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Toward Cleaner and More Sustainable Cement Production in Vietnam via Carbon Capture and Storage

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Abstract: Vietnam is the world's largest cement exporter. In 2022, it produced 118 Mtpa cement while emitting 109 Mtpa cement-related CO_2, equal to 33% of Vietnam's total CO_2 emission. As Vietnam has pledged to achieve net zero by 2050, unabated cement-related CO_2 emission must be drastically reduced in the future. This paper investigates the contribution of carbon capture and storage (CCS) to decarbonizing Vietnam's cement industry to make cement production cleaner and more sustainable. A first-of-a-kind CO_2 source-sink mapping exercise was conducted to map 68 cement plants to subsurface sinks, including oil and gas reservoirs and saline aquifers, using four CCS field development concepts. The results have identified four first-mover CCS projects where CO_2 emissions from 27 cement plants are mapped to nearby offshore subsurface CO_2 sinks. Two of these projects are located in Vietnam-north, one in Vietnam-central, and one in Vietnam-south. In the Vietnam-south CCS project, CO_2 emission from the Kien Giang province is transported and stored in the offshore Block B gas field. In the other three CCS projects, CO_2 emission is transported to nearshore saline aquifers in the Song Hong Basin. At a CO_2 capture rate of 90%, these four projects will mitigate 50 Mtpa CO_2, which is 46% of cement-related CO_2 emission or 15% of total CO_2 emission from Vietnam, thus making Vietnam's cement production cleaner and more sustainable. Future research should focus on subsurface characterization of saline aquifers in the Song Hong Basin. The methodology developed in this study is usable in other cement-producing countries with significant CO_2 sinks in the nearshore continental shelf.

Keywords: carbon capture and storage; Vietnam; low-carbon cement; cleaner cement production; sustainable cement production; CO_2 source-sink mapping; CCS field development concepts

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1. Introduction

Cement is the most widely used man-made material in the world. As a key ingredient of concrete, cement forms a glue with water that binds together the sand and gravel of concrete. It hardens as it dries. Concrete usually contains 10 to 15% cement [1]. Concrete and cement are key materials in buildings, roads, and other infrastructure. Global cement production has reached 4.2 Gt in 2021 [2], while process-related CO_2 emission from cement produced reached 1.61 Gt in 2022 [3].

In 2022, Vietnam was the world's largest exporter of cement and the third-largest cement producer. It exported 31 Mt of cement, with the value reaching USD 1.8 billion (Figure 1) [4–6], to countries including China, the Philippines, Bangladesh, the US, and Guatemala [4]. In fact, Vietnam has experienced steady growth in cement production in the last decade, with annual production increasing from 56 Mtpa in 2010 to 118 Mtpa in 2022 (Figures 2 and 3) [4]. However, all of this has happened at the cost of increasing cement-related CO_2 emission. During cement manufacturing, CO_2 is emitted in the calcination process, which contributes to 40–50% of the CO_2 emitted. In addition, CO_2 is emitted from the burning of fossil fuels. This contributes to 35% of CO_2 emissions. Other processes such as limestone extraction, cooling, milling, and logistics make up the rest. On balance, the production of one ton of cement emits about 0.85–0.925 ton of CO_2 [7]. Using the reported CO_2 emission from the calcination process [3], we estimate that total CO_2 emission from Vietnam's cement production was 109 Mtpa in 2022 or 33% of Vietnam's annual CO_2 emission (Figures 3 and 4). Of this, 56 Mtpa came from calcination, 38 Mtpa from the combustion of fossil flues for heating, and 15 Mtpa from other processes.

As a signatory to the Paris Agreement, Vietnam has pledged to achieve net zero by 2050 [8]. Therefore, reducing cement-related CO_2 emission must be a key element of this pledge. This is also relevant as the European Union (EU) will require cement importers to report the carbon intensity of their products starting in 2023 as part of their carbon border adjustment mechanism [9,10]. It is likely that both the US and the EU will impose a cross-border carbon tax for imported goods in future [11]. However, there has been limited published peer-reviewed research on the decarbonization of Vietnam's cement industry, although a number of consulting firms have published their views on Vietnam's energy transition [12–15].

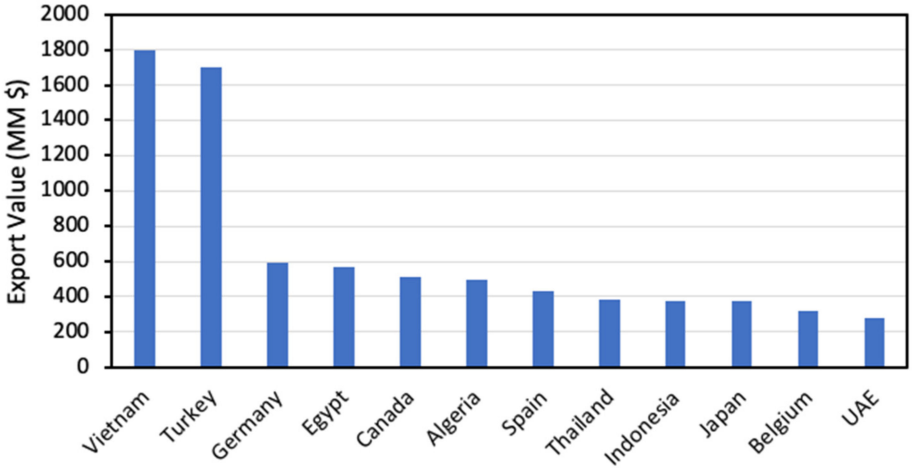

Figure 1. Export value of cement from top cement producers in 2022 [6].

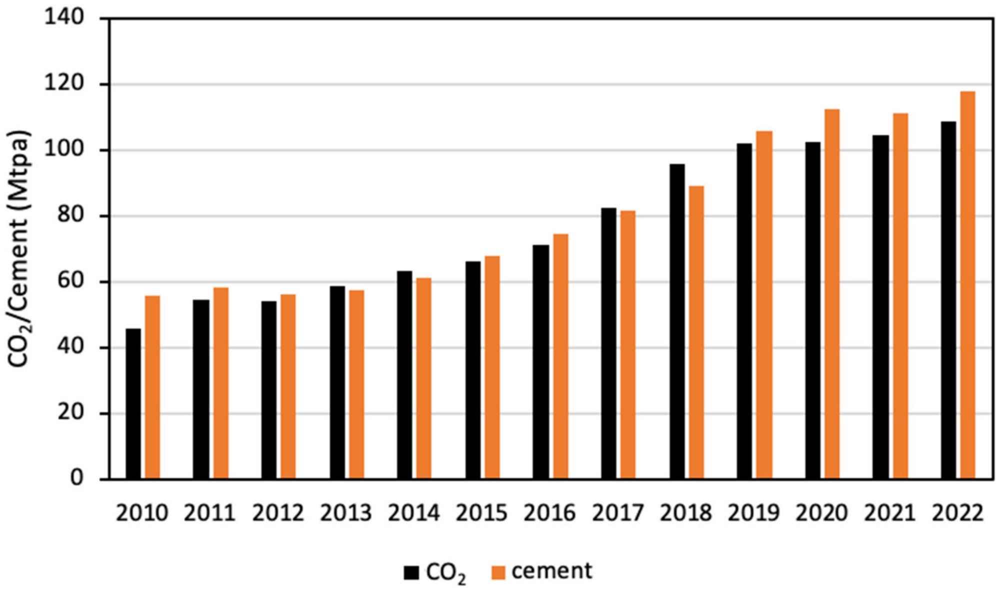

Figure 2. Annual cement production [4] and cement-related CO_2 emissions in Vietnam.

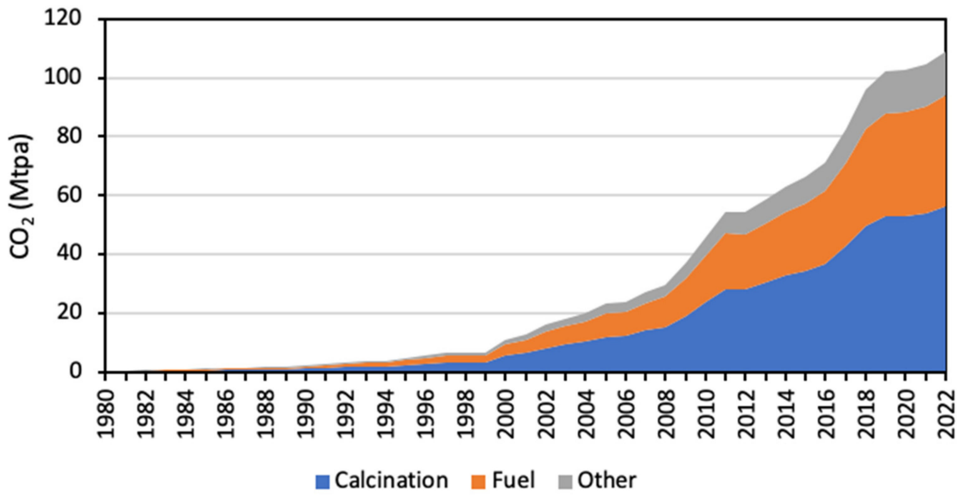

Figure 3. Annual CO_2 emissions from Vietnam's cement industry.

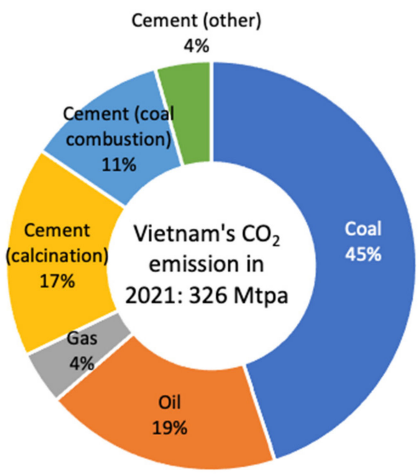

Figure 4. CO_2 emissions from Vietnam by source In 2021.

Carbon capture and storage (CCS) has been recognized as a key technology for reducing CO_2 emissions from cement production since it can be used to mitigate CO_2 coming from both the calcination process and the combustion of fossil fuels providing the heat required for calcination [16]. Recently, Harsha and Lau (2023) published their study on using CCS to decarbonize Vietnam's power and industry sectors [17]. They have estimated the subsurface CO_2 storage capacity of oil and gas reservoirs as well as saline aquifers in Vietnam and conclude that there is adequate capacity to store anthropogenic CO_2 from both the power and industry sectors in Vietnam for over a century. The results of their work are used in our current study.

The purpose of this study is to determine the contribution of CCS to the decarbonization of Vietnam's cement industry. Specifically, we quantify the amount of CO_2 that can be captured and stored in subsurface oil and gas reservoirs or saline reservoirs located relatively close to large cement plants. One of the difficulties of implementing CCS projects is securing the cooperation and knowledge sharing of several industries which are not used to working with each other. These industries include cement production, carbon capture, CO_2 transportation by pipeline, and the upstream oil and gas industry for CO_2 storage in subsurface reservoirs. For example, a cement manufacturer may want to install carbon capture to his plant. However, he is not aware of the location of subsurface CO_2 storage, nor does he possess the expertise of building CO_2 pipelines and constructing wells for CO_2 injection. The contribution of this study lies in integrating the knowhow from four different industries to solve the problem of decarbonizing Vietnam's cement industry.

CO_2 source-sink mapping enables these four industries to work together to find the best solution to decarbonize cement production.

2. Objective and Methodology

The decarbonization of the cement industry can be tackled from either the demand or supply side. On the demand side, one can employ better structural design that uses less cement [18]. Another option is to recycle existing concrete structures to reduce the use of new cement [19–21]. Additionally, another way is to make low-carbon concrete to reduce the clinker content in concrete [22,23]. For example, one can use ready-mix concrete to reduce cement wastage [24,25]. Additives may be added to improve concrete properties and reduce cement requirements [26]. These additives include accelerants that strengthen concrete more quickly and air-entrenching agents which allow for air bubbles to increase volume and replace solid material input for lower-strength applications [27]. In addition, moving away from bagged cement can also reduce both waste and overuse. Recently, research has been conducted to use supplementary cementitious materials (SCMs) to partially reduce clinker content [28]. SCMs have similar properties to clicker when mixed with water and contribute to the strength of the cement blend but cannot fully displace clinker. SCMs include industrial waste such as ground granulated blast furnace slag and fly ash, calcined clays, natural pozzolans, and ground limestone [29]. Selecting cement with high clinker-substitution rates can reduce cement-related CO_2 emissions of a traditional building. Indeed, active research and development (R&D) is ongoing in both academia and in the construction industry to reduce the demand for cement usage.

This paper, however, deals with the supply side of cement. The objective of our study to propose a pathway to decarbonize Vietnam's cement industry on the supply side. This is important not only for Vietnam but also for countries who buy Vietnam's cement. There are several ways to reduce CO_2 emissions from cement plants, such as replacing coal with hydrogen for process heating [30]. Another option is electrification of heating [31–33]. However, these technologies are still in the R&D stage. Currently, the most effective way to decarbonize cement production is to employ CCS technologies on cement plants where CO_2 emitted from both calcination and heating is captured at the plant and transported to a suitable location for permanent storage in a subsurface reservoir [34]. As of September 2022, there were 30 CCS projects operating globally, storing about 43 Mtpa of CO_2, and another 166 projects are at various stages of development [35]. However, the use of CCS to mitigate CO_2 emission from a cement plant is rare in Asia. This study is the first study of its kind to apply CCS to decarbonize a major cement-exporting country on a nationwide scale.

Since post-combustion CCS is a mature technology [36,37] with a technology readiness level (TRL) of 9 [38], our objective is not to propose one or several CCS demonstration projects, but a number of large-scale CCS projects to decarbonize Vietnam's cement industry on a national scale. To achieve this, we are aiming at permanently storing CO_2 at the scale of tens of Mtpa. Our methodology is illustrated in Figure 5. Three sets of input data are used in our study. The first set includes the location and size of all cement-related CO_2 sources in Vietnam. The second set includes the location and size of CO_2 sinks in the country. This is obtained from a recent study by Bokka and Lau (2023) [17]. The third set is field development concepts [39] for commercial scale application of CCS. These input data are then used in a detailed CO_2 source-sink mapping exercise for the whole country. The result of this exercise is a list of first-mover CCS projects in Vietnam.

The novelty of our study lies in several areas. First, this is the first peer-reviewed study on the decarbonization of the cement industry of Vietnam on a national level. This is important because of the magnitude of CO_2 emission from this industry (109 Mt in 2022) and the magnitude of the proposed solution, which involves mitigating tens of million tons of CO_2 per annum. Second, to address the magnitude of the problem, we propose, for the first time, four CCS field development concepts which are generally applicable to connecting multiple CO_2 sources and a common sink. These field development concepts are applicable not only for CO_2 sources from cement plants but also other industrial sources such as power plants and refineries. Third, we take advantage of the fact that many cement-related CO_2 sources in Vietnam are located in coastal provinces while many CO_2 sinks are located in shallow water reservoirs close to the coast. This allows us to map coastal CO_2 sources to nearshore CO_2 sinks. This methodology is applicable to other countries with a long coastline such as China, India, Thailand, Indonesia, and Japan, which are also major producers of cement.

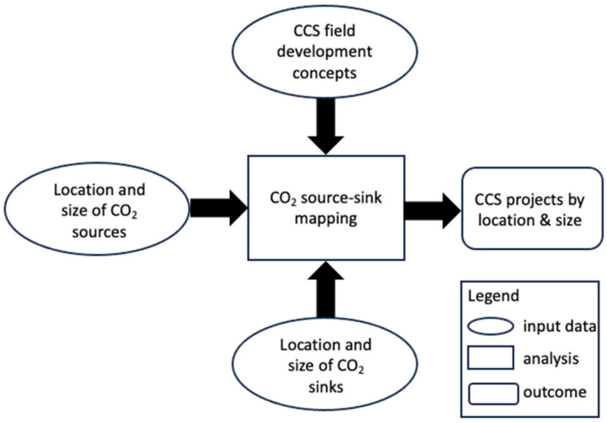

Figure 5. Methodology of study.

3. CO_2 Sources

Table 1 lists the cement-producing provinces in Vietnam [40] and their CO_2 emissions based on the authors' estimate. There were 68 cement plants in Vietnam. Most of the cement production (72%) is concentrated in the north, where production exceeds local demand with the surplus being exported. In the south, cement production is approximately equal to cement demand [41]. In addition, cement factories with the highest production capacity are also located in the north, with one reaching 4.5 Mtpa in the province of Ha Nam [42]. It is worthwhile to note that of the 23 provinces and cities with cement production, 11 are coastal. In fact, they produced 57% (62.09 Mt) of Vietnam total cement production in 2022.

Table 1. Cement production [4] and estimated cement-related CO_2 emission in Vietnam in 2022 by authors.

	Province or City of Cement Production	Location	Number of Cement Plants [42]	Cement Production (Mtpa) [4]	Cement-Related CO_2 Emission (Mtpa) *	Cement-Related CO_2 Emission (% of Total)
Vietnam-north	Hanoi city	Interior	9	15.75	14.57	13.40
	Ha Nam	Interior	6	13.9	12.86	11.82
	Thanh Hoa	Coastal	6	18.3	16.93	15.56
	Quang Ninh	Coastal	5	9.8	9.07	8.33
	Hai Phong	Coastal	3	9.5	8.79	8.06
	Ninh Binh	Coastal	4	6.9	6.38	5.87
	Thai Nguyen	Interior	4	3.8	3.52	3.23
	Hai Durong	Interior	1	3.5	3.24	2.98
	Son La	Interior	1	1.2	1.11	1.02
	Yen Bai	Interior	1	1.0	0.93	0.85
	Lang Son	Interior	1	0.91	0.84	0.78
	Tuyen Quang	Interior	1	0.6	0.56	0.51
	Subtotal		42	85.17	78.78	72.43

Table 1. *Cont.*

	Province or City of Cement Production	Location	Number of Cement Plants [42]	Cement Production (Mtpa) [4]	Cement-Related CO_2 Emission (Mtpa) *	Cement-Related CO_2 Emission (% of Total)
Vietnam-central	Thua Thien Hue	Coastal	6	8.2	7.59	6.97
	Quang Binh	Coastal	2	2.1	1.94	1.79
	Quang Nam	Coastal	1	1.5	1.39	1.28
	Nghe An	Coastal	1	0.91	0.84	0.78
	Subtotal		11	12.71	11.76	10.81
Vietnam-south	Kien Giang	Coastal	3	7.2	6.66	6.12
	Binh Phuoc	Interior	3	5.2	4.81	4.42
	Ho Chi Ming City	Coastal	3	2.3	2.13	1.96
	Hau Giang	Interior	3	2.14	1.98	1.82
	An Giang	Interior	1	1.46	1.35	1.24
	Tay Ninh	Interior	1	1.0	0.93	0.85
	Ben Tri	Coastal	1	0.4	0.37	0.34
	Subtotal		15	19.70	18.22	16.75
Country	Grand total		68	117.58	108.76	100.00

* Authors' estimate.

4. CO_2 Sinks

In estimating the CO_2 storage capacity of oil and gas reservoirs, only major oil reservoirs with an original-oil-in-place (OOIP) larger than 16×10^6 m^3 and gas reservoirs with an original-gas-in-place (OGIP) larger than $20{,}000 \times 10^6$ m^3 were evaluated for permanent CO_2 storage. The CO_2 storage capacity in a gas reservoir can be estimated from the following equation:

$$m_{CO_2} = \rho_{CO_2} \times OGIP \times B_g \times R \tag{1}$$

where m_{CO_2} is the mass of CO_2 stored in kg, ρ_{CO_2} is the CO_2 density at reservoir conditions in kgm^{-3}, OGIP is the original gas in place at standard conditions in m^3, B_g is the gas formation volume factor in fraction, and R is the primary recovery factor in fraction. If a gas reservoir contains gas condensate, the condensate left in the reservoir after gas depletion can be recovered by CO_2-enhanced gas recovery (EGR). The CO_2 storage capacity by CO_2-EGR is given by introducing an additional CO_2-EGR recovery factor:

$$m_{CO_2} = \rho_{CO_2} \times OGIP \times B_g \times \left(R + R_{CO_2}\right) \tag{2}$$

where R_{CO_2} is the additional recovery factor by CO_2-EGR.

For an oil reservoir, CO_2-enhanced oil recovery (EOR) is applicable if the oil gravity is 27° API or larger. The CO_2 storage capacity can be estimated by the following equation:

$$m_{CO_2} = \rho_{CO_2} \times OOIP \times B_o \times \left(R + R_{CO_2}\right) \tag{3}$$

where *OOIP* is the original-oil-in-place at standard conditions in m^3; B_o is the oil formation volume factor in rm^3/Sm^3; R is the recovery factor after secondary recovery; and R_{CO_2} is the recovery factor for CO_2-EOR, which is related to CO_2-oil miscibility. The reservoir pressure must be above the minimum miscibility pressure (*MMP*) for CO_2 to be miscible in the oil. The *MMP* can be estimated from the following equation:

$$MMP = -329.558 + \left[7.727\left(\frac{8864.9}{API}\right)^{1/1.012}(1.005)^T\right] - 4.377\left[\left[\left(\frac{8864.9}{API}\right)^{1/1.012}\right]\right] \quad (4)$$

where T is the reservoir temperature in °F. R_{CO_2} is zero if the oil API is less than 27°.

The CO_2 storage capacity in a saline aquifer can be estimated by the following equation:

$$m_{CO_2} = \rho_{CO_2} \times A \times h \times \varnothing \times E \quad (5)$$

where A is the aquifer area in m^2, h the net sand thickness in m, $\varnothing$ is the porosity in fraction, and E is the CO_2 storage efficiency in fraction. The recovery factors for gas depletion, CO_2-EGR, and CO_2-EOR are given in Table 2. In our calculations, the mid CO_2 storage factor in a saline aquifer is 2% [43,44].

Table 2. Recovery factor for gas depletion, CO_2-EOR, and CO_2-EGR.

Reservoir Recovery Mechanism	Mid Recovery Factor (%)	Reference
Gas depletion	75	Stoian and Telford (1966) [45], Sim et al. (2009) [46]
Primary and secondary oil recovery	35	Li et al. (2021) [47], Abedini and Torabi (2014) [48]
Immiscible CO_2-EOR	8.5	Li et al. (2021) [47], Farajzadeh et al. (2019) [49], Zhang et al. (2018) [50]
Miscible CO_2-EOR	12	Li et al. (2021) [47], Lake et al. (2014) [51]

Table 3 lists the CO_2 storage capacity of gas fields in Vietnam according to region based on research by Bokka and Lau (2023) [17] using the methodology described above. It can be seen that about 53% (1484 Mt) of CO_2 storage capacity resides in the north while 47% (1340 Mt) resides in the south. However, most gas fields are still under depletion and, therefore, are not ready for CO_2 injection, as the breakthrough of CO_2 will contaminate the produced gas, necessitating CO_2 separation before point of sale. The only exception is Block B in the south, with a recovery factor of 63% which is close to the end of pressure depletion. When these gas fields are close to pressure depletion, CO_2 can be injected for displacing the condensate and for permanent CO_2 storage.

Table 3. CO_2-EGR and CO_2 storage capacity of gas fields in Vietnam [17].

	Sedimentary Basin	Gas Field	Recovery Factor (%)	CO_2 Enhanced Condensate Recovery (MMbbl)			CO_2 Storage Capacity (Mt)		
				Low	Mid	High	Low	Mid	High
Vietnam-north	Song Hong	Bao Vang/Bao Den	30	4.0	7.1	10.5	121.9	136.2	150.9
	Song Hong	Ken-Bau	NA	18.8	34.0	50.0	478.7	535.1	592.8
	Song Hong	Hac Long	NA	2.1	3.8	5.6	120.6	134.9	149.4
	Song Hong	Cai Voi Xanh	*	0	0	0	603.3	674.3	747.0
	Song Hong	Tien Hai-C	46	0	0	0	3.1	3.5	3.8
	Subtotal			24.9	44.9	66.1	1327.6	1484.0	1643.9
Vietnam-south	Nam Coo Son	Sao Vang-Dai Nguyen	NA	1.0	1.8	2.6	49.31	55.1	61.0
	Nam Con Son	Hai Thach/Moc Tinh	NA	8.1	14.6	21.5	152.1	170.0	188.3
	Nam Con Son	Lan Tray, Lan Do	NA	0	0.1	0.1	175.1	195.7	216.8
	Nam Con Son	Rong Doi, Rong Doi Tay	56	1.4	2.6	3.8	95.7	107.0	118.5
	Nam Con Son	Thien Ung	20	1.4	2.6	3.8	69.1	77.3	85.6
	Cuu-Long	Su Tu Trang	NA	14.1	25.5	37.5	244.8	273.7	303.2

Table 3. *Cont.*

	Sedimentary Basin	Gas Field	Recovery Factor (%)	CO_2 Enhanced Condensate Recovery (MMbbl)			CO_2 Storage Capacity (Mt)		
				Low	Mid	High	Low	Mid	High
Vietnam-south	Malay-Tho-Chu	Nam Du	NA	0.1	0.1	0.2	4.7	5.2	5.8
	Malay Tho-Chu	U-Minh	NA	0.1	0.2	0.3	3.2	3.6	4.0
	Malay-Tho-Chu	Block B	63	1.2	2.1	3.1	404.7	452.4	501.2
	Subtotal			27.4	49.6	72.9	1198.7	1340.0	1484.4
Total				52.3	94.5	139.0	2526.3	2823.9	3128.3

* Currently under development or has recently begun production. NA = not available.

Table 4 lists the oil fields in Vietnam according to region based on research by Bokka and Lau (2023) [17]. There are only two oil fields in north Vietnam and their combined CO_2 storage capacity is merely 12.4 Mt. In Vietnam, most of the oil fields reside in the south. Their combined mid CO_2 storage capacity is 537 Mt with CO_2-EOR recovery of 1038 MMbbl. Most of them are found in the offshore Cuu Long Basin.

Table 4. CO_2-EOR and CO_2 storage capacity of oil fields in Vietnam [17].

	Basin	Oilfield	CO_2-EOR (MMbbl)			CO_2 Storage Capacity (Mt)			CO_2 Miscibility in Crude
			Low	Mid	High	Low	Mid	High	
Vietnam-north	Song Hong	Ham Rong	6.5	11.7	17.3	5.1	6.4	7.8	Immiscible
	Song Hong	Cat Ba	4.7	8.5	12.5	4.7	6.0	7.2	Miscible
	Subtotal		11.2	20.2	3.0	9.8	12.4	15.0	
Vietnam-south	Nam Con Son	Oh Rong Do	7.9	14.2	20.9	7.6	9.6	11.5	Immiscible
	Nam Con Son	Chim Sao, Dua	10.2	18.4	27.0	9.4	11.8	14.2	Immiscible
	Nam Con Son	Dai Hung	23.5	42.5	62.5	21.8	27.4	33.1	Immiscible
	Cuu Long	Bach Ho	320.0	480.0	720.0	168.9	211.8	255.6	Miscible
	Cuu Long	Ca Ngu Vang	75.9	113.9	170.8	42.3	53.2	64.0	Miscible
	Cuu Long	Diamond	0.6	1.1	1.7	0.4	0.5	0.6	Immiscible
	Cuu Long	Emerald	2.1	3.9	5.7	2.3	2.5	3.5	Miscible
	Cuu Long	Hai Su Den, Hai Su Trang	10.8	19.6	28.9	8.5	10.7	12.8	Immiscible
	Cuu Long	Kinh Ngu Trang	10.0	18.0	26.5	11.0	13.8	16.6	Miscible
	Cuu Long	Lac Da Vang	8.5	15.3	22.5	8.4	10.6	12.8	Miscible
	Cuu Long	Pearl	1.5	2.7	4.0	1.5	1.9	2.3	Miscible
	Cuu Long	Phuong Dong	2.0	3.5	5.2	1.7	2.2	2.6	Immiscible
	Cuu Long	Rang Dong	37.4	67.6	99.4	29.7	37.4	45.0	Miscible
	Cuu Long	Rong	14.1	25.5	37.5	14.2	17.9	21.5	Immiscible
	Cuu Long	Ruby	9.4	17.0	25.0	10.3	13.0	15.7	Miscible
	Cuu Long	Su Tu Den	18.8	34.0	50.0	16.7	21.1	25.4	Immiscible
	Cuu Long	Su Tu Nau	5.6	10.2	15.0	5.0	6.3	7.6	Immiscible
	Cuu Long	Su Tu Vang	4.7	8.5	12.5	4.1	5.2	6.3	Immiscible
	Cuu Long	Te Giac Trang	44.6	80.7	118.6	35.6	44.8	54.0	Immiscible
	Cuu Long	Thang-Long, Dong-Do	7.1	12.9	19.0	5.6	7.0	8.5	Immiscible
	Cuu Long	Vang Dong	3.4	6.2	9.2	3.5	4.3	5.2	Miscible
	Malay-Tho-Chu	PM3-CAA fields	21.9	39.6	58.3	17.8	22.4	26.9	Immiscible
	Malay-Tho-Chu	Song Doc	1.2	2.1	3.1	1.0	1.2	1.5	Immiscible
	Subtotal		641.2	1037.6	1570.0	427.7	537.0	647.3	
Total			652.4	1057.8	1573.0	437.5	549.4	662.3	

Table 5 lists the storage capacity of saline aquifers in different sedimentary basins in Vietnam based on research by Bokka and Lau (2023) [17]. It can be seen that there is abundant CO_2 storage capacity within saline aquifers in the country, with 18% (32.4 Gt) in the north, 45% (82.6 Gt) in the centre, and 37% (67.4 Gt) in the south.

Table 5. CO_2 storage capacity of Vietnam's saline aquifers [17].

	Basin	Area (km^2)	Net Sand (m)	CO_2 Density (kg/m^3)	Porosity (%)	CO_2 Storage Capacity, (Mt)		
						Low	Mid	High
Vietnam-north	Song Hong	120,000	200	450	15	8262	32,400	89,100
Vietnam-central	Phu Khanh	56,000	200	450	15	3856	15,120	41,580
	Hoang Sa + Truong Sa	250,000	200	450	15	17,213	67,500	185,625
	Subtotal					21,068	82,620	227,205
Vietnam-south	Cuu Long	25,000	200	450	15	1721	6750	18,563
	Nam Con Son	90,000	200	450	15	6197	24,300	66,825
	Tu Chinh-Vung May	28,000	200	450	15	1928	7560	20,790
	Malay-Tho-Chu	106,650	200	450	15	7343	28,796	79,188
	Subtotal					17,189	67,406	185,366
Total						46,519	182,426	501,670

Table 6 summarizes the CO_2 storage capacity in Vietnam according to reservoir types and regions. It can be seen that for the whole country 98% of the CO_2 storage space resides in saline aquifers, 1.5% in gas reservoirs, and only 0.35% in oil reservoirs. Also, north, central, and south Vietnam possess 18%, 44%, and 37% of the subsurface storage capacity, respectively.

Table 6. Mid CO_2 storage capacity in different types of reservoirs in Vietnam [17].

Type of Storge Space	Vietnam-North (Mt)	Vietnam-Central (Mt)	Vietnam-South (Mt)	Subtotal (Mt)	Percentage (%)
Oil reservoir	12	0	647	660	0.35
Gas reservoir	1484	0	1340	2824	1.52
Saline aquifer	32,400	82,620	67,406	182,426	98.13
Subtotal (Mt)	33,896	82,620	69,399	185,910	100
Percentage (%)	18.23	44.46	37.33	100	

5. CCS Field Development Concepts

To facilitate commercial scale application of CCS, we introduce four field development concepts for CCS. In these concepts, CO_2 captured from one or more sources is transported to a single common sink for permanent storage. The reason to choose only one common sink with a large enough capacity to store CO_2 from multiple sources is to simplify the logistics and to make use of economies-of-scale to reduce total capital cost. Furthermore, these concepts make use of the ideas of a 'cluster' and a 'hub'. A cluster is a collection of CO_2 sources in close proximity to each other, e.g., all located within one industrial park. If carbon capture is installed at each CO_2 source, the CO_2 streams from multiple sources can be gathered in a collection station, further compressed, and transported via a common pipeline to the CO_2 sink. If the sources are very close to each other, a centralized post-combustion carbon capture facility may be considered as proposed by Lau et al. (2021) [52]. A hub is an onshore facility where CO_2 from different distant sources can be combined and compressed before being transported to the storage site. Use of clusters and hubs can enable sharing of infrastructure to reudce the cost of CCS.

5.1. Emitter-to-Reservoir Concept (One Source-to-One Sink)

In this field development concept, CO_2 from one emitter is captured and transported to one subsurface reservoir for storage (Figure 6). The emitter can be a cement plant, a coal-fired power plant, or a refinery. The CO_2 sink can be a gas reservoir, oil reservoir, or saline aquifer. They can be located onshore or offshore. If the reservoir is offshore, the mode of injection can be either through a dry-tree well on a platform or subsea well at the seabed [53] (Figure 6). This is the simplest field development concept and is used most often, e.g., in Petra Nova in Texas where CO_2 from one coal-fired power plant is transported to a nearby oil field for CO_2-EOR injection [54–56]. Most CCS pilots or demonstration projects use this field development concept [35,57].

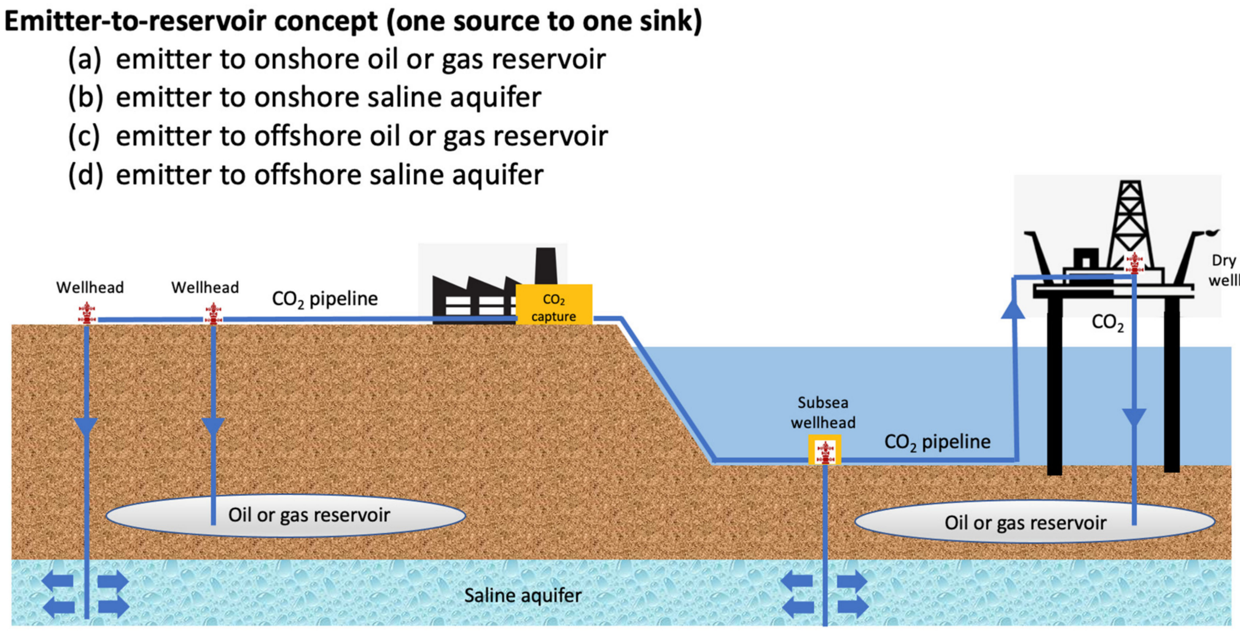

Figure 6. Emitter-to-reservoir CCS field development concept.

5.2. Cluster-to-Reservoir Concept (Multiple Nearby Sources to One Sink)

A cluster is defined as a collection of multiple nearby CO_2 sources. An example is Baytown in Texas, which has multiple chemical plants and refineries [58], or Jurong Island in Singapore [52,58] with over one hundred power plants and chemical plants. In this field development concept, CO_2 from multiple sources is captured and transported to one CO_2 sink for permanent storage (Figure 7). The CO_2 sink may be a gas reservoir, oil reservoir, or saline aquifer which may be located onshore or offshore. The Porthos [59,60] and Aramis [61] CCS projects in the Netherlands use this field development concept.

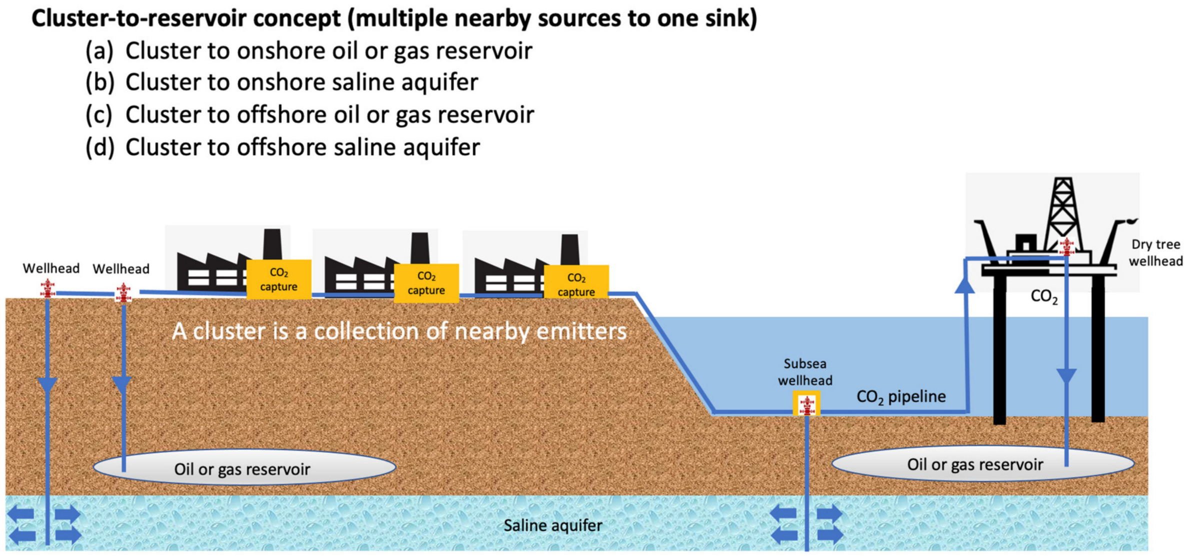

Figure 7. Cluster-to-reservoir CCS field development concept.

5.3. Clusters-to-Reservoir Concept (Multiple Clusters to One Sink)

In this field development concept, CO_2 from two or more clusters is transported to one common sink for storage. Each cluster is a collection of CO_2 sources located close to each other (Figure 8). The clusters may be located in two different cities or provinces of a country. The common CO_2 sink may be a gas reservoir, oil reservoir, or saline aquifer located onshore or offshore. In this case, there will be one dedicated CO_2 pipeline connecting each cluster to the sink. An example of this concept is the East Coast Cluster CCS project in the UK [62], where a plan is made to capture 10 Mtpa CO_2 from the Teesside cluster located in the city of Middlesbrough and 17 Mtpa CO_2 from the Humber cluster located in the cities of Hull and Scunthorpe and transport the captured CO_2 via two pipelines to the offshore Endurance saline aquifer for permanent storage.

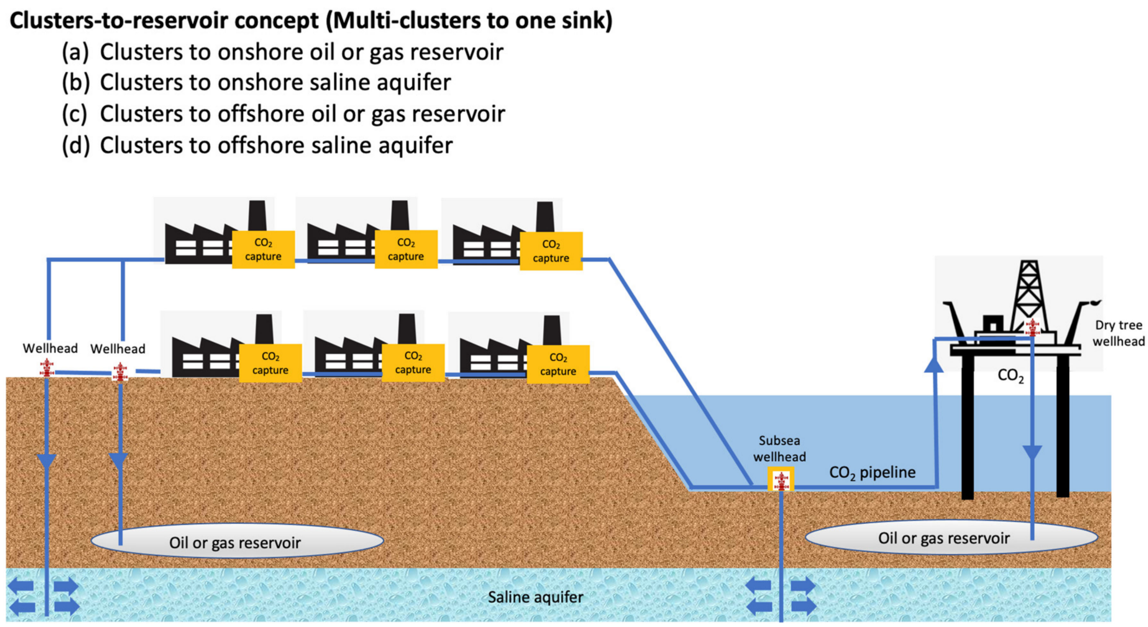

Figure 8. Clusters-to-reservoir CCS field development concept.

5.4. Hub-to-Reservoir Concept (Multiple Distant Sources to a Hub, Then, to One Sink)

A hub is defined as a temporary storage facility for CO_2 collected from two or more distant sources. In addition, the CO_2 from different sources may be shipped to the hub via different modes of transport, e.g., by tanker from one source and by pipeline from another source. In this field development concept, CO_2 from multiple distant sources, such as different countries, is shipped to an onshore hub for temporary storage and then transported from this hub to one common sink for permanent storage. The common CO_2 sink may be a gas reservoir, oil reservoir, or saline aquifer located onshore or offshore (Figure 9). An example of this is the Longship project, which in future will be open to CO_2 sources not only from Norway but also another European country, such as the UK [63].

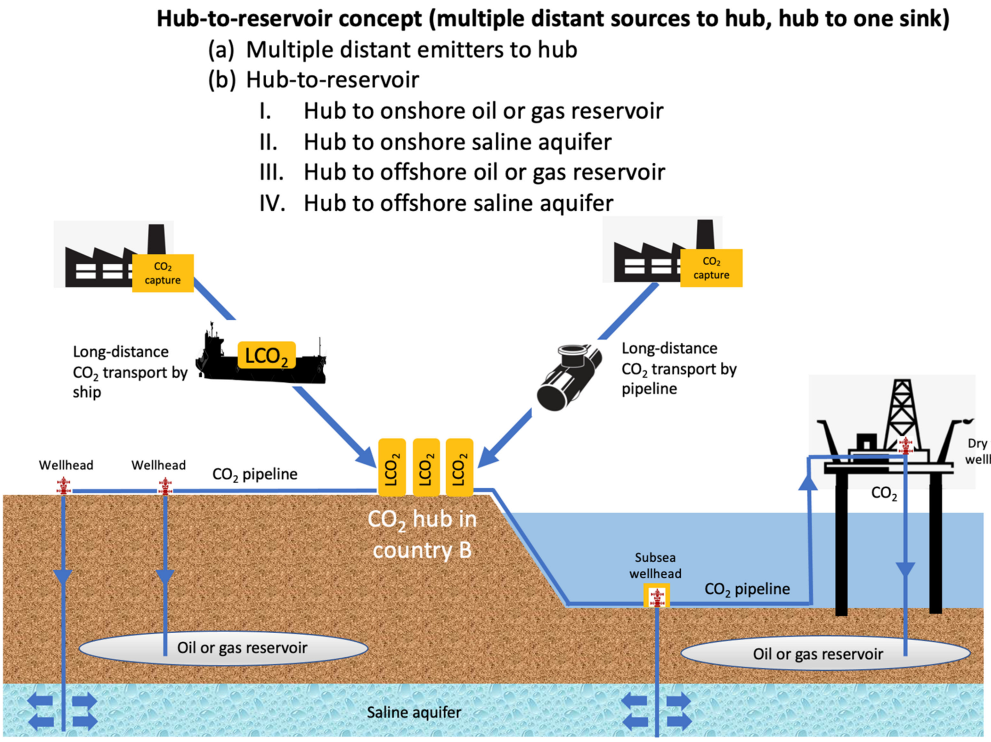

Figure 9. Hub-to-reservoir CCS field development concept.

6. CO_2 Source-Sink Mapping

Figure 10 shows the approximate location of all the cement-related CO_2 sources in Vietnam and all the subsurface CO_2 sinks in Vietnam. In this figure, each blue circle represents CO_2 emissions from one province or municipality, rather than from a cement plant. The area of the circle is proportional to the magnitude of emission. It can be seen that CO_2 sources are located throughout the country, with the majority being in the north. CO_2 sinks are represented by green circles (oil field), red circles (gas field), or a blue patch (saline aquifer). The size of the circle is proportional to the magnitude of the storage capacity. Since practically all the CO_2 sinks are located offshore, we conducted CO_2 source-sink mapping only for the coastal provinces with the largest CO_2 emission from cement factories. The results of our CO_2 source-sink mapping are shown in Table 7.

Table 7. CO_2 source-sink mapping for major coastal cement production clusters in Vietnam.

Region	CO_2 Source (Province or Municipality)	Number of Cement Plants	Cement Prod (Mtpa)	Field Development Concept	CO_2 Sink	CO_2 Source-Sink Distance (km)	CO_2 Storage Capacity (Mt)	Condensate Recovery (MMbbl)
Vietnam-north	Quang Ninh	5	9.80	Clusters-to-reservoir	Saline aquifers in Song Hong Basin	150	32,400	None
	Hai Phong	3	9.50			150		
	Ninh Binh	4	6.90	Clusters-to-reservoir		150		
	Thanh Hoa	6	18.30			150		
Vietnam-central	Thua Thien Hue	6	8.20	Cluster-to-reservoir	Saline aquifers in Song Hong Basin	<200		
Vietnam-south	Kien Giang	3	7.20	Cluster-to-reservoir	Block B gas field	300	452	2.1
Total		27	59.90					

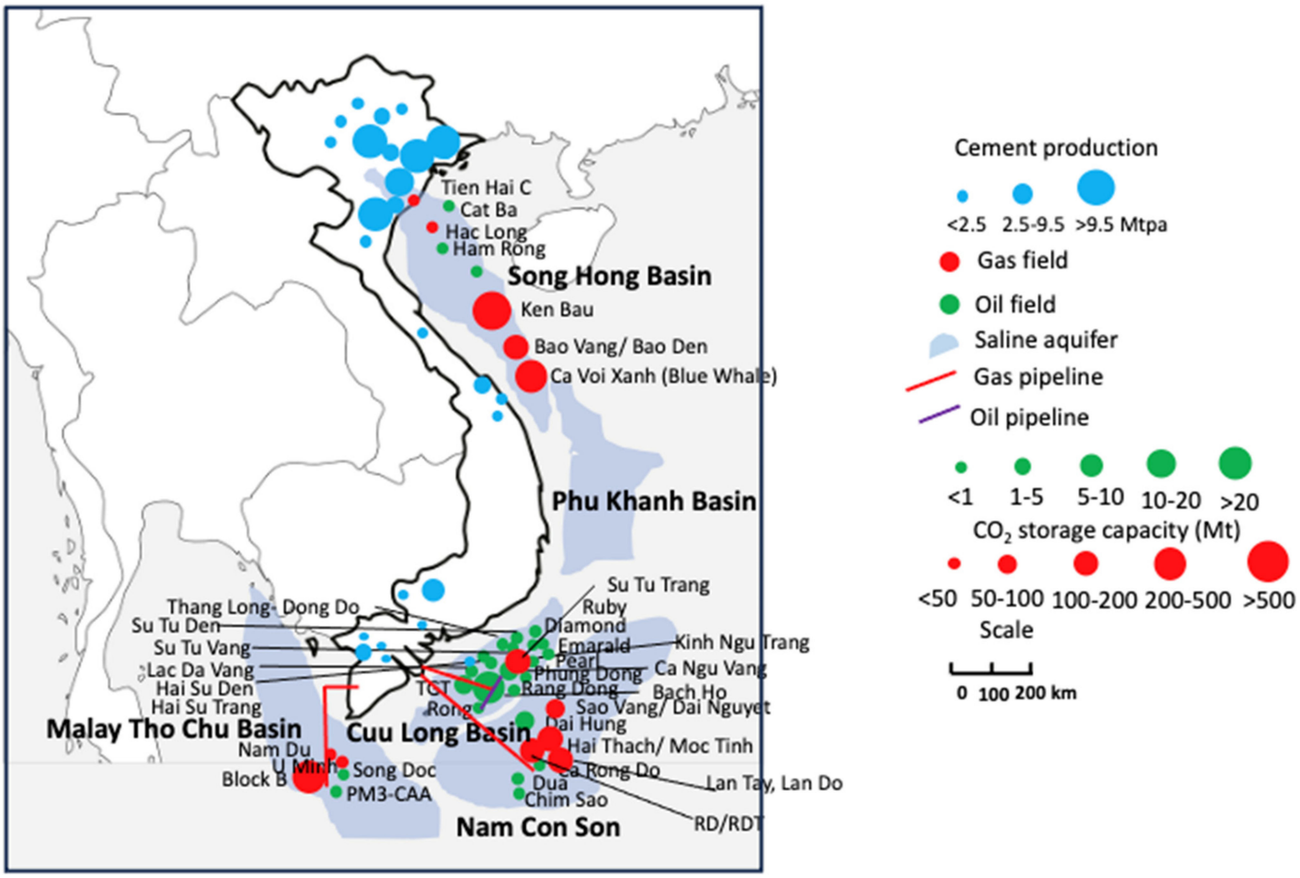

Figure 10. Distribution of cement−related CO_2 sources and CO_2 sinks in Vietnam.

6.1. CO_2 Source-Sink Mapping in Vietnam-North

There are four coastal provinces in Vietnam-north with abundant cement production (Table 7). They are (from north to south) as follows: Quang Ninh, Hai Phong, Ninh Binh, and Thanh Hoa. They have 5, 3, 4, and 6 cement plants, respectively. To facilitate economies-of-scale to reduce CCS cost, we have chosen the clusters-to-reservoir development concept for these provinces. Figure 11 shows how this concept is applied to the Quang Ninh and Hai Phong provinces. The five cement plants in Quang Ninh province can form one CCS cluster (Table 8). The three cement plants in Hai Phong can form another CCS cluster (Table 8). CO_2 captured from these two clusters can be transported by pipelines to a saline aquifer in the Song Hong Basin for permanent storage. Assuming a CO_2 capture efficiency of 90%, which is achievable in post-combustion carbon capture using existing technologies [64], these two clusters can mitigate up to 16.06 Mtpa CO_2 by CCS.

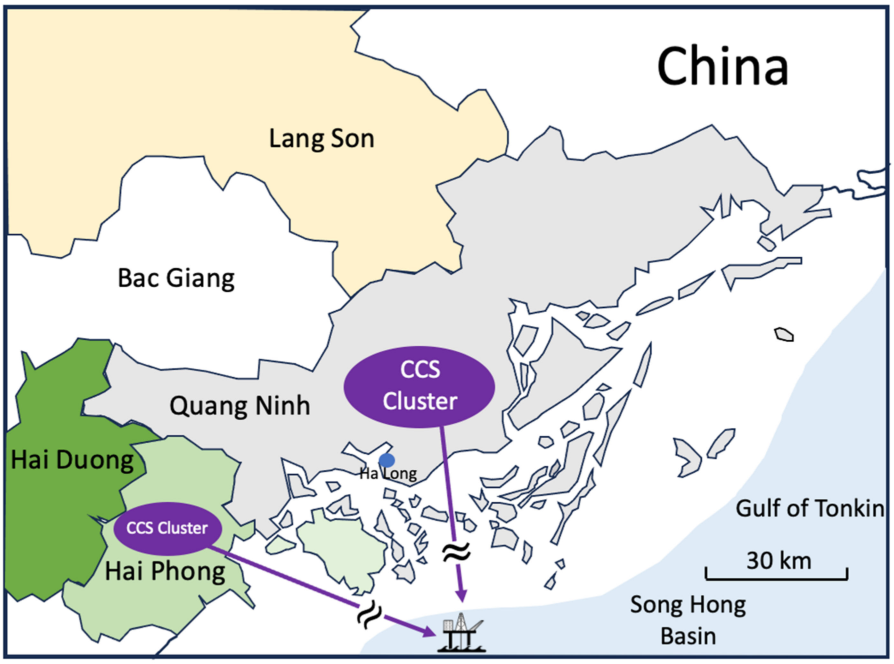

Figure 11. CO_2 source-sink mapping for Guang Ninh and Hai Phong provinces in Vietnam-north.

Figure 12 shows the clusters-to-reservoir concept applied to the northern provinces of Ninh Binh and Thanh Hoa. The Ninh Binh CCS cluster can include four cement plants in the Ninh Binh province (Table 9). The Thanh Hoa CCS cluster can include six cement plants located in the Thanh Hoa province. CO_2 captured from these two clusters will be transported by two pipelines to a saline aquifer in the Song Hong Basin for permanent storage. Assuming a CO_2 capture efficiency of 90%, these two clusters can mitigate 20.98 Mtpa by CCS.

Table 8. CCS clusters in Vietnam-north.

CCS Cluster	Cement Plant	Cement Production in 2022 (Mt)	CO_2 Emisson in 2022 (Mt)	CO_2 Sink
Quang Ninh CCS cluster	Langbang	1.50	1.39	Saline aquifer in Song Hong Basin
	Ha Long	1.20	1.11	
	Thang Long	2.50	2.31	
	Hoan Bo	2.30	2.13	
	Cam Pha	2.30	2.13	
	Subtotal	9.80	9.06	
Hai Phong CCS cluster	Phuc Son	3.60	3.33	
	Chi Fon	4.20	3.88	
	Haiphong	1.70	1.57	
	Subtotal	9.50	8.78	
	Total	19.30	17.84	

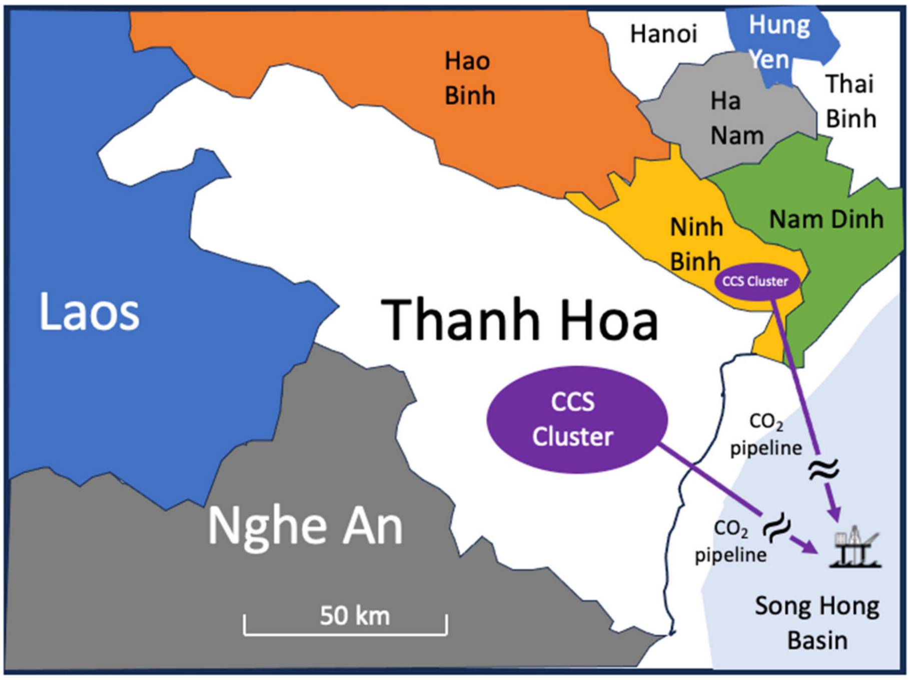

Figure 12. CO_2 source-sink mapping for Ninh Binh and Thanh Hoa provinces in Vietnam-north.

Table 9. CO_2 source-sink mapping for Ninh Binh and Thanh Hoa provinces in Vietnam-north.

CCS Cluster	Cement Plant	Cement Production in 2022 (Mt)	CO_2 Emission in 2022 (Mt)	CO_2 Sink
Ninh Binh CCS cluster	Doyen Ha, Hoa Lu	3.00	2.78	Saline aquifer in Song Hong Basin
	Tam Diep	1.40	1.30	
	Ninh Binh	1.60	1.48	
	Tm Diep	0.90	0.82	
	Subtotal	6.90	6.38	
Thanh Hoa CCS cluster	Nghi Son	6.00	5.55	
	Lang Son	1.00	0.93	
	Bim Son	3.20	2.96	
	Cong Thanh	4.20	3.89	
	Long Son	3.80	3.51	
	Lang Son	0.10	0.09	
	Subtotal	18.30	16.93	
	Total	25.20	23.31	

6.2. CO_2 Source-Sink Mapping in Vietnam-Central

In central Vietnam, the Thua Thien Hue province is a coastal province with six cement plants. The results of CO_2 source-sink mapping are shown in Figure 13 and Table 10. Here, we apply the cluster-to-reservoir field development concept. The CCS cluster includes all six cement plants in this province (Figure 13). CO_2 captured from them can be transported to a saline aquifer in the Song Hong Basin for permanent storage. Assuming a 90% CO_2 capture efficiency, this CCS project can mitigate up to 6.83 Mtpa CO_2.

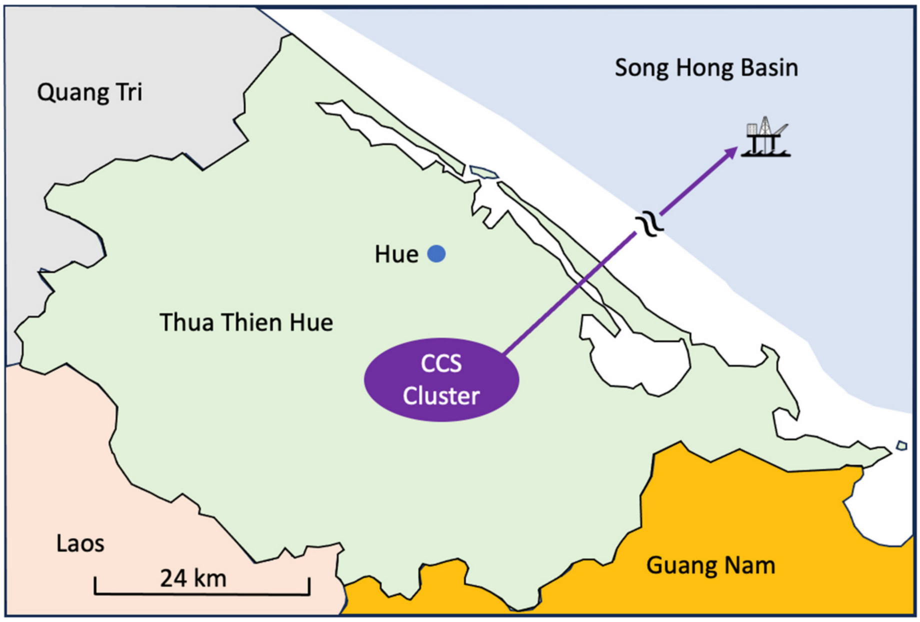

Figure 13. CO_2 source-sinking mapping for Thua Thien Hue province in Vietnam-central.

Table 10. CCS cluster in Vietnam-central.

CCS Cluster	Cement Plant	Cement Production in 2022 (Mt)	CO_2 Emission in 2022 (Mt)	CO_2 Sink
Thua Thien Hue CCS cluster	Dien Bien	0.40	0.37	Saline aquifer in Song Hong Basin
	Dong Lam, Phong Dien	2.00	1.85	
	Thai Nguyen	0.60	0.55	
	Cong Hai	2.20	2.04	
	Huong Tra	1.20	1.11	
	Thuong Quan	1.80	1.67	
	Total	8.20	7.59	

6.3. CO_2 Source-Sink Mapping in Vietnam-South

In Vietnam-south, Kien Giang is a coastal province with three cement plants producing 7.2 Mtpa of cement in 2022 (Table 11). Here, we applied the cluster-to-reservoir field development concept in the CO_2 source-sink mapping. The three cement plants in Kien Gang can form one CCS cluster. CO_2 captured there can be transported through a combination of new and existing pipelines to the offshore Block B gas field for CO_2-EGR and permanent storage (Figure 14). We chose Block B gas field because it is close to the end of pressure depletion and, therefore, ready for CO_2-EGR and permanent CO_2 storage. CO_2 injection will result in an incremental condensate recovery of 2.1 MMbbl. The distance between the Kien Giang CCS cluster and Block B is less than 300 km (Table 7). Assuming a 90% CO_2 capture rate, the Kien Giang CCS cluster will mitigate 5.99 Mtpa CO_2.

Table 11. CCS cluster in Vietnam-south.

CCS Cluster	Cement Plant	Cement Production in 2022 (Mt)	CO_2 Emission in 2022 (Mt)	CO_2 Sink
Kien Giang CCS cluster	Bin An, Ha Tien	0.2	0.18	Block B gas reservoir in Malay Tho Chu Basin
	Hong Chong, Ha Tien (Holcim)	5.0	4.63	
	Hong Chong, Ha Tien (Siam City Cement)	2.0	1.85	
	Total	7.2	6.66	

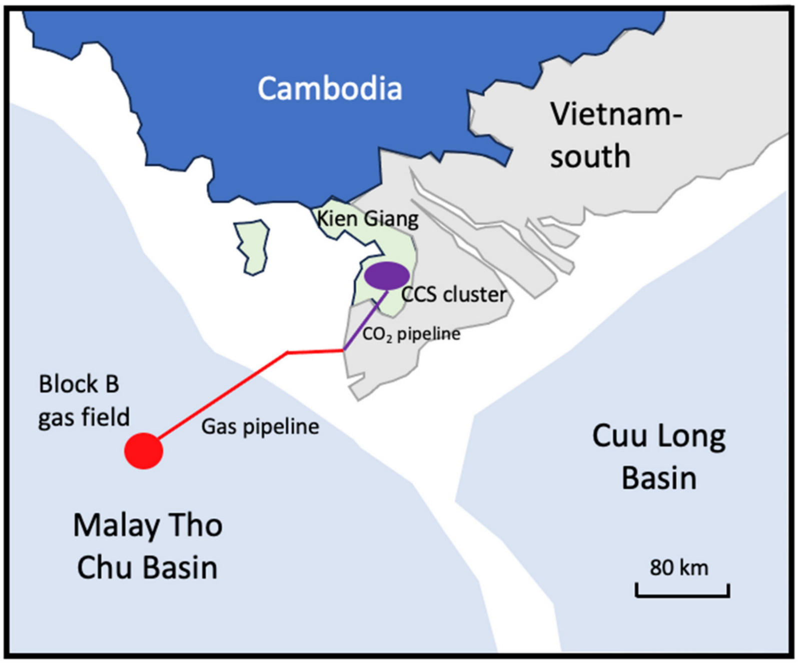

Figure 14. CO_2 source-sink mapping for Kien Giang province in Vietnam-south.

7. Discussion

Our study has resulted in four first-mover CCS projects to decarbonize Vietnam's cement industry. They are named the Northmost, Northern, Central, and Southern CCS projects. Details of these projects are shown in Table 12. The first two projects use the clusters-to-reservoir field development concept, whereas the last two use the cluster-to-reservoir concept. In the first three CCS projects the CO_2 sink is a saline aquifer. In the Southern CCS project, the CO_2 sink is a depleted gas reservoir. Total CO_2 emission from these clusters is 55.40 Mtpa. At a 90% CO_2 capture rate, these projects can mitigate 49.86 Mtpa CO_2, which is 46% of CO_2 emission from Vietnam's cement industry in 2022. This is also equal to 15% of Vietnam's total CO_2 emission in 2021. This is a first-of-a-kind study that considers the large-scale application of CCS toward cleaner cement production in the world's largest cement-exporting country. It will have an impact not only in Vietnam but also globally. As the world is moving away from high-carbon building materials, the production of low-carbon cement in Vietnam will influence cement production worldwide. Today, CCS is the only technology capable of large-scale application to lower the carbon intensity of cement without changing its chemistry. It is hoped that proposal of these projects will encourage scientists, engineers, investors, and policymakers to consider other green cement production projects.

Table 12. Proposed CCS projects to decarbonize Vietnam's cement industry.

Number	CCS Project Name	Region	Development Concept	CCS Cluster	CO_2 Emission (Mtpa)	CO_2 Sink	CO_2 Storage Capacity (Mt)
1	Northmost CCS	Vietnam-north	Clusters-to-reservoir	Quang Ninh	9.06	Saline aquifer in Song Hong Basin	32,400
				Hai Phong	8.78		
2	Northern CCS	Vietnam-north	Clusters-to-reservoir	Ninh Binh	6.38	Saline aquifer in Song Hong Basin	
				Thanh Hoa	16.93		
3	Central CCS	Vietnam-central	Cluster-to-reservoir	Thua Thien Hue	7.59	Saline aquifer in Song Hong Basin	
4	Southern CCS	Vietnam-south	Cluster-to-reservoir	Kien Giang	6.66	Block B gas reservoir in Malay Tho Chu Basin	452
				Total	55.40		

More work will be needed before these CCS projects can be implemented. First, suitable saline aquifers in the Song Hong Basin need to be located for CO_2 geological sequestration in the first three projects (Table 11). This will require detailed subsurface characterization of the Song Hong Basin using seismic, well logs, and coring. Static geological models have to be built to determine the size and boundaries of these aquifers. Reservoir simulation will be run to quantify the maximum CO_2 injection rates per well, the number of wells needed, and the path of CO_2 migration post injection. A CO_2 monitoring program will also be needed to track CO_2 movement in these aquifers. This type of work is rather standard for typical oil and gas field development projects and can be conducted by Vietnam's national oil company in cooperation with international oil companies that have expertise in CCS projects.

In the Southern CCS project, captured CO_2 from the Kien Giang CCS cluster will be injected into the depleted Block B gas reservoir. Since this gas reservoir has been well characterized, less subsurface work will be needed, apart from detailed reservoir simulations to choose the location of CO_2 injection and the reservoir pressure response.

For each project, the number of CO_2 injection wells, their location, and whether they will be dry-tree or subsea well needs to be decided. Given the large quantity of CO_2 that needs to be sequestered, it is expected that each injection well will allow for one-to-several Mtpa of CO_2 injection. Subsea wellheads will probably be preferred to reduce the need to build a new offshore platform. However, workover of subsea wells will be more costly and difficult than dry tree wells installed on a platform. In the Southern CCS project, the existing offshore platform may be used for CO_2 injection.

Given the proximity of the Song Hong Basin to the shore, the construction of a new CO_2 pipeline connecting the CCS clusters in the first three projects to the offshore locations for CO_2 injection is not expected to be too difficult. The costliest part of these projects will probably be the retrofitting of CO_2 capture equipment in the cement plants. Post-combustion CO_2 capture will be the simplest way to go. If the cement plants are located close to each other, then a centralized post-combustion carbon capture plant may be more cost effective than installing CO_2 capture facilities in each cement plant [52,65]. Since each of the CCS projects employs the cluster concept, each CCS cluster can include other CO_2-emitting plants such as coal-fired power stations, refineries, or steel mills.

These four coastal CCS projects are proposed as first-mover projects. If implemented fully, they will mitigate 46% of Vietnam's cement-related CO_2 emission. There are 17 other interior provinces or municipalities with CO_2 emissions from cement plants. They will be the targets for future CCS projects.

The cost of implementing CCS in a cement plant will depend on the carbon capture technology used, the distance of CO_2 transportation, the number and type of CO_2 injection wells, and the monitoring system installed to track post-injection CO_2 migration. According to a study by the United Nations, the toal cost of instaslling CCS in a cement plant is approximately USD 75–100 per tonne of CO_2 captured [66]. This cost consists of 40% capital cost, 30% for heat, and 30% for transpoortation and storage. pipeline cost is about USD 0.9–3.4/t CO_2 for 100 km. Storage costs vary between USD 0.2 to 24/t CO_2 depending on storage site. A detailed cost estimate needs to be performed in the field development stage and is beyond the scope of this study. However, policy incentives for installing CCS in existing cement plants will be helpful.

Based on the findings of this study, the following suggestions are made. First, Vietnam's policymakers should consider promulgating energy policies that will incentivize the production of low-carbon cement. This can come in the form of either a carbon credit or tax and funding of CCS research and development. Second, efforts should be made by PetroVietnam to characterize the saline aquifers in the Song Hong Basin for permanent CO_2 storage. Third, collateral learnings from existing and future CCS projects should be captured and used to develop local expertise in CCS implementation. Fourth, the development of private–public partnership for CCS project management, financing and technology transfer will be helpful to accelerate the rate of CCS adoption in Vietnam's cement industry [34].

8. Conclusions

A detailed CO_2 source-sink mapping exercise has been conducted to map 68 cement-related CO_2 sources in Vietnam and to subsurface CO_2 sinks, such as oil and gas reservoirs or saline aquifers, identified in a previous study using four field development concepts. The results have identified four first-mover CCS projects where 27 cement plants are mapped to subsurface CO_2 sinks. Two of these projects are located in Vietnam-north, one in Vietnam-central, and one in Vietnam-south. In the Vietnam-south CCS project, CO_2 emission from the Kien Giang province is transported and stored in the offshore Block B gas field. In the other three projects, CO_2 emission is transported and stored in offshore saline aquifers in the Song Hong Basin. At a 90% CO_2 capture rate using post-combustion carbon capture technology, these four projects can mitigate 50 Mtpa of CO_2 which is 46% of cement-related CO_2 emissions or 15% of total CO_2 emissions from Vietnam. Together, these projects will significantly reduce the CO_2 footprint of Vietnam's cement industry, thus making it more sustainable. Future research should focus on detailed subsurface characterization of saline aquifers in the Song Hong Basin to identify the optimal saline aquifers for CO_2 storage. Collateral learnings from ongoing CCS projects in the world should also be captured. The methodology developed in this study can be used in decarbonization studies of the cement industry in other countries with substantial offshore CO_2 sinks such as China, India, Thailand, and Indonesia.

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Nomenclature

ASEAN	Association of Southeast Asian Nations
CCS	Carbon capture and storage
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
SCM	Supplemental cementitious material
Gt	10^9 tons
Gtpa	10^9 tons per annum
MMbbl	10^6 barrels
MMP	Minimum miscibility pressure
Mt	10^6 tons
Mtpa	10^6 tons per annum
OGIP	Original-gas-in-place, Sm^3
OOIP	Original-oil-in-place, Sm^3
TRL	Technology readiness level, from 1 to 9
ρ_{CO_2}	CO_2 density, kg/m^3
m_{CO_2}	Mass of CO_2 stored, kg
A	Aquifer area, m^2
B_g	Gas formation volume factor, m^3/Sm^3
B_o	Oil formation volume factor, m^3/Sm^3
h	Average net sand thickness, m
R	Primary recovery factor, fraction
R_{CO_2}	Additional recovery factor by CO_2 injection, fraction

R&D	Research and development
ϕ	Porosity, fraction
E	Efficiency factor, fraction
T	Reservoir temperature, °F
UAE	United Arab Emirates
UK	United Kingdom
USD	United States dollar

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