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Exploring Tradeoffs in Merged Pipeline Infrastructure for Carbon Dioxide Integration Networks

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Abstract: Carbon integration aims to identify appropriate CO_2 capture, allocation, and utilization options, given a number of emission sources and sinks. Numerous CO_2-using processes capture and convert emitted CO_2 streams into more useful forms. The transportation of captured CO_2, which poses a major design challenge, especially across short distances. This paper investigates new CO_2 transportation design aspects by introducing pipeline merging techniques into carbon integration network design. For this, several tradeoffs, mainly between compression and pipeline costs, for merged pipeline infrastructure scenarios have been studied. A modified model is introduced and applied in this work. It is found that savings on pipeline costs are greatly affected by compression/pumping levels. A case study using two different pipe merging techniques was applied and tested. Backward branching was reported to yield more cost savings in the resulting carbon network infrastructure. Moreover, both the source and sink pressures were found to greatly impact the overall cost of the carbon integration network attained via merged infrastructure. It was found that compression costs consistently decreased with increasing source pressure, unlike the pumping and pipeline costs.

Keywords: carbon dioxide; transportation; pipeline; merging; CCUS

1. Introduction

Increased climate change concerns have resulted in various efforts that aim towards mitigating CO_2 emission footprints. This has created pressure on the industrial sector to reduce emissions, especially since stationary industrial sources account for the majority of global emissions. Multiple methods to reduce CO_2 emission have been proposed, which include carbon capture utilization and storage (CCUS), fuel reduction, or fuel switching, including the use of renewable energy. Since carbon dioxide (CO_2) is a primary constituent of greenhouse gases (GHG) emissions, converting CO_2 into valuable products has been the main subject of many recent studies. Various utilization routes exist due to the versatile nature of CO_2; it becomes quite a challenge to identify the most viable option to consider [1]. Given that industrial emission sources can both be from energy use or as a product from processing activity, deployment of carbon capture sequestration and utilization infrastructure reduction schemes can be effective [2]. Many works have been published on carbon capture, Leung et al. [3] conducted a review that examines CO_2 capture and storage decisions that can meet a prescribed emission reduction target. Absorption processes were reported as the most utilized option, due to their relatively low cost and high efficiency. Shahbazi and Nasab [4] also investigated various carbon capture and storage (CCS) technologies that were reported to induce a noticeable decrease in the greenhouse gas emissions. Many CCS techniques were reported to be highly effective in serving to decarbonize the energy sector, particularly in countries that highly depend on fossil fuels for electricity production [4]. Having an efficient transportation scheme as part of the (CCUS) infrastructure is vital to ensure optimized sequestration and CO_2 utilization [5]. This paper presents a novel approach to reduce CCUS transportation cost in industrial clusters through pipeline merging.

CO_2 utilization can take several forms: (1) non-conversion methods, and (2) conversion of CO_2 into value-added products. Examples of non-conversion methods include applications such as enhanced oil recovery (EOR) [6] and other similar applications that involve utilizing CO_2 within a process in its original chemical form. On the other hand, attempts for converting CO_2 into other value-added chemicals are classified as CO_2 conversion. For instance, CO_2 can be used as a weak acid or even as an oxidizing agent and can be reduced electrochemically, photochemically, or even chemically. CO_2 may also react with many different chemicals from hydrocarbons to nitrogen-containing compounds [7]. Various CO_2 conversion routes assessment through economic and/or environmental criteria have been studied. Xiaoding and Moulijn [7] discussed the various possibilities for CO_2 use in chemical applications and presented a very thorough literature analysis for CO_2 utilization opportunities in an attempt to reduce GHG emissions. Kongpanna et al. [8] assessed several chemical processes for the production of dimethyl carbonate (DMC) based their respective CO_2 utilization, in addition to carrying out a techno-economic evaluation for each route. In their work, four different CO_2 conversion pathways were investigated: (1) direct synthesis from CO_2 and methanol, (2) synthesis from urea, (3) synthesis from propylene carbonate, and (4) synthesis from ethylene carbonate [8]. The use of toxic chemicals such as phosgene, carbon monoxide (CO), and nitric oxide (NO), which are usually present in conventional DMC production processes, was completely avoided. Dimitriou et al. [9] studied the large-scale conversion of different process designs involving the conversion of CO_2 into liquid hydrocarbon fuels, using a biogas as a CO_2 source. In order to establish whether the production of hydrocarbon fuels from such commercially proven technologies is economically viable or not, their main objective was to estimate fuel production yields, and the costs of different CCU process configurations in terms of raw materials, and utility requirements. Milani et al. [10] developed a comprehensive model for CO_2 reuse in methanol synthesis, using methane fuel, in which the syngas is mixed with high-purity CO_2 produced by the power-plant capture unit. The process achieved 25.6% reduction in methane uptake in addition to a 21.9% CO_2 emission reduction. In subsequent work, Luu et al. [11] further studied CO_2 utilization opportunities in methanol synthesis. Dutta et al. [12] presented a CO_2 neutral framework for producing chemicals and electricity in an integrated manner, and quantitatively estimated the global impact of carbon dioxide utilization. Pan et al. [13] provided a very useful review that summarized the key the principles and applications of CO_2 conversion, as well as any associated environmental benefits. Their overall aim was to identify effective CO_2 reduction techniques while minimizing social and economic costs.

More recently, CO_2 integration technique, which falls under CCUS, have been introduced as an effective method that can identify low-cost carbon dioxide emission reduction schemes as a source-sink connectivity problem involving multiple CO_2 sources and sinks [14]. CO_2 integration mainly targets the recovery of CO_2 streams and assesses the allocation of those recovered streams into CO_2-using sinks, with an overall aim of attaining a minimum cost for CO_2 networks [14,15]. Meeting emission targets often introduces numerous challenges, especially when energy-intensive processes are involved. The best CO_2 network design is quite challenging to identify, especially when many sources and sink options are available. Moreover, a systematic framework that assesses all CO_2 allocation options is of great importance since it helps identify which alternatives are superior in terms of cost-efficiency.

Despite all the above contributions in this field, and their eminent importance, very few works have focused on the assessment of appropriate infrastructure enhancement opportunities in such settings, to enable improved transportation efficiency of CO_2. So far, CCUS transportation infrastructure framework usually consists of pipelines, in addition to compressors and booster pumps. Okezue and Kuvshinov [16] introduced a tool that assists in the selection and sizing of centrifugal compressors and booster pumps to be installed on a supercritical carbon dioxide transport pipeline. A quasi-dimensional model that studies the effect of various impurities on the performance of a centrifugal machine handling supercritical CO_2 of varying purity was introduced in this regard. Peletiri et al. [17] investigated the impact of the presence of impurities on pipeline performance using binary mixtures. Each binary fluid was studied at the maximum allowable concentration, and deviations from pure CO_2 at the same conditions were determined. These deviations were graded to rank the impurities in order of the degree of impact on each parameter. Liu and Gallagher [18] investigated cost-efficient solutions for the transportation of CO_2 in China. While growing efforts in China are underway to understand CO_2 capture and storage, comparatively less attention has been paid to CO_2 transportation issues, as no publicly available China-specific cost models for CO_2 pipeline transportation are available. Hence, a first-order estimate of China's cost of onshore CO_2 pipeline transportation was provided by Liu and Gallagher [18]. For this, an engineering–economic model based on China-specific data and codes was provided in their study. This included a sensitivity analysis in order to examine the effect of pipeline length and soil temperature on pipeline diameter onto the cost of such systems. Mack and Endemann [19] focused on investigating the legal and policy issues surrounding sequestration infrastructure, mainly CO_2 pipelines that will carry CO_2 from where it is removed from fuel or waste gas streams to sequestration sites. Ultimately, Mack and Endemann [19] recommended developing a federally regulated CO_2 pipeline program to foster the implementation of efficient carbon sequestration technologies. Guo [20] combined CO_2 supply of carbon capture and storage (CCS) with CO_2 injection rates to increase the net economic profit using a systematic optimization approach. The work utilized a special type of network structure and simultaneously addressed the optimal location of the potential hubs [20]. The proposed framework was applied to four different instances of the CCS and EOR network design combined with hub location selections.

Previous work focused on matching CO_2 sources with geological sequestration or utilization such as EOR. It explored CO_2 transportation over large distances in CCS/CCUS networks. This leaves a clear gap in CCUS pipeline network design in industrial clusters. Therefore, this study focuses on simultaneously assessing the added benefits of allowing merged pipeline infrastructures for the transportation and allocation of captured CO_2 streams into CO_2 using sinks, within industrial clusters. This approach provides the first assessment of simultaneous carbon integration and pipeline network optimization in close-range clusters. It is enabled by the systematic carbon integration technique that treats, compresses, transports, and utilizes CO_2 into value-added products. This capability gives a comprehensive evaluation of CCUS implementation costs. Pipeline merging methodology has been previously introduced for the design of interplant water networks [21]. The incorporation of such aspects into CO_2 network design has not been attempted before and was inspired by Alnouri et al. [21] since the pipeline merging concept itself is independent of the type of fluid flow involved. The various merging techniques that have been previously introduced simply describe how the pipe segments can be assembled to form a merged pipe, and the different techniques through which a merged pipe may connect sources to sinks. Moreover, since there has been very little research effort that is aimed towards addressing and improving CO_2 transportation across short distances, within industrial clusters, this paper helps demonstrate the sensitivity of carbon integration networks towards various elements that are inevitably important factors that enable cost-effective carbon dioxide transportation, via utilizing the novel pipeline merging techniques for assembling CO_2 networks. The next section outlines the new CCUS pipeline merging method, followed by case study results and discussion.

2. Materials and Methods

In industrial clusters, many sources and possible sinks of CO_2 exist. CO_2 sources are CO_2-emitting streams within an industrial process or a plant with a given CO_2 purity, pressure, temperature, and known location. CO_2 sinks are CO_2 utilization industrial processes, which can convert or sequester CO_2 at a given purity, pressure, temperature, and have a given location [14]. A single pipe allocation is often used to establish connectivity between any sources to any sink within a network. Figure 1 shows the network superstructure and illustrates a typical connection of CO_2 exchange from source to sink. The connection involves treatment, where CO_2 separation takes place, which is located at the source, compression through a compressor, and/or pumping to deliver to the sink. However, the notion of pipeline merging involves the utilization of common pipe infrastructure to transport material from source-to-sink locations. This is done via common segments that can be assembled together in shared regions, in order to eliminate the use of single pipeline connectivity that establish one on one source-to-sink allocations. Single connections and pipeline merging designs are shown in Figure 2. Pipeline merging greatly eliminates the unnecessary use of parallel pipelines that transport similar materials under similar conditions to and from common locations. It can be observed from the literature that both compression and pumping activities are vital for conditioning the CO_2 into an acceptable form that is safe to transport. Usually, critical or supercritical conditions may be favored for the transportation of CO_2 over large distances. Thus, compressed, treated pure CO_2 is included in this work.

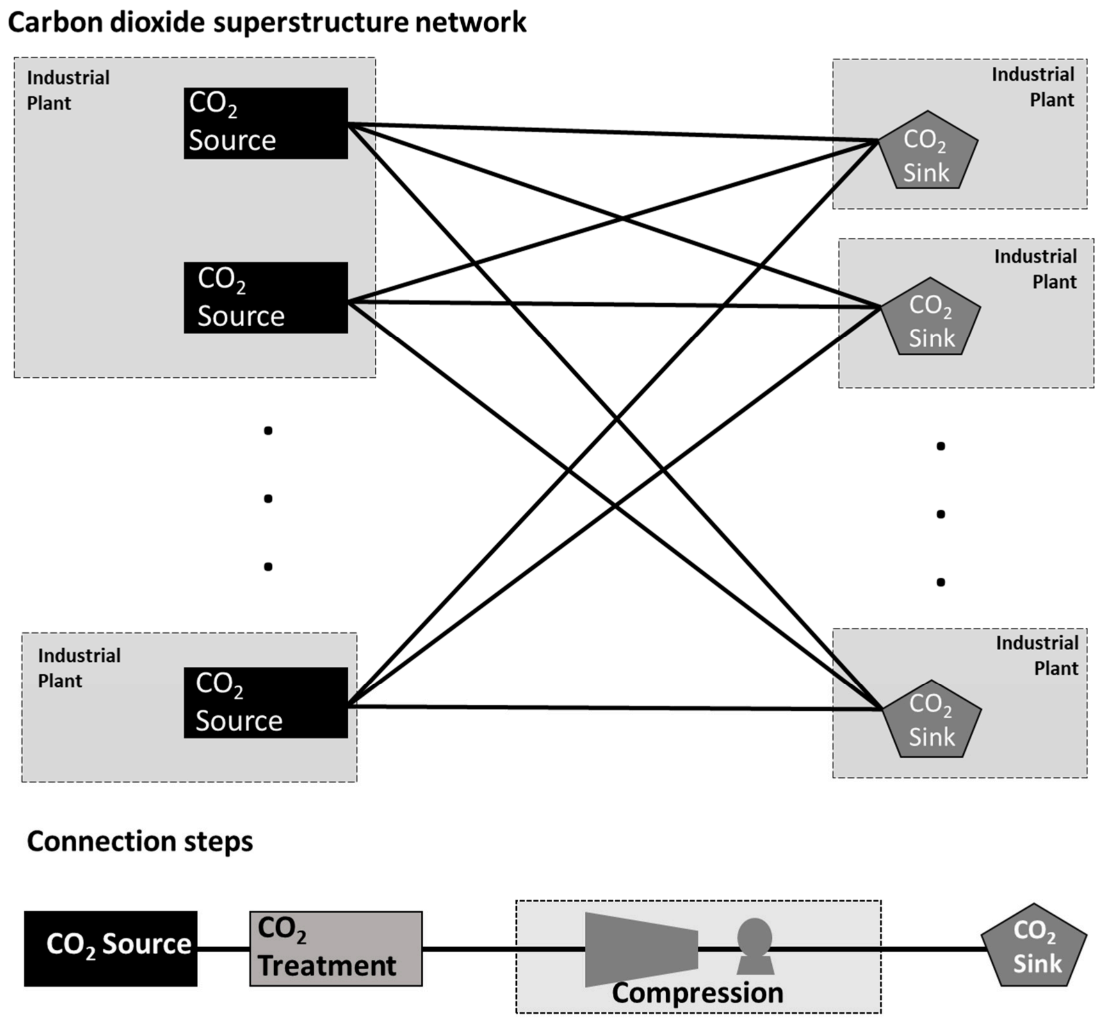

Figure 1. A CO_2 integration network within an industrial city [14].

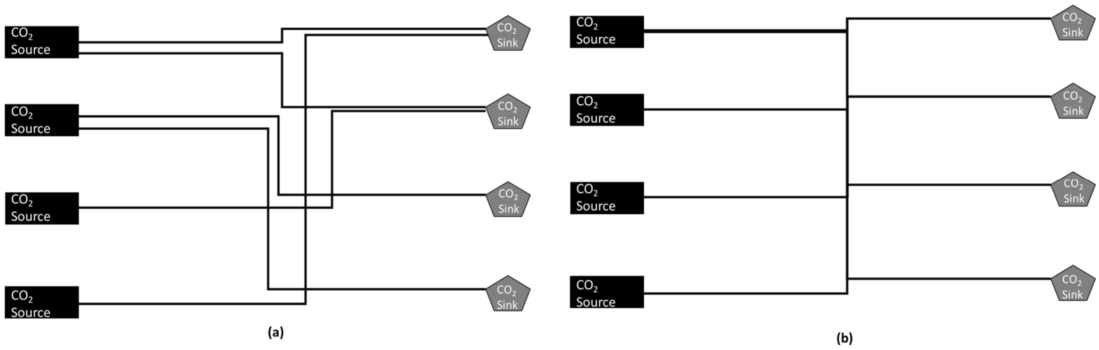

Figure 2. Illustration of (**a**) unmerged pipeline connectivity, (**b**) merged pipeline connectivity.

It should be noted that compression usually consumes most of the required energy input when compared to pumping requirements. Moreover, booster pumps are only needed when it is desired to go beyond the critical conditions for CO_2. Hence, most of the cost expenditures for a standard pipeline that is designed to transport CO_2 transport would entail the operating expenditures associated with any compressors and pumps in the system. In order to assess the long-term economic feasibility of effectively running CO_2 pipeline networks, the operating costs must be correlated to the energy consumption of both types of pressure changing equipment, and ideally, should be kept to a minimum whenever possible. Given the number of connections possible of similar CO_2 qualities (pressure and composition), introducing pipeline merging into the picture would certainly allow additional cost savings to be attained in CO_2 networks. Pipeline merging can reduce the overall capital expenditures on the pipelines, in addition to other associated costs. Thus, in addition to CO_2 allocation, pipeline installment is optimized as outlined in Section 2.1.

2.1. Mathematical Model

Pipeline merging modeling equations were obtained from the previous work [21]. The model involve the application of different merging techniques and are independent of the nature of the fluid being transported. The rest of the model has then been modified to accommodate the transportation of CO_2 in the context of interplant networks.

Hence, the objective function that was previously utilized by Alnouri et al. [21] for merged water networks, has been replaced by Equation (1) below, which aims to minimize the total cost of the carbon network as follows:

$$\text{Min. } C^{comp,\ TOTAL} + C^{pump,\ TOTAL} + C^{pipe} \tag{1}$$

where $\left(C^{comp,\ TOTAL}\right)$ represents the total compression costs for the network, $\left(C^{pump,\ TOTAL}\right)$ represents the total pumping costs for the network, and $\left(C^{pipe}\right)$ represents the total pipeline costs for the network. Each of the cost items above has been computed using Equations (2)–(9), which have been adopted from Al-Mohannadi and Linke [14] and are summarized in below.

The overall cost of compression and pumping are given below

$$C^{comp,\ TOTAL}\left(\frac{\$}{y}\right) = C^{comp,\ CAPEX}\left(\frac{\$}{y}\right) + C^{comp,\ OPEX}\left(\frac{\$}{y}\right) \tag{2}$$

$$C^{pump,\ TOTAL}\left(\frac{\$}{y}\right) = C^{pump,\ CAPEX}\left(\frac{\$}{y}\right) + C^{pump,\ OPEX}\left(\frac{\$}{y}\right) \tag{3}$$

The annualized capital cost of compressor and pump are given by Equations (4) and (5).

$$C^{comp,\ CAPEX}\left(\frac{\$}{y}\right) = 158,902 \times \left(\left(\frac{P^{comp}(F)}{224}\right)CRF\right)^{0.84} \tag{4}$$

$$C^{pump,CAPEX}\left(\frac{\$}{y}\right) = \left(1.11 \times 10^{6}\frac{P^{pump}(F)}{1000} + 0.07 \times 10^{6}\right) \times CRF \quad (5)$$

The operating costs of the compressor and the pump are shown in Equations (6) and (7)

$$C^{comp,\ OPEX}\left(\frac{\$}{y}\right) = P^{comp}(F) \times Elec.\left(\frac{\$}{KWh}\right) \times 365\left(\frac{days}{year}\right) \times 24\,h \quad (6)$$

$$C^{pump,OPEX}\left(\frac{\$}{y}\right) = 0.8 \times P^{pump}(F) \times Elec.\left(\frac{\$}{KWh}\right) \times 8760 \quad (7)$$

The cost of piping and pipe segments diameter are shown Equations (8) and (9) respectively,

$$C^{pipe}\left(\frac{\$}{y}\right) = [95,230(D^{c}) + 96,904] \times L \times CRF \quad (8)$$

$$D = \sqrt{\left(\frac{4}{\pi}\right)\frac{8.314T}{vm_{s}\left[\Delta P + \Delta P^{pipe}\right]}} \quad (9)$$

In the equations above, ΔP is the pressure difference in pipe segment, ΔP^{pipe} is the pressure drop parameter associated with pipe segment, and *Elec* is the electricity price in \$/kWh. D is the diameter of pipe, v is the outlet velocity of source s to sink k, m is the molecular mass of carbon dioxide, and CRF is the capital recover factor. F is the CO_2 volumetric flowrate in pipe, T is the temperature of carbon dioxide source, and L is the length of pipe segment. C^{Pipe} is the cost parameter of the pipe segment, P^{comp} is the power parameter for the compressor, $C^{comp,CAPEX}$ is the capital cost of compression, $C^{comp,\ OPEX}$ is the operating cost of compression, $C^{pump,CAPEX}$ is the capital cost of pumping, and $C^{pump,\ OPEX}$ is the operating cost of pumping. The rest of the formulation that has been adopted from Alnouri et al. [21], namely equations (10)–(51), describe how the various pipeline merging techniques can be applied. The formulation have been kept the same and can be found in their article [21]. This non-linear problem was implemented using "What's Best 10.0" LINDO Global Solver for Microsoft Excel via a laptop with Intel Core i5 Duo processor, 8 GB RAM, and a 64-bit operating system.

3. Results

3.1. Case Study Data

An illustrative example of an industrial cluster was used to study the cost trends and their variation using pipeline merging techniques as introduced by Alnouri et al. [21]. The industrial city considered has 6 carbon dioxide sources and 6 carbon dioxide sinks, which are distributed amongst 4 chemical plants operating within geographic proximity. The layout and distances were adopted from [21], in addition to the same two pipeline-merging techniques: (a) forward branching and (b) backward branching. Tables 1 and 2 below provide CO_2 source and CO_2 sink information in terms of volumetric flowrates under different pressures.

Table 1. Volumetric flowrates (in m^3/s) of CO_2 sources at different source pressures that have been studied.

CO_2 Source * Number	Pressure									
	1 bar	2 bar	5 bar	7 bar	10 bar	15 bar	20 bar	30 bar	40 bar	50 bar
1	67,416	33,520	13,319	9317	6414	4152	3017	1872	1285	914
2	44,944	22,346	8879	6211	4276	2768	2012	1248	857	609
3	78,652	39,106	15,538	10,870	7483	4844	3520	2184	1499	1066
4	44,944	22,346	8879	6211	4276	2768	2012	1248	857	609
5	109,551	54,469	21,643	15,140	10,422	6747	4903	3043	2088	1484
6	56,180	27,933	11,099	7764	5345	3460	2514	1560	1071	761

* CO_2 sources are CO_2-emitting streams from an industrial process that has a given CO_2 purity, pressure, temperature, and known location.

Table 2. Maximum volumetric flowrate (in m^3/s) of CO_2 sinks at different sink pressures that have been studied.

CO_2 Sink ** Number	Pressure		
	151 bar	101 bar	74 bar
1	137	147	158
2	91	98	105
3	91	98	105
4	160	171	184
5	91	98	105
6	222	238	257

** CO_2 sinks are CO_2 utilization industrial processes that can convert or sequester CO_2 at a given purity, pressure, temperature, and has a given location.

Ten different source pressures (ranging from 1 bar to 50 bar) have been considered in this study, in addition to 3 different sink pressures (74, 101, and 151 bar). It should be noted that in real situations, it is unlikely to have all source pressures equal. However, the purpose of this study is to investigate the effects of different source pressures on the cost of the network. Hence, to conduct a fair comparison between the different cases, all 6 source pressures were assumed to be equal, and the same applies to all the 6 sink pressures. For instance, the case of 1 bar source pressure and 74 bar sink pressure, all 6 source pressures were considered to be at 1 bar, and each of those sources may supply various sinks together with 74 bar each as a sink pressure. Therefore, in this study, this extra condition has been assumed for pressure, and was applied for the various cases tested. This greatly facilitated the comparison process between the different cases studied and allowed for some substantiated conclusions in this regard. Source and sink volumetric flow data for the various pressures considered are provided in Tables 2 and 3, respectively. The contamination data for all the carbon dioxide streams (both sources and sinks) are provided in Table 3. The thickness required for carbon dioxide pipes is influenced by the pressure that the pipeline can withstand. In general, higher pressures would require thicker pipes. In this work, three different thickness levels were utilized (5, 10, and 20 mm), depending on the pressure level being applied [22]. The thickness was a specified parameter and was not optimized in this work. All sources have been assumed produce carbon dioxide, at no treatment costs, with the presence of some minor impurities. The respective impurity information (in ppm) for sources and the acceptable impurity levels for sinks is provided in Table 3, in which three different contaminants were considered.

Table 3. Carbon dioxide stream contaminant data (ppm) present in source entities (Y_1, Y_2, Y_3), and the maximum contamination levels acceptable in the sink entities (Z_1^{MAX}, Z_2^{MAX}, Z_3^{MAX}) (ppm).

Source	Y_1	Y_2	Y_3	Sink	Z_1^{MAX}	Z_2^{MAX}	Z_3^{MAX}
1	0	0	30	1	100	50	30
2	50	50	80	2	140	100	60
3	50	70	100	3	180	150	130
4	140	100	100	4	230	180	180
5	170	120	130	5	250	190	200
6	240	130	150	6	100	190	210

3.2. Case Study Results

Tables 4 and 5 presents a cost breakdown for piping, compression, as well as pumping costs that are associated with the two different pipeline merging scenarios. There are no pumping costs associated with Case C for both branching and backward branching scenarios. This was due to the sink pressure setting at supercritical conditions, which can be achieved by compression only.

Table 4. Cost breakdown summary (in USD/y) for Cases A, B, and C, using forward branching techniques for pipeline merging.

Cases	Source Pressure (bar)	Pipeline Costs	Pumping Costs	Compression Costs	Total Network Costs
Case A: Sink Pressure = 15,148 kPa	**1**	154,979,765	11,784,526	87,205,902,838	87,372,667,129
	2	131,447,518	11,706,826	35,559,532,020	35,702,686,364
	5	112,478,369	11,629,126	12,499,282,829	12,623,390,324
	7	108,466,438	11,473,726	8,645,385,233	8,765,325,397
	10	103,768,504	11,078,233	5,980,650,478	6,095,497,216
	15	100,617,625	10,745,233	3,960,957,219	4,072,320,077
	20	97,819,208	10,301,233	2,953,429,063	3,061,549,505
	30	95,508,090	9,524,233	1,924,839,835	2,029,872,158
	40	93,168,585	8,747,233	1,382,392,876	1,484,308,694
	50	91,706,690	7,970,233	1,027,484,015	1,127,160,939
Case B: Sink Pressure = 10,148 kPa	**1**	187,380,366	7,899,526	48,592,697,183	48,787,977,077
	2	160,179,190	7,821,826	19,814,410,667	19,982,411,683
	5	135,705,463	7,588,726	6,964,825,152	7,108,119,342
	7	129,318,545	7,433,326	4,817,364,111	4,954,115,983
	10	125,663,808	7,193,233	3,332,525,989	3,465,383,031
	15	120,492,769	6,804,733	2,207,116,588	2,334,414,091
	20	118,877,115	6,416,233	1,645,703,782	1,770,997,131
	30	115,220,013	5,639,233	1,072,555,368	1,193,414,615
	40	113,592,532	4,862,233	770,294,168	888,748,934
	50	111,607,856	4,085,233	572,532,569	688,225,658
Case C: Sink Pressure = 7380 kPa	**1**	221,084,373	0	12,605,088,021	12,826,172,394
	2	186,736,944	0	5,139,916,181	5,326,653,125
	5	159,041,372	0	1,806,696,051	1,965,737,423
	7	152,715,957	0	1,249,638,365	1,402,354,322
	10	146,565,591	0	864,467,006	1,011,032,596
	15	141,408,745	0	572,532,510	713,941,255
	20	138,139,589	0	426,900,383	565,039,972
	30	135,109,351	0	278,224,005	413,333,356
	40	132,831,350	0	199,816,564	332,647,914
	50	130,896,350	0	148,516,626	279,412,976

Table 5. Cost breakdown summary (in USD/y) for Cases A, B, and C, using backward branching techniques for pipeline merging.

Cases	Source Pressure (bar)	Pipeline Costs	Pumping Costs	Compression Costs	Total Network Costs
Case A: Sink Pressure = 15,148 kPa	1	208,080,964	11,779,723	74,508,938,510	74,728,799,197
	2	116,586,392	11,702,023	23,035,120,868	23,163,409,283
	5	66,149,503	11,468,923	4,886,257,289	4,963,875,715
	7	52,890,594	11,313,523	2,680,743,924	2,744,948,040
	10	46,156,491	11,073,430	1,431,627,451	1,488,857,371
	15	32,742,953	10,684,930	689,613,261	733,041,144
	20	32,040,774	10,296,430	409,039,754	451,376,957
	30	25,877,762	9,519,430	180,928,226	216,325,417
	40	22,138,768	8,742,430	96,153,615	127,034,812
	50	20,196,990	7,965,430	54,187,100	82,349,519
Case B: Sink Pressure = 10,148 kPa	1	264,208,192	7,894,723	41,517,720,345	41,789,823,259
	2	143,061,128	7,817,023	12,835,583,561	12,986,461,712
	5	78,388,594	7,583,923	2,722,710,425	2,808,682,942
	7	64,412,455	7,428,523	1,493,758,719	1,565,599,696
	10	53,025,708	7,188,430	797,728,559	857,942,696
	15	44,776,125	6,799,930	384,264,910	435,840,965
	20	35,332,471	6,411,430	224,742,760	266,486,661
	30	29,204,020	5,634,430	100,816,461	135,654,911
	40	25,662,672	4,857,430	53,578,523	84,098,625
	50	22,093,606	4,080,430	30,194,026	56,368,061
Case C: Sink Pressure = 7380 kPa	1	299,208,375	0	10,769,818,300	11,069,026,674
	2	164,367,170	0	3,329,587,983	3,493,955,153
	5	90,291,391	0	706,279,062	796,570,453
	7	75,135,176	0	387,485,388	462,620,564
	10	60,681,811	0	206,933,125	267,614,937
	15	48,553,531	0	99,679,443	148,232,974
	20	44,103,086	0	58,298,930	102,402,016
	30	31,769,896	0	26,152,085	57,921,981
	40	28,928,652	0	13,898,426	42,827,078
	50	28,928,652	0	13,898,426	42,827,078

4. Discussion

From the results obtained, it is evident that backward branching was able to yield more cost-effective network schemes when compared to forward branching, regardless of the source or sink pressure being considered. The total carbon dioxide network cost was found to be the most expensive for Case A (considering the highest sink pressure), and the least expensive for Case C (considering the lowest sink pressure). The source pressure had a great effect on the overall network cost. It was found that higher source pressures (50 bars) tend to reduce the compression cost requirements. While the highest compression costs were associated with the lowest source pressure (1 bar) scenarios, for forward branching, as well as backward branching. This trend was a result of the higher-pressure difference between sources and sinks that needed to be supplied for all lower source pressure scenarios. Higher source pressures tend to reduce the pipeline cost requirements, while the highest pipeline costs were associated with the lowest source pressure scenarios, for both forward and backward branching. However, in varying sink pressures, the higher sink pressures (Case C) tend to increase the pipeline cost requirements. Whereas, the lowest pipeline costs were always associated with the highest sink pressure scenarios (Case A). This was seen in both forward and backward branching pipeline merging scenarios. It was due to the lower volumetric flowrate (and subsequently lower segment diameters) that needed to be transported and delivered to the various sinks, in case of all high sink pressure scenarios. The relative costs have been compared for the three different entities. The attained trends associated with backward pipeline branching are depicted in Figures 3–5 for compression, pumping, and piping costs, respectively. The trends associated with forward pipeline branching are depicted in Figures 6 and 7 for compression, pumping, and piping costs, respectively.

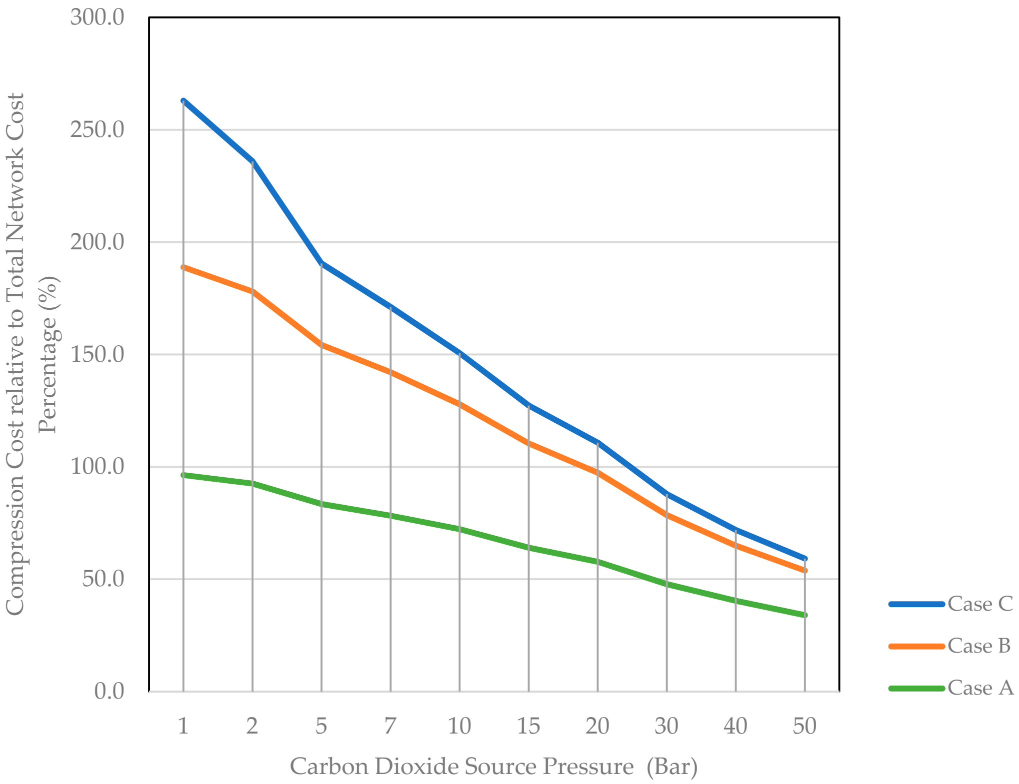

Figure 3. Compression costs relative to the total network cost with backward pipeline merging applied and tested for different carbon dioxide source pressures with A—sink pressures set to 151 bars, B—sink pressures set to 101 bars, and C—sink pressures set to 74 bars.

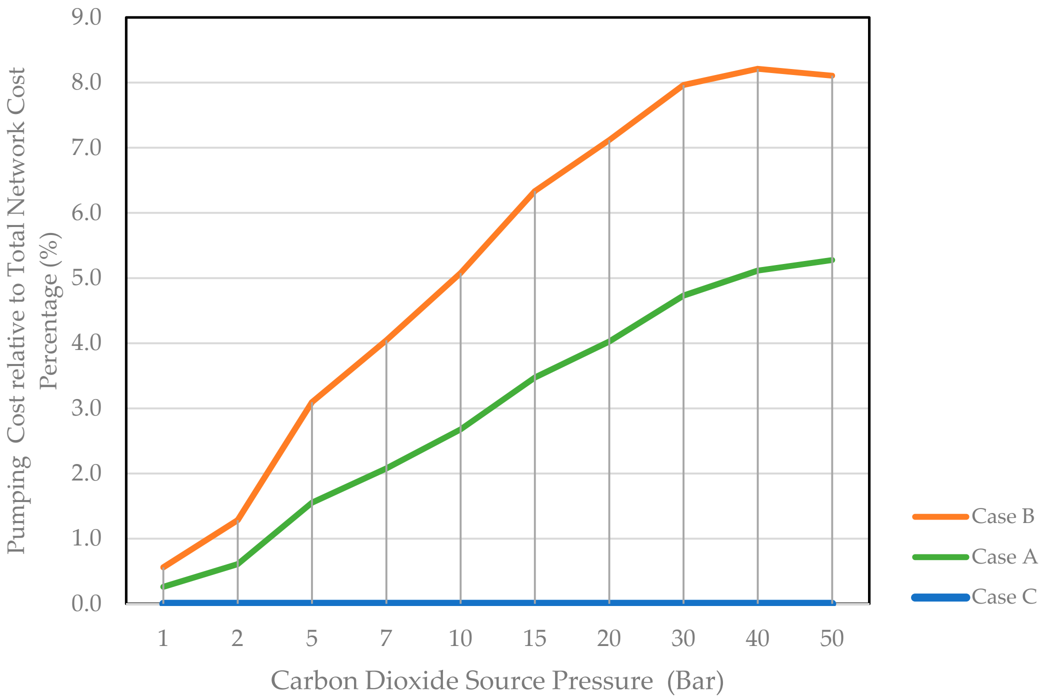

Figure 4. Pumping costs relative to the total network cost with backward pipeline merging applied and tested for different carbon dioxide source pressures with A—sink pressures set to 151 bars, B—sink pressures set to 101 bars, and C—sink pressures set to 74 bars.

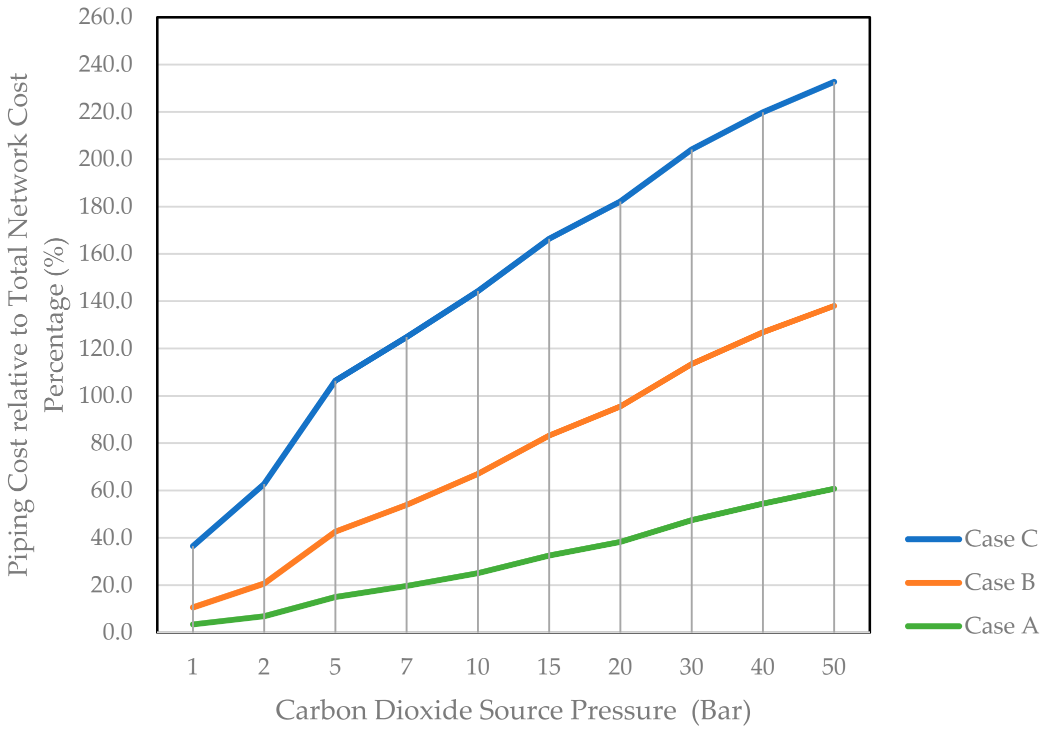

Figure 5. Piping costs relative to the total network cost with backward pipeline merging applied and tested for different carbon dioxide source pressures with A—sink pressures set to 151 bars, B—sink pressures set to 101 bars, and C—sink pressures set to 74 bars.

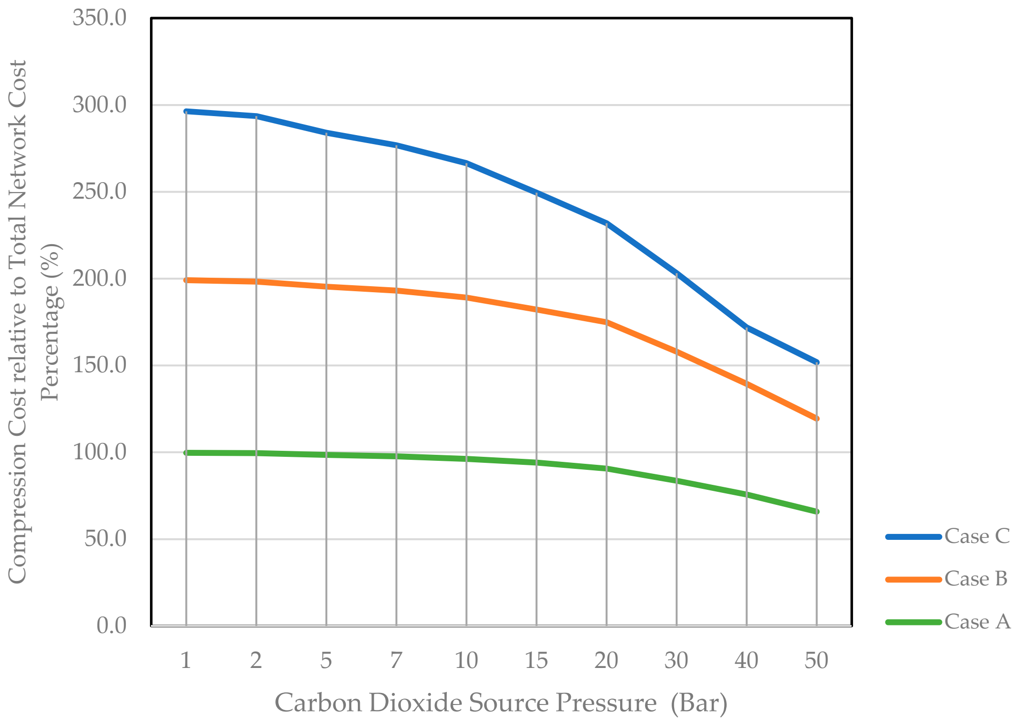

Figure 6. Compression costs relative to the total network cost with forward pipeline merging applied and tested for different carbon dioxide source pressures with A—sink pressures set to 151 bars, B—sink pressures set to 101 bars, and C—sink pressures set to 74 bars.

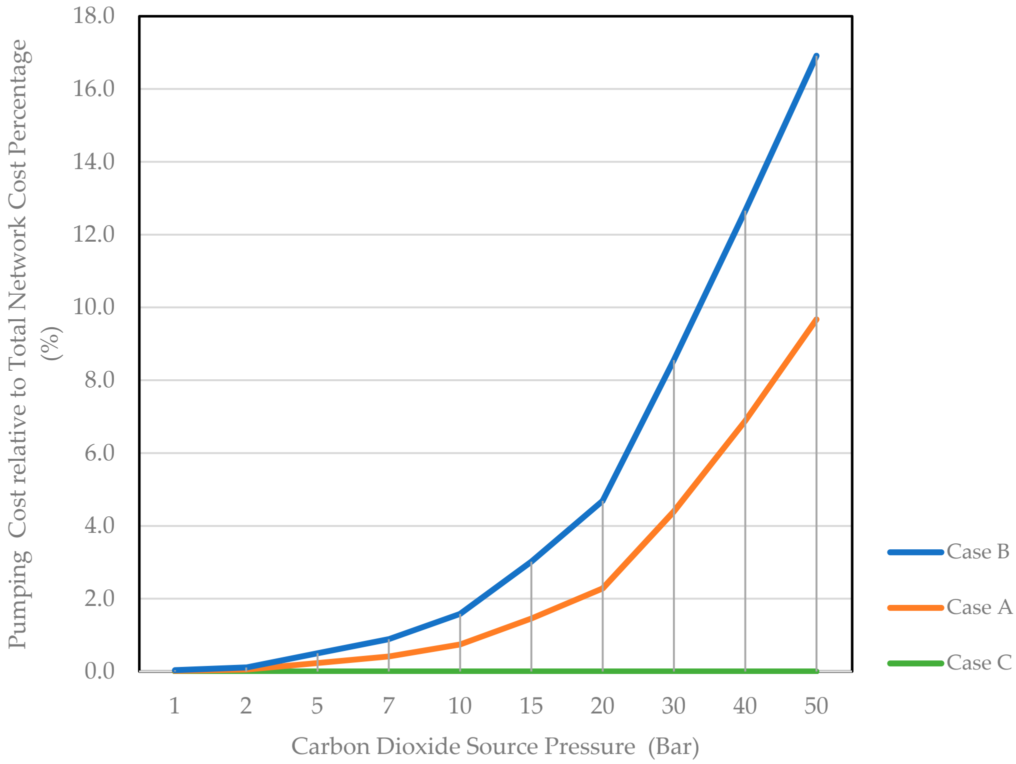

Figure 7. Pumping costs relative to the total network cost with forward pipeline merging applied and tested for different carbon dioxide source pressures with A—sink pressures set to 151 bars, B—sink pressures set to 101 bars, and C—sink pressures set to 74 bars.

From the results obtained, both the source and sink pressures have a great effect on the overall cost of the merged network. The compression costs always tend to follow a decreasing trend with increased source pressure, unlike the pumping and pipeline costs. Hence, when more compression and pumping were required, pipe costs tend to generate more savings in the carbon integration design attained via merged infrastructure. On the other hand, compression costs tend to generate more savings when pipeline costs were reported to be the highest.

5. Conclusions

This paper discusses the various tradeoffs between compression, pumping, and pipeline costs associated with carbon networks. It investigated the application of the two different merged infrastructure scenarios, forward branching and backward branching, which was previously studied for water networks. A case study that involved the exploration of 30 different scenarios was tested for each merging technique, in order to identify which merging technique leads to more cost savings. It was found that backward branching was able to yield up to 15% more savings compared to forward branching schemes in carbon integration networks. Moreover, for cases where more compression/pumping is required, compression costs tend to increase, while the resulting pipeline costs decrease as a result of the lower volumetric flowrate transported. In contrast, pipeline costs tend to be on the higher side when the network compression requirements reduced, as a result of the higher volumetric flowrate transported. Additionally, compression costs consistently decreased with increasing source pressure, unlike the pumping and pipeline costs in the case of both forward and backward merging infrastructure.

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Nomenclature

$C^{comp,\ Total}$	Total cost of compression ($/y)
$C^{pump,\ Total}$	Total cost of pumping ($/y)
C^{Pipe}	Cost of pipe segment ($/y)
ΔP	Pressure difference in pipe segment (bar)
ΔP^{pipe}	Pressure drop parameter associated with pipe segment (bar)
Elec.	Electricity price in $/kWh
D	Diameter of pipe (m)
v	Outlet velocity of source s to sink k (m/s)
m	Molecular mass of carbon dioxide g/mol
CRF	Capital Recover Factor
F	Mass flowrate in pipe (m^3/s)
T	Temperature of carbon dioxide source (°C)
L	Length of pipe segment (m)
C^{Pipe}	Cost parameter of the pipe segment ($/y)
P^{comp}	Power parameter for the compressor ($/y)
$C^{comp,CAPEX}$	Capital cost of compression ($/y)
$C^{comp,\ OPEX}$	Operating cost of compression ($/y)
$C^{pump,CAPEX}$	Capital cost of pumping ($/y)
$C^{pump,\ OPEX}$	Operating cost of pumping ($/y)

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