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Systematic Framework for CO_2 Transport Design of CCS System in the Archipelagic State

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Abstract

In the carbon capture and storage system, carbon dioxide transport plays an essential role in connecting the source and sink points. A series of design stages should be developed to obtain a feasible transport design from an economic perspective. This paper presents a systematic framework for feasible CO_2 transport design. The framework combines various methods and procedures in an integrated manner. The framework consists of two stages. The first stage involves task and system boundary identification, design, and evaluation of the carbon capture and storage (CCS) network. Three design schemes with overall, regional, and pseudo-regional approaches are used to generate the CCS network. The second stage involves designing CO_2 transport in a CCS network with different transport technologies and evaluating all identified transport designs in terms of technical feasibility and economics. Two transport design scenarios are used in this stage, standalone design and shared facilities design. The framework is implemented for the CCS system candidate in the central and eastern parts of Indonesia. The specific cost is used to select the most effective transport designs. The results show that the framework is applicable for the CCS system with many sources and sinks separated in different regions. In such cases, offshore pipelines are not feasible to be applied because the CO_2 transport volume is relatively small and the high-pressure drop. The most effective transport design can be achieved by the regional scheme in which CO_2 transport is restricted only in the same regions.

Keywords CO_2 transport design · Multi-region · Specific cost · CCS system

Introduction

Carbon capture and storage (CCS) is the primary solution to reduce global CO_2 emissions effectively. CCS can reduce emissions from many large industrial emission sources. Application of CCS on a commercial scale requires rigorous decision support due to various issues involved including technical, environmental, and economic (Tan et al. 2012). In several emerging countries, the implementation of CCS still has a significant barrier. The main obstacle in developing CCS is relatively high investment costs (Rubin et al. 2013). There are three major elements involved in this technology, each of which has significant investment costs, namely, CO_2 capture, transport, and storage. In the CCS supply chain, CO_2 transport costs can reach 30% of the total cost, especially for larger distances (Weihs et al. 2014). Therefore, the proper

CO_2 transportation design can reduce investment costs. Various transportation facilities distribute CO_2 from sources to sinks, ranging from pipelines, road tankers, rail tankers, and ship tankers, depending on the volume (Leung et al. 2014). Pipelines and ship tankers are the only viable method to transport a large amount of CO_2 in a CCS system (Mallon et al. 2013). Pipeline transport has been widely studied and well deployed for CCS projects, while ship transport is still a less developed concept for these applications.

In 2018, there were 542.88 Mt CO_2 emitted by fossil fuel combustion in Indonesia, where industrial activities contribute almost 60% of CO_2 emission (IEA 2020). Indonesia has potential geological storage formation that can be used as a long-term CO_2 storage option. Hence, the CO_2 transport is required to connect between the CO_2 source and sink. Pipelines are the most used option to transport CO_2, especially for EOR (Mallon et al. 2013). However, for a large scale of CO_2 sources and large distances, the CO_2 ship transport can be more attractive. At larger distances, ship transport is cheaper, and the operational expenditure (OPEX) can be decreased while

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spending a lower time fraction for loading–unloading (Yoo et al. 2013).

In the literature, the cost for CO_2 transporting over 100 km was estimated. The Global CCS Institute (GCCSI) estimates at 0.4–15 euro/tCO_2 for onshore pipeline, 3.4–51.7 euro/tCO_2 for offshore pipeline, and 11.1–19.3 for ship transport (GCCSI 2011). Decarre et al. (2010) estimate the cost of CO_2 ship transport. The study confirms that the transport cost varies from 24 to 32 euro/tCO_2 and more economics when the distance exceeds 350 km. Several cost models that describe costs of CO_2 transport have been developed. Most of the cost models in the literature focus only on pipeline costs. The International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) developed the capital costs model for CO_2 pipelines. The model can be categorized in quadratic equations and be developed for onshore as well as offshore (IEA GHG 2002). Gao et al. (2011) estimated the costs for different modes of CO_2 transport for a given case study. They developed a cost model that is specific to the Chinese market. However, the model can be used for other parts of the world with a few adaptations. There are a diversity of different cost models in the literature. The decision on which model to use is ad hoc.

The economical design of CO_2 transport infrastructure to match sources with appropriate sinks is a significant driving force for realizing the CCS project (Brunsvold et al. 2011). In the archipelagic state, CO_2 transport is more technically challenging. Either a pipeline or a ship can be used for transportation—unfortunately, ships for transporting a large scale of CO_2 across the sea are still in the development stage. Only a few studies addressed ship transportation.

In many cases, ship transport of CO_2 provides a more flexible and more cost-effective transport solution (IEA 2020). Yara International has been operating a small-scale semi-pressurized CO_2 ship for shipping liquid CO_2 in ten European import terminals. The vessel sizes vary between 870 and 1250 tonnes, and the transport pressure is about 14–16 barg (Hegerland et al. 2005). However, these ships are not suitable to transport liquid CO_2 on a large scale. The intermediate storage and ship tank's capacities should be enlarged, and as a consequence, lower pressure is required.

A CCS network design would affect the effectiveness of CO_2 transport where the more complex CO_2 transportation route may increase transportation costs. Sometimes, several sources with a specific emission rate would be required to meet the capacity of single CO_2 storage. Thus, in this case, a single trunk line or a large-scale CO_2 carrier might be used to transport CO_2 from several sources to the sink. Transport facilities are required to deliver CO_2 from sources to sinks. To obtain a feasible CO_2 transport design, the CCS network should be designed properly. Pinch analysis is a useful tool for CCS network design problems.

Pinch analysis was originally developed for energy targeting in the process plants (Kemp 2007). The procedure to target minimum energy requirement was given by Hohmann (1971) and Linnhoff and Flower (1978). Hohmann introduced temperature-enthalpy analysis as the foundation for the pinch technology. The procedure to identify the feasible heat recovery in heat exchanger network (HEN) design through the network temperature pinch was first described by Linnhoff and Flower (1978). Both procedures identify the best possible degree of process heat recovery as a function of the minimum temperature difference. The application of pinch analysis for carbon emission targets has been reported in the literature. Tan and Foo (2007) presented a graphical procedure for energy sector planning with emission constraints based on pinch analysis. The technique has been used for various applications and provides graphical displays that are intuitively easier to understand than is possible with mathematical programming. Ooi et al. (2013) proposed a pinch-based graphical tool known as carbon storage composite curves (CSCC) to handle the CCS planning problem. According to their work, the CSCCs are plotted as a time vs capacity diagram, where the carbon storage is defined as the total accumulated CO_2 load for carbon capture and storage and plotted as the capacity axis, while the time axis represents the temporal aspects in the planning period. They also developed the grand composite curve (GCC) for scheduling storage capacity surplus or deficit.

A novel graphical technique based on pinch analysis is proposed to address CCSU planning and targeting problems. The pinch-based technique can be used as a general technique to analyzing the sensitivity of system targets, especially in economic and emission targets (Mualim et al. 2022a). A pinch analysis approach for the planning of carbon management networks (CMNs) based on CO_2 emission in industry is developed (Tan et al. 2021). A pinch-based approach has been used to calculate optimum values of CO_2 capture and storage (CCS) retrofit and compensatory renewable power (Ilyas et al. 2012). Diamante et al. (2013) proposed a graphical approach based on pinch analysis to determine the optimum source-sink matching in the CCS system. The technique uses the physical characteristics of the geological sinks in capacity and injectivity as constraints for CCS planning. The proposed method assumes that all sources and sinks exist at the beginning of the planning period, while in the actual case, all sources and sinks may not be readily available at the same time period. Thus, it still leaves a time planning problem. The later work by Joseph Angelo R Diamante et al. (2014) presented an improved pinch analysis-based methodology to address the multi-period of CCS planning problems with injectivity constraints. The method may be implemented in either graphical or algebraic form. Thengane et al. (2019) developed a pinch analysis–based approach for optimal matching

of CO_2 sources and sinks in the CCUS system. The proposed method consists of an algebraic technique to determine preliminary CCUS targets and the graphical GCC tool to verify those targets.

It should be noted that the pinch model proposed by researchers focused on the issue of optimum source and sink matching, maximizing CO_2 capture for the temporal, flow rate, and storage constraints in the CCS system, and the actual target of CO_2 captured in the CCUS system. However, the works had not given a clear analogy in the matching of the source and sink by grid diagram. The grid diagram used to obtain exact pairing between sources and sinks is proposed by Handogo (2018). This work uses time difference to evaluate the amount of CO_2 that has to be stored. The later work by Putra et al. (2018) has proposed detailed approaches via algebraic techniques for multi-period and multi-region CCS planning problems in a realistic situation. Recently, Mualim et al. (2021) applied the pinch design method for designing the CCS network and assessing its cost-effectiveness of the CCS system. The design of CCS networks is represented by a grid diagram. The procedure to generate a grid diagram of the CCS network refers to the strategy for the design HEN developed by Linnhoff and Hindmarsh (1983).

The design of CO_2 transport is a part of CCS system design, which must be viewed holistically. Varying CCS network designs will result in different transport costs. The design stage sequence should be performed based on the hierarchical approach to obtain a more feasible CO_2 transport design solution. This approach may be started from the planning stage to get CCS network design and maximum CO_2 captured. Based on the possible design of the CCS network, several alternative transport designs can be developed. All identified alternative design results are potentially feasible. Therefore, a set of predefined performance criteria must be defined to determine the most viable design. The most important criteria to evaluate the performance is economic criteria. Then, the cost of all alternative designs of CO_2 transport should be evaluated. The process integration approach can be used to achieve feasible transport design effectively. El-Halwagi (2012) proposed that process integration involves task identification, targeting, generation and selection of alternatives, and analysis of selection alternatives.

This paper aims to propose the method for the design of CO_2 transport, which combines the planning and evaluation stage in the CCS system through process integration. The method will combine CCS target and network design, pipeline design and ship-based transport design technique, and cost evaluation in an integrated manner. The second is to highlight the application of the framework to obtain CO_2 transport design for CCS systems in the central and eastern parts of Indonesia. In this study, two options of offshore transport, offshore pipeline, and ship transport will be

applied to obtain the more attractive design option for CO_2 transportation. The net present value (NPV) and specific cost (SC) will be introduced as a new parameter to assess the CO_2 transport design's cost-effectiveness in multiple times of the CCS system.

Methods

The methodological framework to develop a more feasible CO_2 transport design is proposed in this section. The workflow of the framework proposed in this study is shown in Fig. 1. The framework consists of several steps involving identification, design, and evaluation steps. A detailed description of the workflow is given in the next subsection.

Source and Sink Selection

The first step of developing a CO_2 transport design is to select the CO_2 emission sources and CO_2 storage sinks. The source and sink candidates are selected based on the method proposed by Usman et al. (2014). Some data needed for this research are source and sink of CO_2, time availability, operation lifetime, capacity, and flow rate for both source and sink. The amount of CO_2 captured is assumed as 90% of the CO_2 that is produced (IPCC (2005)).

Development of CCS Network Design

This step is broken down into two sub-steps, CCS targeting and network design. CCS targeting aimed to obtain the magnitude of CO_2 captured and transferred between a source and sink in a multi-period CCS system. The cascade table is used to calculate the CO_2 sequestration targets of the CCS system. This technique has been conducted by Diamante et al. (2014), known as carbon capture and storage cascade analysis. The objective of CCS network design is to get a suitable design of the CCS network after identifying the CCS planning target. There are several methods to design a CCS network. In this study, the design of the CCS network is conducted based on nearest neighbor algorithm (NNA) principles, where each sink is matched by sources that are the nearest available neighbors in terms of operating time and CO_2 flowrate (emission rate and injection rate) to meet the established carbon targets. The conceptual approach of NNA was developed earlier by Prakash and Shenoy (2005) to design a minimum freshwater network for fixed contaminant load problems. The later work by Shenoy (2010) used a similar approach that is extended to synthesizing energy allocation networks for reduced carbon emissions. The multi-period CCS network will be described using a grid diagram to obtain a clear CCS network design vision. The grid diagram can describe the CCS network with details of

Fig. 1 The methodological
framework for CO_2 transport
design
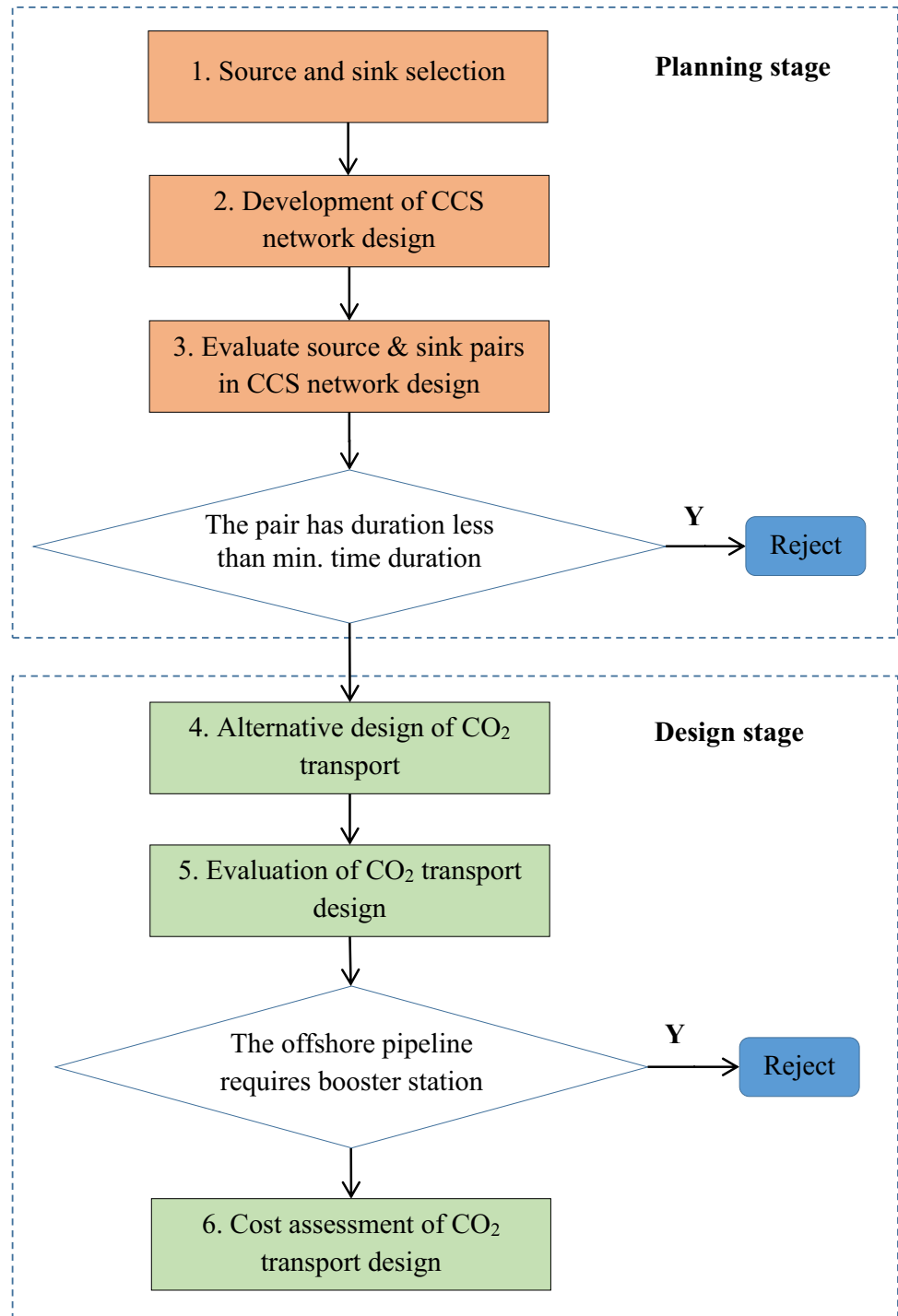
connection or pairing between sources and sinks, but the real integration must be investigated later to give better results.

The network will be made in three ways, overall, regional, and pseudo-regional. In an overall approach, there is no consideration about which region do source and sink belong to; every source and sink can be paired without any region limitation. In the regional approach, region limitation of source and sink is considered. Hence,

the source can only be paired with the sinks in the same region. The pseudo-regional is developed from the regional approach. The source and sink which belong to the same region are paired first. The excess CO_2 emissions that arise from one region are then transferred to another region that has a suitable excess CO_2 sink. The final results for the maximum CO_2 sequestration will equal to overall approach.

The proposed CCS network design approach is similar to inter-plant process integration. The process plant consists of several interconnected process unit. The heat integration of process plant may be performed simultaneously by exchanging the heat from one process unit to another. Likewise, the heat integration of process plant may be performed sequentially by exchanging the heat in every single process unit independently without involving other processing units (Santi et al. 2018).

One common reason for imposing heat integration constraints results from the area of integrity (Smith 2016). Some areas or process unit are maintained to be operationally independent for reasons such as operational flexibility and safety. In the multi-region CCS system, some constraints result from the geographical locations which does not allow CO_2 transfer from source to sink. Thus, the CSS network can only be designed with regional approach. If geographic barriers can be overcome and the CO_2 transport from source to sink in different regions is possible, then the CCS network can be designed with overall approach.

Evaluate Each Pair in CCS Network Design

Every possible pair should not be applied in the CCS network. The pairs with short time periods can be eliminated from the network design to avoid the potential high annual cost. In this study, the pairs that operate less than 5 years of a time period are not considered for CCS network design.

An Alternative Design of CO$_2$ Transport

A problem with CCS may occur when the source and sink locations are not necessarily in a single region, so it is possible that the CCS process can occur in a multi-region where the source and sink locations are far apart and with many regions (Dwiputro et al. 2021). Two design scenarios will be developed in this step, namely standalone design and shared

facilities design. The standalone design of CO_2 transport is performed for three CCS network designs from step 2. The transport facilities of each source and sink pairs are designed to have their own transport facilities. The shared facilities design is developed from a pseudo-sequential CCS network. The transport facilities from two sources or more in one region are considered to design as a single shared facility. A single pipeline or a single ship transport facility will be used to transport CO_2 from several sources to a particular sink. The principle of shared facilities design is depicted in Fig. 2. The CO_2 captured from the multiple point sources then feeds into the single diameter trunkline or a single ship transport facility. The results of this step involve the design parameter of equipment (for example, pipe length and diameter), transportation mode of CO_2 (ship or pipeline), the number of ship tankers, and its capacity.

Pipeline Design

In the CCS network, the distance between source and sink points may vary. The variation in the distance and transport capacity makes a supercritical phase not an effective pipeline transport condition (Mualim et al. 2022b). The pipeline design involves a minimum wall thickness and nominal size of diameter according to API specification 5L standard. The maximum design pressure of the pipeline is assumed 10% higher than the inlet pressure. The steel X–grade material, according to API 5L, is selected for pipe material. The chosen material used in an onshore piping system is carbon steel pipe from grade X42 to X70 or equal to ANSI 900#. The pipe steel grade X80 or equivalent to ANSI 1500# is assumed to be used for the offshore pipeline material.

The booster station will be built to accommodate the pressure drop along the pipeline. The pressure drop below 100 bar must be avoided, even though the dense phase's minimum pressure is 78 bar. The booster station will be installed if the pipe pressure drops to 100 bar to ensure that

Fig. 2 Shared facilities design concept of CO_2 transport

Multiple source

Single ship transport facilities

OR

Single diameter trunkline

CO_2 storage
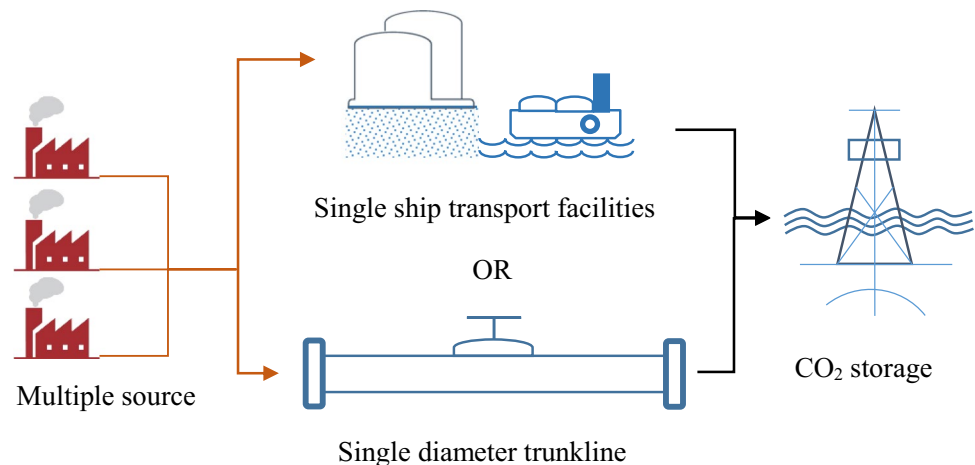
CO_2 will not undergo a phase change. The feasible pipeline design is determined following the procedure given by Knoope et al. (2014) and Mualim et al. (2022b). The illustration of components in pipeline transport facilities resumes in Figs. 3 and 4. The characteristics and conditions of the pipeline transport options are resumed in Table 1.
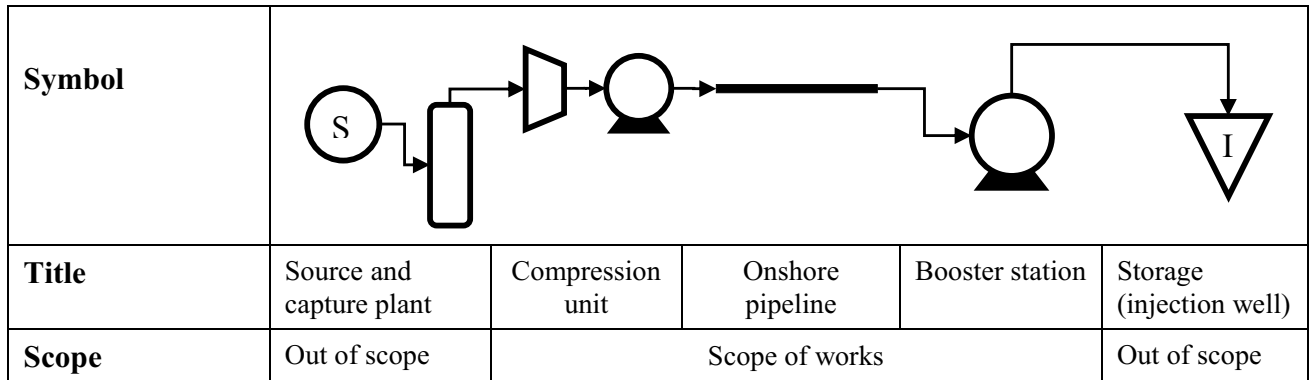
Symbol					
Title	Source and capture plant	Compression unit	Onshore pipeline	Booster station	Storage (injection well)
Scope	Out of scope	Scope of works			Out of scope

Fig. 3 Onshore pipeline transportation components and route symbol

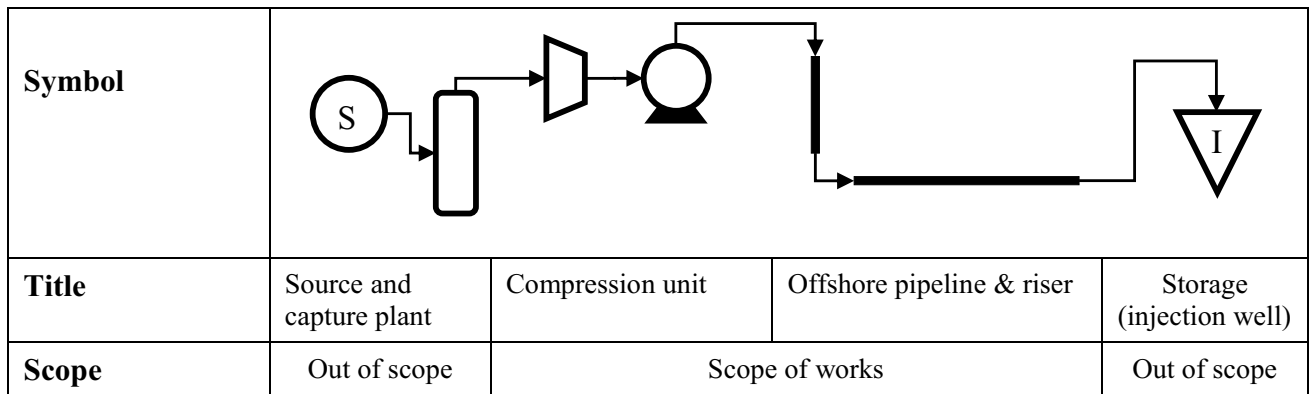| Symbol				
Title	Source and capture plant	Compression unit	Offshore pipeline & riser	Storage (injection well)
Scope	Out of scope	Scope of works		Out of scope

Fig. 4 Offshore pipeline transportation components and route symbol

Table 1 Transport characteristic of CO_2 via pipeline

Parameter	Unit	Onshore	Offshore	Reference/comments
Pressure inlet compressor	Bar	1	1	
Temperature inlet compressor	°C	25	25	
Compression stage		7	7	Estimate from pressure ratio
Compressor pressure ratio		2	2	
Inlet cooling water temperature	°C	30	30	Average cooling water temperature
Gas temperature after cooling	°C	35	35	
Compressor adiabatic efficiency	%	85	90	(Roussanaly et al. 2014)
Pump adiabatic efficiency	%	75	75	(Knoope et al. 2014)
Pressure after pumping	Bar	150	200	(Roussanaly et al. 2014)
Temperature after pumping	°C	45	45	HYSYS simulation
Flexible pipeline riser length	m	–	>200	The depth of the seabed
Average pipeline temperature	°C	30	4	
Outlet pressure	Bar	100	70	(ZEP 2011)
Over length factor	%	10	10	(Roussanaly et al. 2014)
Design pressure	Bar	165	250	1.1 × Operating pressure

Several assumptions are given to obtain more realistic conditions. The scope of the base case design for the CO_2 pipeline system is as follows:

- Onshore pipeline transportation facilities include compression facilities from custody transfer point, piping, and booster station.
- Offshore pipeline transportation facilities include compression and pumping facilities and the flexible pipeline riser to transport the CO_2 from the onshore to the seabed. The booster station is not considered along the offshore pipeline due to the high cost.

CO_2 has to be pressurized up to 150 bar or more to obtain a dense phase or supercritical state at the inlet pipeline. A series of compression and pumping stages are required to achieve the design pressure: pump and compressor, both types of turbomachinery. Standard turbomachinery design practice limits the inlet flow Mach number at the stage inlet to avoid generating shock waves in blade passages. This speed limitation results in a pressure ratio per stage of approximately 1.7 to 2.0:1 on CO_2 (Baldwin and Williams

2009). Hence, to pressurize CO_2 up to 150 bar or more requires at least seven compression stages. The CO_2 outlet compressor can be liquefied by decreasing the temperature to ambient conditions and should be pumped further to achieve the necessary operating pressure in the pipeline.

Ship-Based Transport Design

The conditioning of CO_2 before shipping is required to obtain the liquid phase. The illustration of components in pipeline transport facilities resumes in Fig. 5. The conditioning facilities are onshore and consist of a liquefaction process, intermediate cryogenic storage, and loading equipment, with the characteristics given in Table 2. Based on the previous study, some basic assumptions and input parameters are determined as follows:

- The ship capacities are optimized for each calculation based on IEA GHG (2004). Three different size options of 10,000 tons, 30,000 tons, and 50,000 tons are used because the CO_2 load capacities vary from small to large capacities.
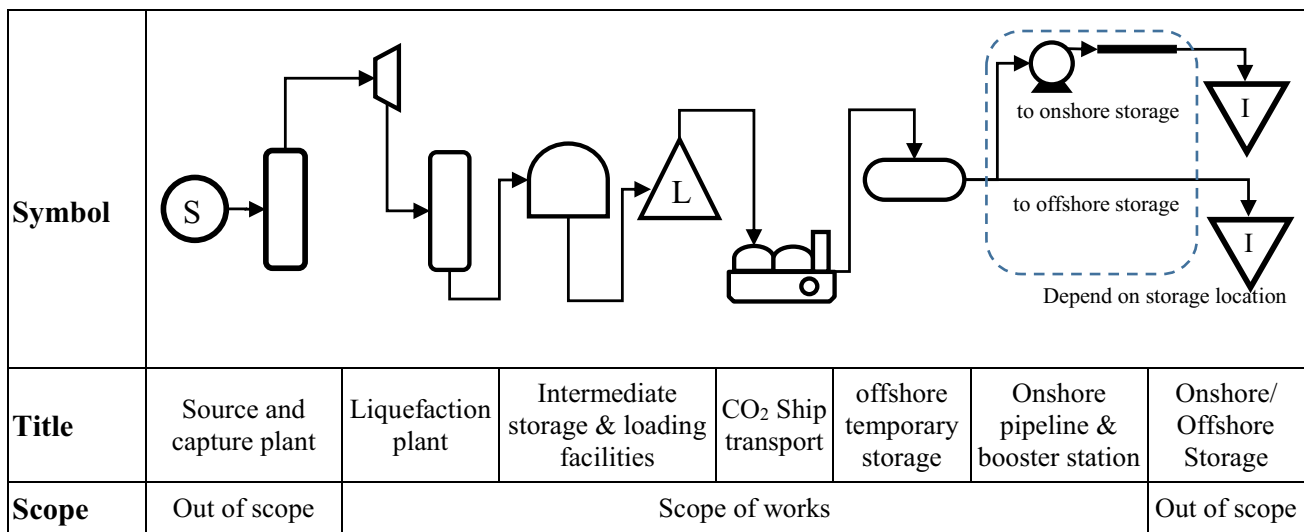

Symbol	
Title	Source and capture plant	Liquefaction plant	Intermediate storage & loading facilities	CO_2 Ship transport	offshore temporary storage	Onshore pipeline & booster station	Onshore/ Offshore Storage
Scope	Out of scope	Scope of works					Out of scope

Fig. 5 Ship transportation components and route symbol

Table 2 Transport characteristic of CO_2 via ship

Parameter	Value	Unit	Reference/comments
Inlet pressure	1	Bar	
Inlet temperature	25	°C	
Pressure after conditioning	8	Bar	
Temperature after conditioning	− 50.3	°C	(Alabdulkarem et al. 2012)
Shipping cycle duration	16	h	IEA GHG (2004)
Shipping service speed	15 and 18	Knot	MHI (2004)
Ship operating time	350	d/y	(Roussanaly et al. 2013)

- The ship has two options of speed, 15 knots and 18 knots.
- The CO_2 stream condition before liquefaction is atmospheric.
- The liquefaction plant is sized based on the CO_2 capture rate annually.
- The sizing of the intermediate storage corresponds to the size of ships required for the transport.

The shipping speed is selected first to determine the number of ships and ship capacity. The ship's operating schedule is calculated to get CO_2 volume delivered per cycle or ship's round trip. The equations are developed as follows

$$RTD = \frac{1}{24}\left(\frac{2 \times Distance}{v_S} + \frac{V_T}{L_R} + \frac{V_T}{U_R} + 16 \right) \tag{1}$$

where RTD is round-trip days or the one cycle of the ship for loading, sail from source to sink, unloading, and back again to the source to repeat the cycle (days); *distance* is the geographical distance between sources and sinks by sea (km); v_S is vessel or ship speed (km/h); V_T is the capacity of CO_2 transported according to selected ship size (ton); L_R and U_R are loading rate and unloading rates respectively, with the average speed rate for loading and unloading set to 500 ton per hour; the number 16 is the time consumed (hour) for mooring, sailing, loading–unloading preparation, and another harbor maneuvering; and the number 24 is the conversion factor in obtaining RTD in a unit of days.

Total capacities of intermediate storage are obtained from RTD and liquefaction plant capacities, as shown in Eq. 2. The number of storage is determined from Eq. 3. The size of an existing cylindrical pressure vessel is approximately 6500 m^3 (Seo et al. 2016). The cylindrical pressure vessel is selected to store liquid CO_2 temporarily, with a maximum size of 4500 m^3 assumed. The vessel's size refers to the optimal size of the cylindrical tank for CO_2 intermediate storage proposed by Decarre et al. (2010). A margin of 20% is added as buffer volume to anticipate the ship's time delay caused by damage, weather, or accident.

$$Q_S = 1.2 F_C \times \frac{RTD}{NOS} \tag{2}$$

$$N_S = ROUNDUP\left(\frac{Q_S}{4500\rho} \right) \tag{3}$$

where Q_S is the required capacities of intermediate storage (ton), F_C is CO_2 transfer rate (ton/day), *NOS* is the number of the ship, and N_S is the number of the storage tank. The result may be in a fractional number; then, the numbers generated have to be rounded up to obtain integer results.

Evaluation of CO_2 Transport Design

This step aims to evaluate the proposed design in terms of technical feasibility to obtain the proper design. In this step, evaluation is only performed for the offshore pipeline based on whether the booster station is required or not. The presence of a booster station in an offshore pipeline is a significant issue. Installation of offshore's booster stations should be avoided due to the difficulties in design and uncertainty in investment, which may affect the overall cost. The offshore pipeline design that does not meet the technical feasibility can be re-designed to be feasible.

Cost Assessment of CO_2 Transport Design

The cost assessment is an important step in developing the CO_2 transport design to achieve a more economical design. Transportation costs are expressed on a mass basis (dollar per ton CO_2 transported). All of the transport designs should be evaluated in the same manner for comparison. The various CO_2 ship transport elements' cost assessment will be estimated based on the selected literature.

Cost Escalation

An escalation model is used to extrapolate the calculated costs in certain times into future potential costs based on Chemical Engineering Plant Cost Index (CEPCI). The costs were expressed in euro or other currency first converted into USD for the year the reference was published. Then, the costs are escalated to the year 2021 by multiplicative of equivalent cost index. The correlation for cost escalation is given in Eq. 4. The value of the cost index of selected years is shown in Table 3.

$$C_{2021} = C_T \times \frac{INDEX_{2021}}{INDEX_T} \tag{4}$$

where C_{2021} is equipment or process unit cost in the year 2021, C_T is equipment or process unit cost at year T,

Table 3 Chemical engineering plant cost index

Year	2000	2004	2010	2014	2015	2019	2021
CE Index	394.1	444.2	550.8	576.1	556.8	607.5	776.3
Pumps and compressors	665.3	719.4	902.6	937.6	956.2	1069.2	1179.3
Pipe, valves, and fittings	545.9	600.6	824.4	877.4	835.6	963.3	1414.8

$INDEX_{2021}$ is cost index at the year 2021, and $INDEX_T$ is cost index at year T.

Capital Cost

Two capital cost estimation methods are used. The first method is to estimate CO_2 liquefaction plant, intermediate storage, and ship. The capital cost estimation for CO_2 ship transport refers to the literature as given in Table 4. The second method is to estimate the costs of pipeline transport. The pipeline capital costs are determined using the linear cost pipeline equations developed by IEA GHG (2002). The power law of capacity is used to scale the investment costs of process units and equipment from the selected literature. The power-law correlation is given in Eq. 5. The factor and coefficient of the unit and equipment are obtained from several sources that are available in the open literature (Peters et al. 2003).

$$C_P = C_B \left(\frac{Q}{Q_B} \right)^y \tag{5}$$

where C_P is process equipment or process unit cost with capacity Q, C_B is known base cost for process equipment or process plant with capacity Q_B (ton per day), and y is cost exponent constant of process equipment or process unit.

The capital costs are estimated based on the year as per reference and will be updated further using CEPCI (2021). The capital costs are expressed annually because the capital costs have been borrowed over a fixed period at a fixed rate

of interest of 11.02% per year. The capital cost can be annualized according to Eq. 6.

$$ACC = CC \times \frac{r(1+r)^n}{(1+r)^n - 1} \tag{6}$$

where ACC is annualized capital cost, CC is capital cost, r is the interest rate per year, and n is the number of years.

Operating and Maintenance Cost

In this study, the annual O&M costs of the CO_2 pipeline are expressed in terms of an equation as a function of length and diameter according to IEA GHG (2002), while the annual O&M costs of ship transport are estimated based on the parameters shown in Table 5.

Economic Criteria

In the CCS system, the design of CO_2 transport is not an individual project. The CCS system consists of several transport design networks with different periods. Therefore, specific economic criteria are required to evaluate the project performance. The following criteria are used to estimate the proposed design's price, namely net present value (NPV) and specific cost (SC). These economic criteria are also used to screen the proposed transport design. Every transport design scheme has several pairs of sources and sinks with their transport design. Each pair in the transport design scheme has a different operating time.

Table 4 Selected capital cost of CO_2 shipping

Cost element	Base capacity	Scale factor	Construction cost (M$)	Source year price	Reference
Liquefaction[1]	2.5 Mt CO_2/y	0.9	30.19	2010	(ZEP 2011)
Intermediate storage[2]	4500 m^3	1	7.48	2014	Decarre et al. (2010) (Seo et al. 2016)
Loading equipment[3]	0.8 Mt CO_2/y	1	1.463	2014	(Skagestad et al. 2014)
Ship building[4]	10 kton	n.a	34 (15 knot)	2004	MHI (2004)
		n.a	35 (18 knot)	2004	MHI (2004)
	30 kton	n.a	58 (15 knot)	2004	MHI (2004)
		n.a	60 (18 knot)	2004	MHI (2004)
	50 kton	n.a	82 (15 knot)	2004	MHI (2004)
		n.a	85 (18 knot)	2004	MHI (2004)
Floating vessel[5]	10 kton	0.69	13.57	2015	(Knoope et al. 2015)
	30 kton	0.69	28.95	2015	Knoope et al. (2015)
	50 kton	0.69	41.19	2015	Knoope et al. (2015)

[1] Appendix B1
[2] Appendix B2
[3] Appendix B3
[4] Appendix B4
[5] Appendix B5

Table 5 The operating and maintenance cost of CO_2 shipping

Cost element	Capacity	O&M component	Value
Liquefaction		O&M	5% of investment/year
Intermediate storage		O&M	5% of investment/year
Loading equipment		O&M	$2,000,000/year
Transport ship	10 kton	CIM	5% of investment/year
		Harbor fee	2 × $21,690/cycle/ship
		Fuel cost	$9150/day/ship
	30 kton	CIM	5% of investment/year
		Harbor fee	2 × $34,270/cycle/ship
		Fuel cost	$11,480/day/ship
	50 kton	CIM	5% of investment/year
		Harbor fee	2 × $45,850/cycle/ship
		Fuel cost	$12,700/day/ship
Floating vessel		O&M	5% of investment/year

The NPV is one of the most insightful economic criteria. It can be used to accounts for different durations of project alternatives and the inflows and outflows of cash over the life of the project (El-Halwagi 2012). In such cases, the TAC is selected to meet the performance criteria, but it does not account for the time value of money. When competing for the four proposed transport designs, the design with the lowest NPV is won because the CCS project is categorized as an environmental compliance project that is not expected to make revenue. The following equations are given to obtain the NPV.

$$NPV = Annual\ Cost \times \left[\frac{(1+r)^n - 1}{r(1+r)^n} \right] \quad (7)$$

$$Annual\ Cost = AOC + ACC \quad (8)$$

$$F = C(1+r)^n \quad (9)$$

where *Annual Cost* is a uniform annual number that distributes the *NPV* of the project over a given period, *AOC* is the annual operating cost (US$/year), *ACC* is the annual capital cost (US$/year), *C* is current price/cost at 2021 (US$), *F* is future price/cost (US$), and *r* is the interest rate (11.02%).

In addition to assessing the proposed transport design's effectiveness, the SC is used for the purposes. To obtain the SC, the NPV can be normalized on per mass CO_2 basis by dividing the NPV by the total mass load of the CO_2 recovered, as given in Eq. 10.

$$SC = \left[\frac{NPV}{\sum_{i=1}^{M} \sum_{j=1}^{N} FS_{ij}} \right] \quad (10)$$

where FS_{ij} is the CO_2 mass transfer rate from source to sink (Mt/year), *i* is the number of sources from 1 to M, and *j* is the number of sinks from 1 to N.

Results and Discussion

Source and Sink Selection

The case study focuses on a multi-region CCS system with four selected regions: East Kalimantan, South Sulawesi, North East Java, and Papua. According to the "Source and Sink Selection" subsection, five types of industries were selected consisting of Pupuk Kaltim, Badak LNG, Semen Bosowa, Semen Tonasa, and LNG Tangguh. Carbon storage comes from three places, Papua, East Kalimantan, and North East Java. The name of each sink is Site Salawati Basin, Kutai-Tarakan-Barito (KTB) Basin, and North East Java (NEJ) Basin, respectively. KTB basin is three different geological storage in a separated location but in the same region of East Kalimantan. Among the three sinks, the Kutai basin has the largest CO_2 storage capacity, while the other two sinks' capacity is relatively small compared to that of the Kutai Basin. It is assumed that the Barito

Table 6 Source data for CCS in the central and eastern part of Indonesia

Code	Industrial source	Start time (year)	Duration (year)	End time (year)	Average CO_2 emission rate (Mt/year)	CO_2 production load (Mt)
S1	Pupuk Kaltim	5	25	30	2.403	60.075
S2	Badak LNG	5	15	20	5.514	82.71
S3	Semen Bosowa	7	20	27	1.575	31.5
S4	Semen Tonasa	8	20	28	3.791	75.82
S5	LNG Tangguh	5	20	25	4.302	86.04
Total CO_2 produced						336.145

Table 7 Sinks data for CCS in the central and eastern part of Indonesia

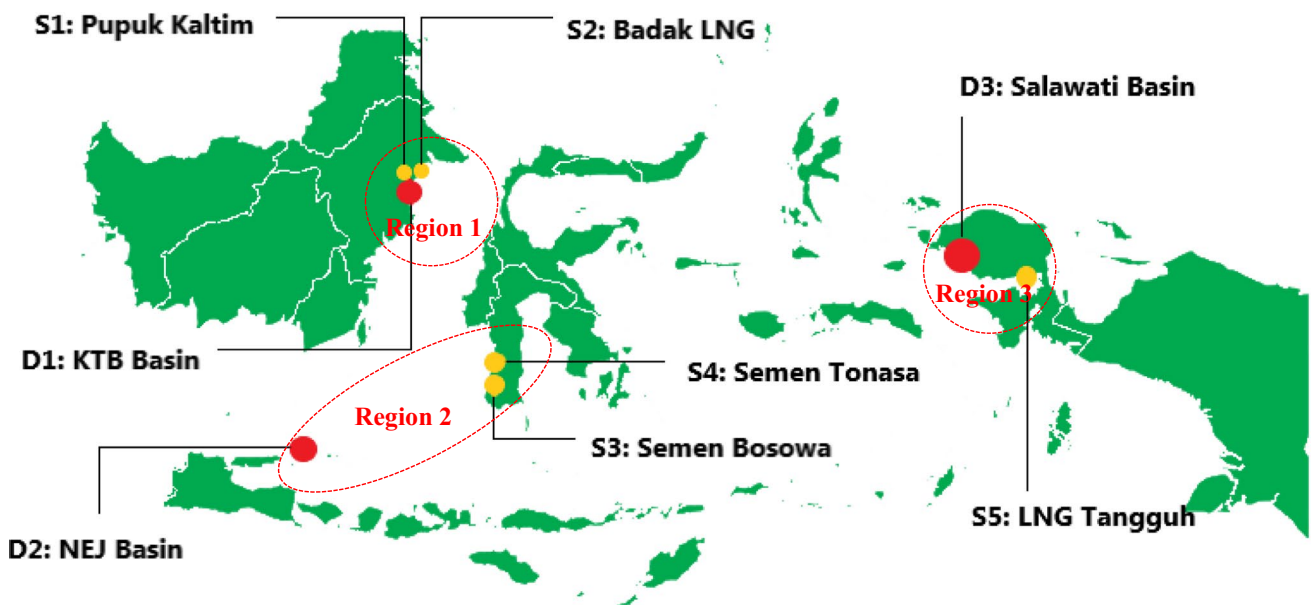| Code	Geological sink	Start time (year)	Duration (year)	End time (year)	Average CO_2 injection rate (Mt/year)	Storage capacity (Mt)
D1	KTB Basin	5	30	35	4.65	139.50
D2	NEJ Basin	7	25	32	3.76	94.0
D3	Salawati Basin	5	20	25	0.885	17.70
Total storage capacity						251.2

Fig. 6 The map represents source and sink locations and their region

and Tarakan basins would be unutilized storage in some level of CCS planning. Therefore, the Kutai basin has a bigger opportunity for CO_2 storage in the CCS planning and prioritizes CO_2 storage in the East Kalimantan region. Kutai, Tarakan, and Barito basins are considered single sinks with a total capacity of 139.5 Mt, the sum of Kutai basin capacity of 129 Mt, the Tarakan basin capacity of 0.5 Mt, and Barito basin capacity of 10 Mt.

The sources data are given in Table 6, and the sink data are shown in Table 7. Both types of data were obtained from the previous study by Handogo et al. (2020) and Mualim et al. (2021) and the sustainability report of an Indonesian energy company in 2016. The sources and sinks locations are represented on the map, as shown in Fig. 6. The figure shows the distribution of sources and sinks by region. Based on the map images, the distance between sources and sinks can be estimated. The

Table 8 Cascade table of overall approach

t (y)	Source, $S_{i,t}$ (Mt/y)					Sink, $D_{j,t}$ (Mt/y)			Δt	CO_2 rate (Mt/y)	CO_2 load (Mt)	Cum. CO_2 load (Mt)	Feasible CO_2 load (Mt)
	S1 2.403	S2 5.514	S3 1.575	S4 3.791	S5 4.302	D1 4.65	D2 3.76	D3 0.885					
5	→	→			→	→		→	2	−6.684	−13.368	0	131.227
7	→	→	→		→	→	→	→	1	−4.499	−4.499	−13.368	117.859
8	→	→	→	→	→	→	→	→	12	−8.290	−99.480	−17.867	113.36
20	→	→	→	→	→	→	→	→	5	−2.776	−13.880	−117.347	13.88
25	→		→	→	→	→	→	→	2	0.641	1.282	−131.227	0 **Pinch**
27	→		→	→		→	→		1	2.216	2.216	−129.945	1.282
28	→			→		→	→		2	6.007	12.014	−127.729	3.498
30	→					→	→		2	8.410	16.820	−115.715	15.512
32						→	→		3	4.650	13.950	−98.895	32.332
35						→	→					−84.945	46.282

Table 9 Cascade table of regional approach for region 1

t (y)	Source, $S_{i,t}$ (Mt/y)		Sink, $D_{j,t}$ (Mt/y)	Δt	CO_2 rate (Mt/y)	CO_2 load (Mt)	Cum. CO_2 load (Mt)	Feasible CO_2 load (Mt)
5	S1	S2	D1				0	49.005
	2.403	5.514	4.65	15	−3.267	−49.005		
20	↓	↓	↓				−49.005	0
	↓		↓	10	2.247	22.470		
30	↓		↓				−26.535	22.47
			↓	5	4.650	23.250		
35			↓				−3.285	45.72

Table 10 Cascade table of regional approach for region 2

t (y)	Source, $S_{i,t}$ (Mt/y)		Sink, $D_{j,t}$ (Mt/y)	Δt	CO_2 rate (Mt/y)	CO_2 load (Mt)	Cum. CO_2 load (Mt)	Feasible CO_2 load (Mt)
7	S3		D2				0	28.360
	1.575		3.76	1	2.185	2.185		
8	↓	S4	↓				2.185	30.545
	↓	3.791	↓	19	−1.606	−30.514		
27	↓	↓	↓				−28.329	0.031
		↓	↓	1	−0.031	−0.031		
28		↓	↓				−28.360	0
			↓	4	3.760	15.040		
32			↓				−13.320	15.04

Table 11 Cascade table of regional approach for region 3

t (y)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	CO_2 rate (Mt/y)	CO_2 load (Mt)	Cum. CO_2 load (Mt)	Feasible CO_2 load (Mt)
5	S5	D3				0	68.340
	4.302	0.885	20	−3.417	−68.340		
25	↓	↓				−68.340	0

estimation will be used to calculate the operating and capital costs of carbon transportation in CCS planning.

Development of CCS Network Design

Cascade table is used to determine the amount of maximum CO_2 sequestration target for the CCS system. The technique is referred to Diamante et al. (2014) and Thengane et al. (2019). The CO_2 sequestration target is the amount of CO_2 transfer from sources to sinks in the CCS system.

The cascade tables for the overall and regional approaches are given in Tables 8, 9, 10, and 11. Table 8 is the cascade table of the overall approach, and Tables 9, 10, and 11 are the cascade tables of a regional approach. In this case, the area distribution of sources and sinks is divided into three regions for a regional approach. The maximum CO_2 sequestration target is obtained by subtracting the total CO_2 produced from Table 6 from the amount of uncaptured CO_2 emission from cascade table. The cascade table solution for the CCS system's carbon target in Indonesia's central and eastern parts gives the maximum sequestration target for the overall and pseudo-regional approach as 336.145 Mt − 131.227 Mt = 204.918 Mt CO_2. The amount of uncaptured CO_2 emission from the regional approach is 49.005 Mt for region 1, 28.36 Mt for region 2, and 68.34 Mt for region 3, as shown in Tables 9, 10, and 11. Hence, the maximum sequestration target for regional approach is 336.145 Mt − (49.005 Mt + 28.36 Mt + 68.34 Mt) = 188.255 Mt CO_2. The CCS network planning is required to determine how much CO_2 will be transported from source to sink. The difference in the design of the CCS network will provide different transportation costs. Based on the CCS network design
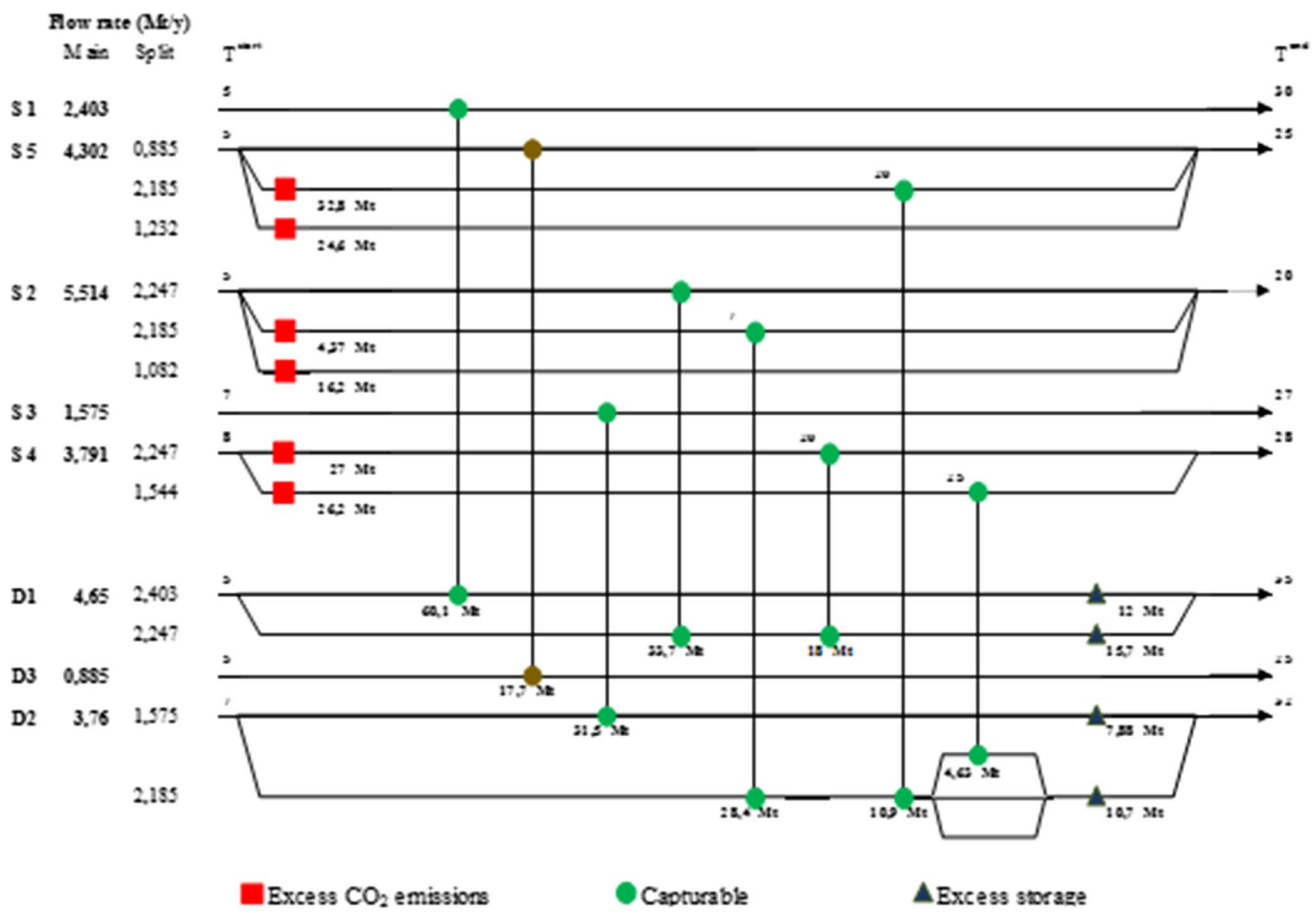
Fig. 7 Grid diagram for CCS network with overall approach

procedure, the CCS network's grid diagram can be made in three ways, as shown in Figs. 7, 8, 9, and 10.

The difference in CO_2 sequestration target between overall and regional approaches results from the penalty in carbon transfer. The regional approach results in a carbon penalty of 16.663 Mt. The penalty can be removed when the area of integrity between the regions is not considered. In the pseudo-regional approach, the carbon penalty is overcome by pairing the suitable sources and sinks in different regions. The amount of CO_2 sequestration target will be equal to the overall approach.

Evaluation of Individual Pairs in CCS Network Design

Regarding the CCS network design with an overall approach, one source and sink pair has an operating time of 3 years. The pair is S4 to D2, which operates from years 25 to 28. Furthermore, with a regional approach, it is found that one pair of source and sink had an operating time of 1 year. The pair is S4 to D2, which operates from years 27 to 28. The last, with a pseudo-regional approach, found that one pair

of source and sink had an operating time of 1 year. The pair is S2 to D2, which operates from years 7 to 8. These pairs should be eliminated to avoid the high annual cost. The results can be highlighted as follows:

- The CCS network design with the overall approach has seven pairs with the amount of CO_2 sequestration target as 204.29 Mt.
- The CCS network design with a regional approach has five pairs with the amount of CO_2 sequestration target as 186.7 Mt.
- The CCS network design with a pseudo-regional approach has seven pairs with the amount of CO_2 sequestration target as 202.73 Mt.

Design and Evaluation of CO_2 Transport

The CCS network design has been generated in the previous section represents the transport link or connectivity between source and sink in the CCS system. Three designs of the CCS network with overall, regional, and pseudo-regional approaches are used as base case designs. The base case
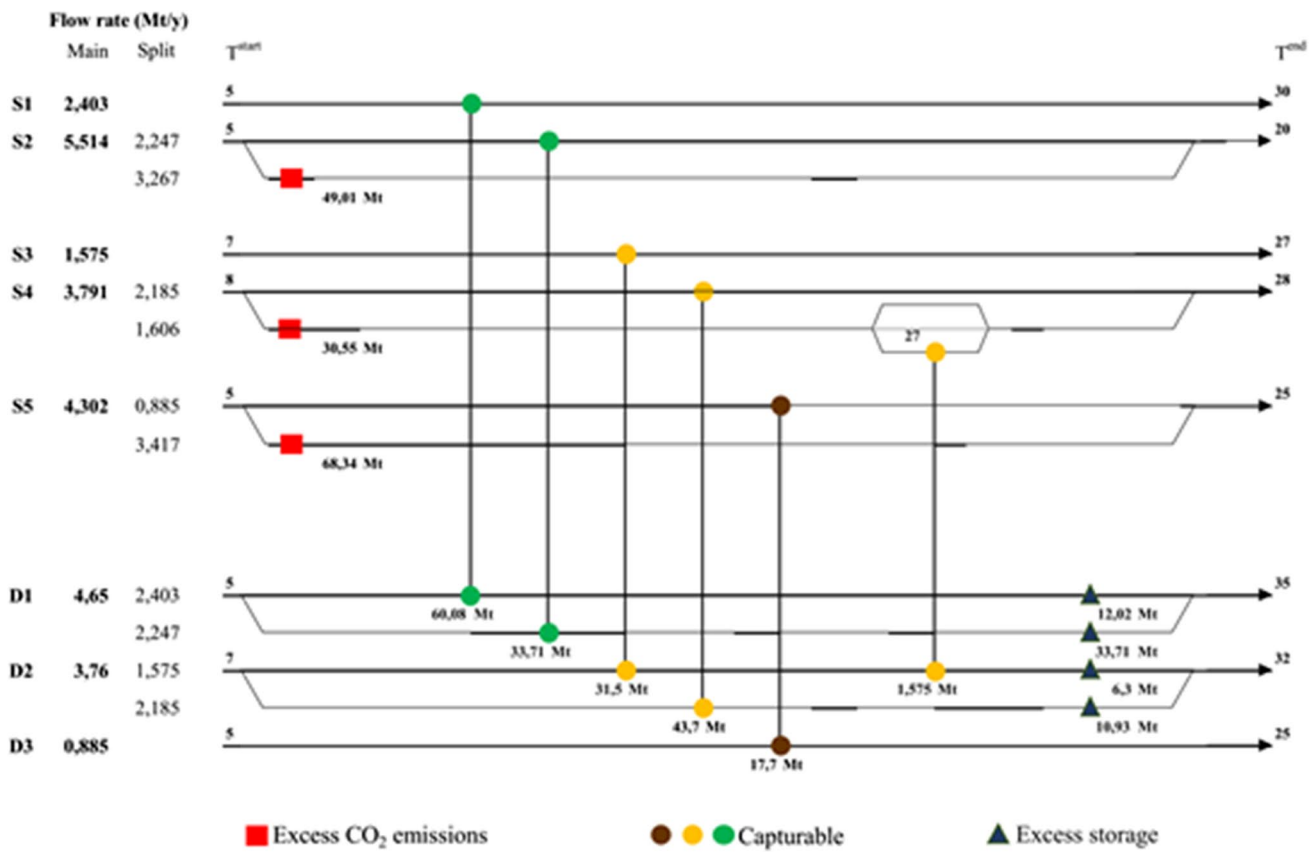
Fig. 8 Grid diagram for CCS network with regional approach

design of CO_2 transport is assumed as new facilities where each source and sink matching has its transport facilities or is referred to as a standalone facility. The further development of base case design is shared facilities design, which is developed from pseudo-regional design. Thus, there are four transport design schemes used in this study. As shown in Fig. 10, two pairs in region 1 (S1 and S2 to D1) and two pairs in region 2 (S3 and S4 to D2) can be shared as single transport facilities.

The sinks of D1 and D3 are located onshore, whereas the sink of D2 is located offshore. Therefore, several CO_2 transportations require a combination of onshore pipelines and offshore pipelines or ships. In an overall design (Fig. 7), the transportation of CO_2 via onshore pipelines is performed for S1 to D1, S2 to D1, and S5 to D3 because the sources and sinks are located onshore and in the same region. The transportation of CO_2 via offshore pipelines or ships is performed for S3 to D2, S2 to D2, S4 to D1, and S5 to D2. The connection from all sources to sink D2 is performed by ship or offshore pipeline because the location is offshore. The combination of onshore pipelines and offshore pipelines or ships can be found on the connection of S4 to D1. The location of the sources, S4 with the sink D1, is on a different island. The sink D1 is located onshore with a long distance

from the port. Thus, both onshore and offshore transportation is needed.

In the regional design (Fig. 8), there are three pairs with onshore transport and two pairs with offshore transport. The onshore transport via pipeline is performed for S1 to D1, S2 to D1, and S5 to D3. CO_2 transport via offshore pipelines or ships is performed for S3 to D2 and S4 to D2. The pseudo-regional design connection (Fig. 9) is similar to regional design with two additional pairs of S4 to D1 and S5 to D1. Both pairs require a combination of offshore transport and onshore pipelines. The results of the CO_2 transport design are given in Tables 12, 13, 14, and 15. The distance of the selected transport connection is estimated based on GIS.

The results show that the offshore pipeline is not included in the list of transport facilities. In this study, the offshore pipelines are not feasible for CO_2 transport, because it requires booster stations. The booster station must be avoided in CO_2 offshore pipelines. The installation of the offshore's booster stations is an unaccountable and high cost because of the complexity in installation and operations, such as the needs of an offshore platform, electrical supply to the offshore, and the difficulties in operations and maintenance. The requirement of the offshore booster stations can be removed by using a larger pipeline diameter
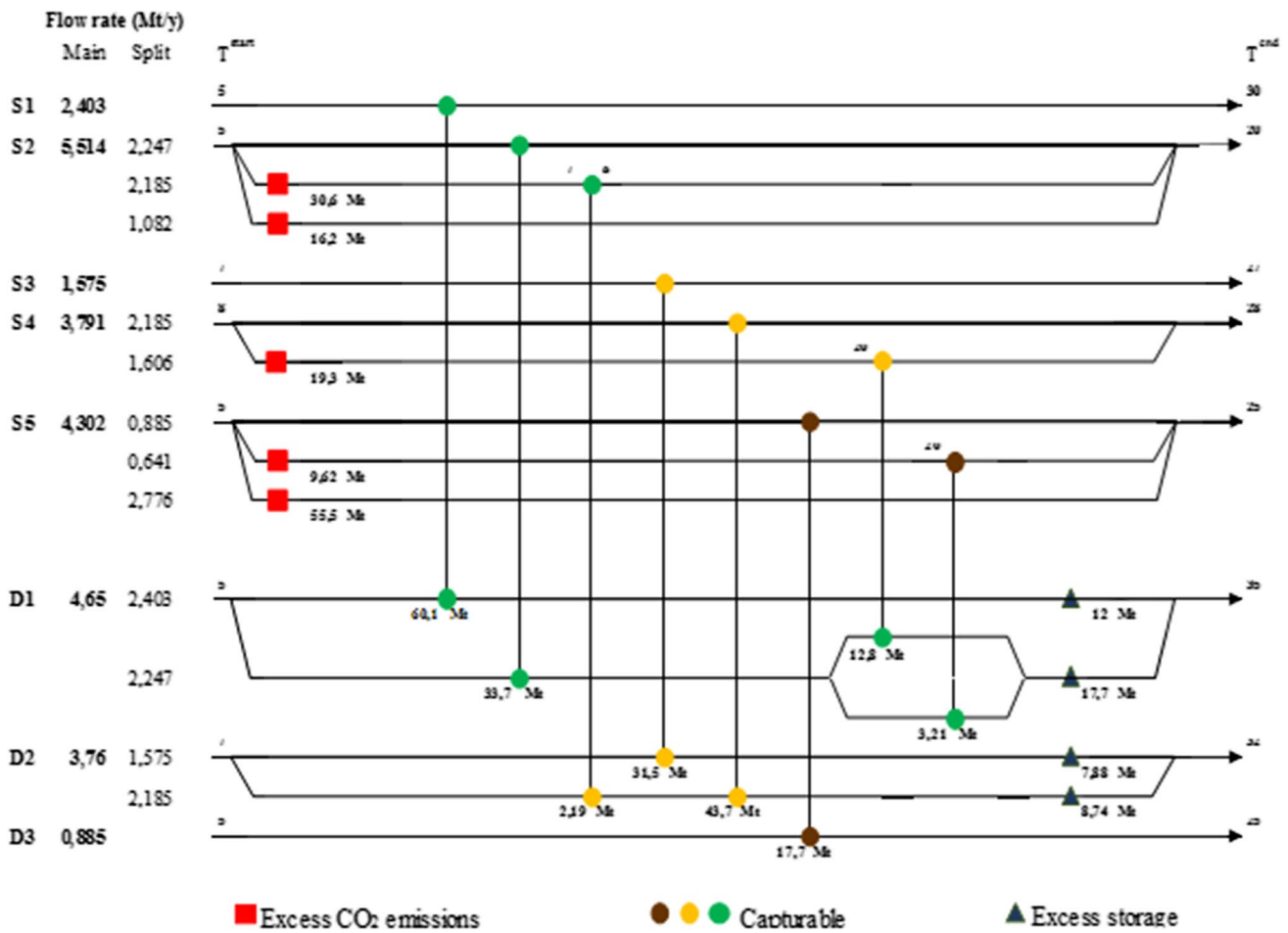
Fig. 9 Grid diagram for CCS network with pseudo-regional approach

and inlet pressure. The use of 14 inches of pipeline diameter looks feasible but will reduce the flowing velocity of CO_2 transported to below 2 m/s and may cause piping problems such as corrosion and lead to intermittent slug flow.

The CO_2 flow rates vary from 0.641 to 2.247 Mt/y for an offshore pipeline in four proposed designs. These capacities are too small for offshore pipelines and can lead to high costs due to booster stations' requirements. Hence, the ships are the most viable for offshore CO_2 transport. The smallest capacity of ships (10,000 tons) is the best choice for CO_2 transport from an economic perspective.

Cost Assessment of CO_2 Transport Design

The CO_2 transport design is developed to achieve minimum transport costs and minimum CO_2 emission. The transport cost of the CCS system is affected by the transport route and capacities. The larger capacity provides more efficient costs. There are four CO_2 transport design schemes. Each scheme is evaluated based on an economic approach using NPV and SC to determine the most efficient transport design scheme.

The magnitude of NPV and SC for each scheme is given in Figs. 11 and 12. In this study, NPV is the cumulative value of expenses adjusted to the reference time set at 2021.

As shown in Fig. 11, the highest result is obtained from an overall approach. The amount of NPV varied from million US$ 574.5 to million US$ 1563. The value is affected by the selected location of the sources and sinks in the multi-region CCS system. The cost of CO_2 transport in the CCS system is generally influenced by the distance of sources and sinks and transportation mode choice. The ship transport resulted in greater NPV compared to the pipeline. This is understandable because CO_2 ship transport requires more complex facilities, consisting of gas liquefaction, intermediate storage, loading–unloading, and shipping. Ship investment costs give the largest contribution of all facilities. The harbor fee gives high operating costs, especially for ships that frequently enter and exit the port to load or unload activities. The loading–unloading activities will be more intensive at a distance of less than 500 km. In general, with a distance of less than 500 km, one loading–unloading cycle can be completed within 2 days. The best transport scheme is given
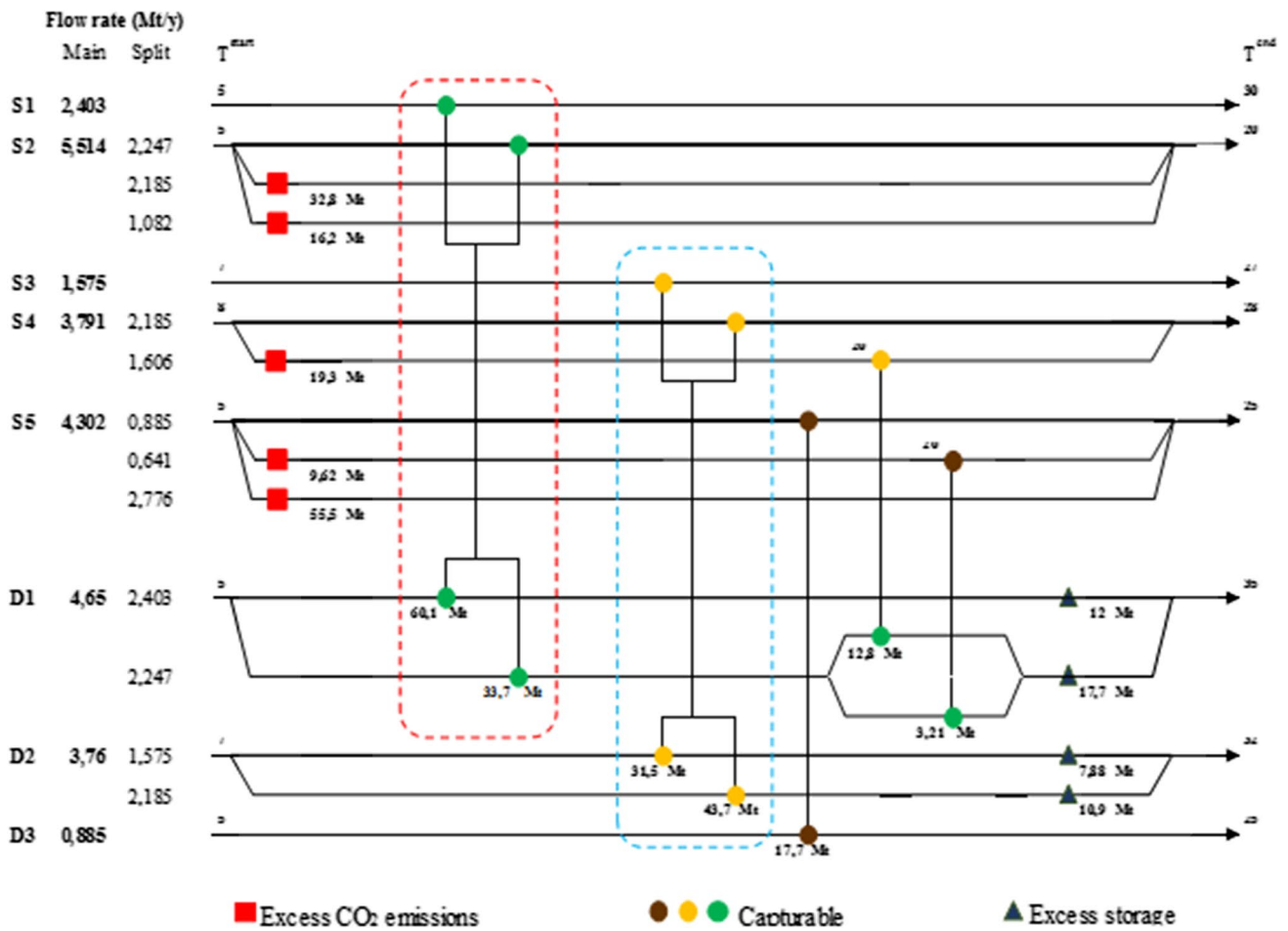
Fig. 10 Grid diagram for CCS network with shared facilities

Table 12 The base case design of CO_2 transport with an overall approach

Design parameters	Unit	Pairing						
		S1-D1	S5-D3	S3-D2	S2-D1	S2-D2	S4-D1	S5-D2
Transport location		Onshore	Onshore	Offshore	Onshore	Offshore	Combine	Offshore
Source-sink distance	Km	211	695	504	210	816	642 (off) 210 (on)	2041
Onshore pipeline								
Transport capacity	Mt/y	2.403	0.885		2.247		2.247	
Pipe diameter (NPS)	Inch	8	6		8		8	
Pipe thickness	Sch. no	60	80		60		60	
Steel grade material		X42	X42		X42		X42	
No. of booster station		8	18		7		7	
Booster capacity	MWe	0.862	0.317		0.806		0.806	
Ship								
Liq. plant capacity	Mt/y			1.575		2.185	2.247	2.185
Ship capacity	Ton			10,000		10,000	10,000	10,000
Number of ships				2		2	4	6
Ship speed	Knot			15		18	15	15
No. of interm. storage				2		4	2	2
Floating vessel capacity	Ton			10,000		10,000	10,000	10,000

Table 13 The base case design of CO_2 transport with a regional approach

Design parameters	Unit	Pairing S1-D1	S2-D1	S3-D2	S4-D2	S5-D3
Transport location		Onshore	Onshore	Offshore	Offshore	Onshore
Source-sink distance	km	211	210	504	504	695
Onshore pipeline						
Transport capacity	Mt/y	2.403	2.247			0.885
Pipe diameter (NPS)	Inch	8	8			6
Pipe thickness	Sch. no	60	60			80
Steel grade material		X42	X42			X42
Number of a booster station		8	7			18
Booster capacity	MWe	0.862	0.806			0.317
Ship						
Liquefaction plant capacity	Mt/y			1.575	2.247	
Ship capacity	Ton			10,000	10,000	
Number of ships				2	4	
Ship speed	Knot			15	15	
No. of intermediate storage				2	3	
Floating vessel capacity	Ton			10,000	10,000	

Table 14 The alternative design of CO_2 transport with a pseudo-regional approach

Design parameters	Unit	Pairing S1-D1	S2-D1	S3-D2	S4-D2	S5-D3	S4-D1	S5-D1
Transport location		Onsh	Onsh	Offsh	Offsh	Onsh	Comb	Comb
Source-sink distance	Km	211	210	504	504	695	642 (off) 210 (on)	2715 (off) 210 (on)
Onshore pipeline								
Transport capacity	Mt/y	2.403	2.247			0.885	2.247	0.641
Pipe diameter (NPS)	Inch	8	8			6	8	8
Pipe thickness	Sch. no	60	60			80	60	60
Steel grade material		X42	X42			X42	X42	X42
No. of a booster station		8	7			18	7	7
Booster capacity	MWe	0.862	0.806			0.317	0.806	0.806
Ship								
Liq. plant capacity	Mt/y			1.575	2.247		2.247	0.641
Ship capacity	Ton			10,000	10,000		10,000	10,000
Number of ships				2	4		4	1
Ship speed	Knot			15	15		15	18
No. of intermediate stor				2	3		2	4
Floating vessel capacity	Ton			10,000	10,000		10,000	10,000

by the regional approach, which has the lowest NPV. The second alternative for the CO_2 transport scheme is shared facilities. This scheme has an advantage in the amount of CO_2 sequestration target which is greater than the regional scheme. The principles of shared facilities design have an opportunity to be applied in the regional scheme so that a lower-cost scheme can be obtained.

The next evaluation parameter is SC that indicates the magnitude of transport costs per unit of CO_2 delivered. The SC is affected directly by the volume of the CO_2 load to be transported. A small amount of CO_2 load results in higher SC. As shown in Fig. 12, the magnitude of SC for each scheme varies from US$ 3.07/ton CO_2 to US$ 7.16/ton CO_2. The SC can be used to measure the effectiveness of the CO_2 transport scheme. The scheme with high SC value is not an effective design. The largest SC value is obtained from an overall scheme, and a regional scheme gives the smallest value. This indicates that the regional scheme is the most effective for CO_2 transport design.

Table 15 The alternative design of CO_2 transport with a shared facilities

Design parameters	Unit	Pairing				
		S1&S2-D1	S3&S4-D2	S5-D3	S4-D1	S5-D1
Transport location		Onshore	Offshore	Onshore	Combine	Combine
Source-sink distance	km	211	504	695	642 (off) 210 (on)	2715 (off) 210 (on)
Onshore pipeline						
Transport capacity	Mt/y	4.65		0.885	2.247	0.641
Pipe diameter (NPS)	Inch	12		6	8	8
Pipe thickness	Sch. no	60		80	60	60
Steel grade material		X42		X42	X42	X42
No. of a booster station		4		18	7	7
Booster capacity	Mwe	1.67		0.317	0.806	0.806
Ship						
Liquefaction plant capacity	Mt/y		3.791		2.247	0.641
Ship capacity	Ton		10,000		10,000	10,000
Number of ships			5		4	1
Ship speed	Knot		15		15	18
No. of intermediate storage			5		2	4
Floating vessel capacity	Ton		10,000		10,000	10,000

Fig. 11 The net present value for transport scenarios
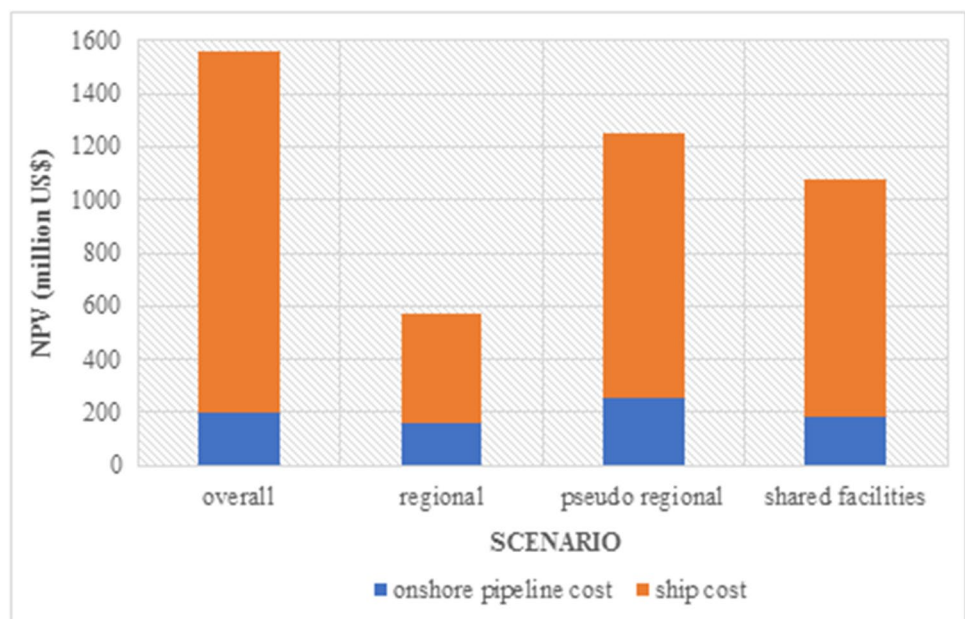
The magnitude of SC is indirectly affected by other factors such as the source and sink operations' time duration and the type of CO_2 transportation mode. The larger SC value will occur in the source and sink pairs with a short time duration. The ship's specific cost was greater than that of the pipelines in all schemes. The ship transport has an SC value four times greater than that of pipeline. Several sources and sink pairs in an overall scheme have a short time duration and use the ship to transport a small amount of CO_2.

Besides shared facilities, reuse of the existing transport facilities that have been used for natural gas transportation gives several opportunities. This opportunity requires further investigation. As stated in Indonesia CCS Study Working Group (2009), Indonesia doesn't have an existing infrastructure for transporting CO_2. Still, Indonesia has several long-distance pipelines for transporting natural gas that might be used for transporting CO_2 in the future.

Conclusions

The CO_2 transport contributes significantly to the investment costs of the CCS system. Design of CO_2 transport should be performed in an integrated manner with CCS

Fig. 12 The specific cost for transport scenarios
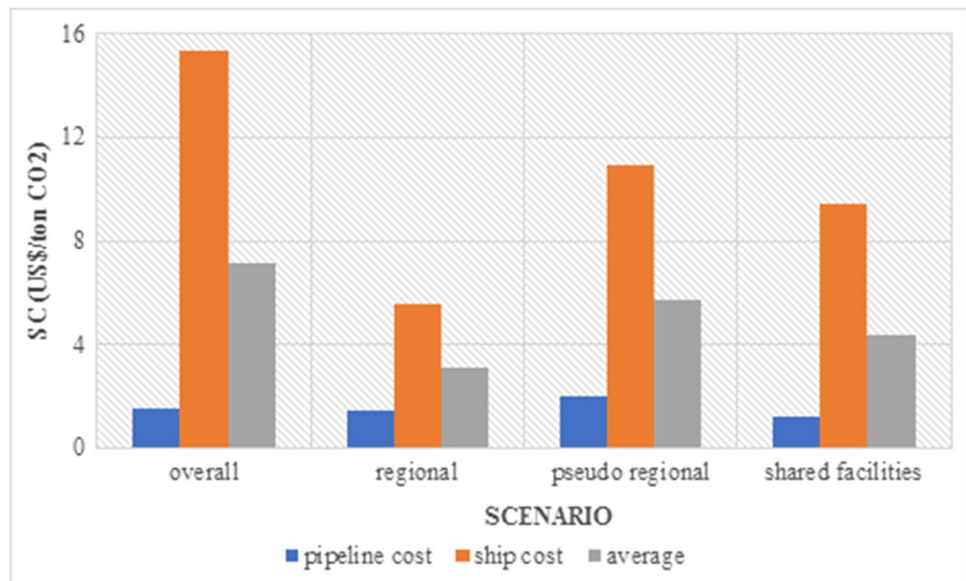
network design and several performance criteria to obtain a more feasible solution with minimum costs. A simple methodological framework to design CO_2 transport in the multi-region and multiple-time CCS system has been proposed. The proposed method combines the new procedure for CCS network design, the new procedure for CO_2 transport design via ship and pipeline, and a new definition of an economic parameter to assess CO_2 transport design. Based on the framework, the CO_2 transport schemes of the CCS system in the central and eastern parts of Indonesia were investigated. Four transport schemes were designed with the nearest neighbor algorithm approach, and the selected transport options were evaluated with technical constraints in the offshore transport area. Two economic criteria, NPV and SC, were used to compare the proposed transport schemes.

The calculation of CO_2 transport design via ship and pipeline was implemented to the four CO_2 transport schemes. The results show that the offshore pipelines are not feasible to transport CO_2 in this CCS system. The flow rate of CO_2 was relatively small that was transported via an offshore pipeline. It led to a high-pressure drop along the pipeline that was followed by the need for a booster station. The small size of the ship, with 10,000 tons of capacity, was the most viable option for CO_2 transport offshore and gives the lowest cost for ship transport design options. The lowest transport cost in terms of NPV and SC was obtained from a regional scheme with the value of US$ 574.5 for NPV and US$3.07/ ton CO_2. The SC indicates the effectiveness of CO_2 transport. Hence, based on the present work, the regional scheme was the most effective scheme, where the CO_2 transport cost was the lowest per mass of CO_2 transported. Although the regional scheme had the lowest cost, another scheme, such as shared facilities, was an attractive option because it had maximum CO_2 sequestration target with low transport

cost. The cost of the shared facilities scheme accounted for million US$ 1079 of NPV and US$ 4.37/ton CO_2 of SC. However, the amount of CO_2 sequestration target was 202.73 Mt for shared facilities scheme which was larger than that for regional scheme with 186.7 Mt. The principles of shared facilities design had an opportunity to be applied on a regional scheme to reach more economic advantage. The costs of the ship transport were generally 4–10 times larger than onshore pipeline costs. That is, the main factor affecting the cost of transportation was ships. In the archipelagic state of Indonesia, the CO_2 sources and sinks were deployed on the entire region to make the ships the best choice for CO_2 transport option offshore.

The study was conducted on the specific case of the CO_2 transport system. However, the proposed framework is generic and can be applied to another case of CO_2 transport multiple times of the CCS/U system. For further improvement, another measure such as sustainability metric and life cycle analysis (LCA) has been introduced to complement the framework. Sensitivity analysis has been conducted to understand the impact of design variables such as transport capacity and transport distance on the system performance. Additionally, the existing natural gas or LPG transport facilities have been investigated to examine the opportunities for reusing existing facilities.

Appendix A. A CCS network design through the nearest neighbor algorithm

Shenoy (2010) proposed the principle of the nearest neighbor algorithm to synthesize energy allocation networks to meet the carbon emission targets. The CCS

network should be designed to ideally have the optimum pairing of carbon source and sink. In the context of the CCS network, the nearest neighbor algorithm (NNA) principle may be stated as follows: To transport a particular carbon from sources to sinks, the source streams to be chosen are the closest neighbor available to sink in terms of operating time and carbon exchange rate. The particular demand for CO_2 injection can be supplied from two or more neighbor sources where the amounts of CO_2 required are dictated by material balance. The starting time is the first consideration in pairing the source and sink. If a source does not have the same starting time as a sink, then the next neighbor source is considered to pair with the sink.

In general, the problem statement which aims to determine CCS network design may be stated as follows:

- Consider CCS network with i sources and j sinks. The sources are serially numbered from S_1 to S_i, and the sinks are similarly numbered from D_1 to D_j.
- Each source is defined by a fixed CO_2 flow rate that can be captured from an industrial emission source and denoted as FS_i.
- Time availability for each source is the time that the industry starts its first CO_2 capturing process until it stops operating, $T_i^{ava} = T_i^{end} - T_i^{start}$.
- Each CO_2 sink is defined by maximum CO_2 injected to each sink and denoted as FD_j.
- Time availability for each sink is the time while CO_2 is injected to sink for the first time until its full capacity. $T_j^{ava} = T_j^{end} - T_j^{start}$.
- Sources and sinks are arranged in chronological order of starting time.

The source flowrates required to fulfill the sinks are determined by the material balance equation

$$FS_{ij} = FD_{ij} \tag{A1}$$

$$FS_{ij} T_{ij}^{ava} = FD_{ij} T_{ij}^{ava} \tag{A2}$$

$$T_{ij}^{ava} = T_{ij}^{end} - T_{ij}^{start} \tag{A3}$$

where FS_{ij} is the CO_2 flowrate from source i to sink j, FD_{ij} is the CO_2 flowrate received by sink j from source i, T_{ij}^{ava} is the operating time available to the sources and sinks to conduct a mass exchange of CO_2, T_{ij}^{start} is the beginning time of the CO_2 mass exchange between sources and sinks and determined by slower T^{start}, and T_{ij}^{end} is the end time of the CO_2 mass exchange between sources and sinks and determined by faster T^{end}.

The flow rate is obtained from selected data. The time availability of source and sink is the difference between

the end of connection time and the beginning of connection time. The connection time indicates the CO_2 transfer from source to sink. The sink will start operating for the first time after CO_2 flow from the source to be injected into it. Therefore, the start time of the sink will not overtake the start time of the source, except for the second connected source. The source stream can be either the main-stream or split stream. The main-stream is the original source stream before divided or splits into many streams with lower flow rates when paired.

The algorithm based on the principles of nearest neighbor consists of a number of rules that are considering start time (T^{start}), the flowrate of CO_2 transfer (FS_i), and end time (T^{end}). The grid diagram elements that are considered in the procedure include the split stream, the main-stream, and time availability. The steps in the algorithm are given below:

R1: Start by the sink that has the earliest start time and is denoted by D_1 (i.e., $j = 1$). If there are sinks with an equal start time of more than one, select the sink with the largest flow rate.

R2: Select the source with the same start time as the sink, and go to R5, else go to R3. If the sources with an equal start time of more than one, select the source with the smallest flowrate.

R3: Select the source that has the start time earlier than the sink, to the smallest time start difference between source and sink, and go to R5, else go to R4.

R4: If all stream, include main-stream and split stream, has been paired, select the source that has the start time which is later than the sink, to the shortest time start difference between source and sink, and go to R5, else go to R8

R5: If $FS_i > FD_j$, the source flowrate is sufficient to meet the entire sink. Update $FS_i^* = FS_i - FD_j$; $FS_i = FD_j$, and $j = j + 1$, and go to R2, else go to R6. Where FS^* is the source splitting stream.

R6: If $FS_i \leq FD_j$, the source flowrate is not sufficient to meet the entire sink. Update $FD_j^* = FD_j - FS_i$; $FD_j = FS_i$, and $j = j + 1$, and go to R2, and repeat with other sources. (FD^* is the sink splitting stream).

R7: Identify the splitting stream of sinks and go to R1. Repeat the pairing with another source that has not been paired. Don't pair the source splitting stream until all main streams have been paired, except the sources that have the start time, which is later than the sinks stated in R4.

R8: Identify the time availability of each pairing. Start from the sources. If $T_{ij}^{end} = T_i^{end}$, there is no excess emission from the source after the end of the pairing period, else if $T_{ij}^{end} < T_i^{end}$, check the excess emission, set T_i^{end} as new T_i^{start}, and update $i = i + 1$. Proceed to the sinks; if $T_{ij}^{end} = T_j^{end}$, there is no excess storage of the sink, else if

$T_{ij}^{\text{end}} < T_j^{\text{end}}$, check the excess storage and set T_j^{end} as new T_j^{start}, update $j = j + 1$, and go to R2.

Based on the rules above, the sources and the sinks are arranged in a specific order in the grid diagram to facilitate pairing. The sources and sinks sequence must be rearranged according to start time chronologies, lowest source rate, and largest sink rate. For the regional design of the CCS network, the order of sources and sinks placement in the grid diagram is arranged based on location proximity.

R9: Identify the location of each source and sink. Sort the source and based on the proximity of location. Start from the west region and go to R1.

The grid diagram for the CCS network is not divided like the heat exchanger network (HEN). The grid diagram in HEN is divided into sections, above pinch and below pinch, because heat cannot be transferred across the pinch due to temperature constraints. In a multi-period CCS network, the pinch point indicates when the amount of CO_2 supply from the sources is equal to the amount of CO_2 demand from the sink, and pinch time is not a constraint in CO_2 transfer. The constraint in CO_2 transfer is time availability between sources and sinks.

Appendix B. Notes for selected capital cost of CO_2 shipping

Appendix B1. Notes for CO_2 liquefaction costs

ZEP estimated the liquefaction unit's capital cost, including construction interest for 2.5 $MtCO_2$/y and 20 $MtCO_2$/y on 22.7 and 147 M€, respectively. These costs are used to estimate the scale factor of 0.9. The cost expressed in M€ should be converted to M\$ by multiplying with the number 1.33.

Appendix B2. Notes for CO_2 intermediate storage costs

The intermediate storage is based on the concept of storage tanks developed by Decarre and Seo. Decarre et al. (2010) proposed the design for 4500 m³ of the horizontal cylindrical tank as an optimum design for CO_2 storage. The intermediate storage is composed of a contained double casing. The outer casing has 10 mm of thickness from a stainless steel material with 9% Ni compound, containing perlite vacuum packed (thickness 30 cm), having an external diameter of 14.7 m and 32.3 m in length. Seo et al. (2016) estimated the capital cost for a cylindrical tank with a maximum capacity of 5000 m³ and a maximum thickness of 40 mm. In this

work, the 4500 m³ of tank capacity with the maximum thickness of 40 mm and tank dimension from Decarre et al. (2010) are used for tank sizing. The capital cost estimation is obtained from www.matche.com based on the proposed design.

Appendix B3. Notes for loading equipment costs

The loading equipment is assumed to be installed at the harbor. MHI (2004) estimated the costs for loading equipment are M\$ 8 for handling 6.2 Mt/y of CO_2 mass flow. Apeland (2011) assumes that the costs of loading equipment are 9.5 M€ for handling mass flows of 1, 3, or 5 $MtCO_2$/y. Skagestad et al. (2014) proposed the lower cost of 1.1 M€ for loading 0.8 $MtCO_2$/y. The cost estimation of Skagestad et al. (2014) is used in this study. The average euro-dollar exchange rate of 1.33 is used to convert the euro into a dollar.

Appendix B4. Notes for ship building costs

The Mitsubishi Heavy Industries (MHI 2004) proposed the initial design of shipbuilding with three ship sizes (10,000 ton, 30,000 ton, and 50,000 ton) and two service speeds (15 knots and 18 knots for full load conditions) to accommodate the smaller to larger of CO_2 transport. The sizes are applied to estimate the costs of ship transport in this study.

Appendix B5. Notes for floating vessel temporary storage costs

A floating vessel is used as offshore temporary storage and can be an old converted ship. The floating vessel's size is assumed to be similar to the size of the selected ship in use. Knoope et al. (2015) estimate the conversion costs of three sizes of a ship to be used as a floating vessel. The costs are 23 M€ for 25 $ktonCO_2$, 28 M€ for 35 $ktonCO_2$, and 33 M€ for 45 $ktonCO_2$. A scale factor of 0.69 can be derived from the estimation. This scale factor is used to estimate the conversion costs of three sizes of the floating vessel that are used in this study (10 $ktonCO_2$, 30 $ktonCO_2$, and 50 $ktonCO_2$). The average euro-dollar exchange rate in 2015 of 1.11 is used to convert the euro's currency value into a dollar.

Data Availability The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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