.8
Pątnów - Konin branch					
9+15	2 568	9	250	1.4	4.6
18	304	3	150	0.3	0.9
9+15+18	2 872	19	300	3.5	11.7
Kozienice - Ostrołęka branch					
2	4 326	150	350	30.6	101.9
14	951	11	200	1.3	4.4
2+14	5 277	19	350	3.9	12.9

Table 4.2. Power plants individual CAPEX.

Power Plant	Total cost (M€)	Flow weighted unit cost EUR/(m^3/h)
Rogowiec	174.9	4 415
Kozienice	186.5	26 005
Pątnów	58.9	5 850
Warszawa	23.0	7 060
Konin	7.3	6 973
Będzin	61.0	31 390
Trzebinia	56.9	38 605
Skawina	44.1	48 295

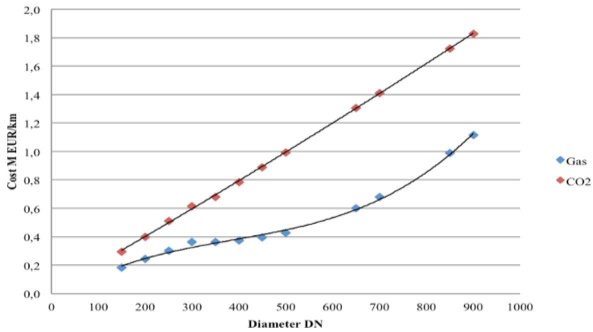

Fig. 4.1. Comparison between natural gas and CO_2 pipeline costs incl. assembly works.

The estimation of CO_2 pipeline infrastructure cost cannot be achieved based on natural gas infrastructure data. The difference lays in maximum operating pressure (MOP) of the pipelines, which in turn determine the pipe wall thickness. The CO_2 networks will be operated under much higher MOP compared to onshore natural gas networks currently operated by Polish transmission system operator, which leads to an increased material cost due to greater pipe wall thickness. These differences in costs are presented in Figure 4.1

5 Summary

The operational time for selected geological structure is too short to consider it as a long-term delivery storage site despite fulfilling physical criteria for CO_2 storage. In order to accommodate future capacity additional onshore storage locations, or preferably supra-national scale offshore transport network as proposed in [22], should be considered. Future, detailed calculations of the pipeline options should be on a GIS platform with the help of 3D spatial analysis and consideration of terrain factors, and should also include the costs of compression facilities.

References

1. European Commission. *Energy Roadmap 2050* (2011)
2. M.M.J. Knoope, A. Ramírez, A.P.C. Faaij, Int. J. Green. Gas Cont. **16**, 241–70 (2013)
3. M.K. Chandel, L.F. Pratson, E. Williams, Energy Convers. Manage. **51**, 12, 2825–34 (2010)
4. G.F. Weihs, D.E. Wiley, Int. J. Green. Gas Cont. **8**, 150–168 (2012)
5. U. Zahid, U. Lee, J. An, Y. Lim, C. Han, Environ. Prog. Sust. Energy **33**, 978–92 (2014)
6. J.Y. Jung, C. Huh, S.G. Kang, Y. Seo, D. Chang, Appl. Energy **111**, 1054–60 (2013)
7. T. Suzuki, M. Toriumi, T. Sakemi, N. Masui, S. Yano, H. Fujita, H. Furukawa, Energy Proced. **37**, 2989–2996 (2013)
8. P. Jain, K. Pathak, S. Tripathy, Energy Proced. **37**, 3233–3241 (2013)
9. N. Elahi, N. Shah, A. Korre, S. Durucan, Energy Proced. **63**, 2655–62 (2014)
10. X. Luo, M. Wang, E. Oko, C. Okezue, Appl. Energy **132**, 610–20 (2014)
11. J. Hetland, J. Barnett, A. Read, J. Zapatero, J. Veltin, Energy Proced. **63**, 2458–66 (2014)
12. B. Bai, X. Li, Y. Yuan, D. Zhou, P. Li, Acta Geotech. **9**, 1, 115–26 (2014)
13. C. Han, U. Zahid, J. An, K. Kim, C. Kim, Curr. Opin. Chem. Eng. **10**, 42–8 (2015)
14. M. Chaczykowski, A.J. Osiadacz, Int. J. Green. Gas Cont. **9**, 446–56 (2012)
15. B. Wetenhall, J.M. Race, M.J. Downie, Int. J. Green. Gas Cont. **30**, 197–211 (2014)
16. M. Witek, J. Nat. Gas Sci. Eng. **27**, 374–84 (2015)
17. Polish Geological Institute. *Assessment of Formations and Structures Suitable for Safe CO_2 Geological Storage Including the Monitoring Plans. Final report.* (2013) (in Polish)
18. H. Mahgerefteh, G. Denton, Y. Rykov, Institution of Chemical Engineers Symposium Series **154**, 869 (2008)
19. A. Ghasemkhani, A. Anvari-Moghaddam, J.M. Guerrero, B. Bak-Jensen, *Proceedings of IEEE PES Innovative Smart Grid Technologies* (ISGT, 2016)
20. M. Chaczykowski, A.J. Osiadacz, Arch. Min. Sci. **57**, 1, 23–38 (2012)
21. E. Mechleri, S. Brown, P.S. Fennell, N. Mac Dowell, Chem. Eng. Res. Des. **119**, 130–9 (2017)
22. R.J. Stewart, V. Scott, R.S. Haszeldine, D. Ainger, S. Argent, Gren. Gases: Sci. Technol. **4**, 4, 481–94 (2014)