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ScienceDirect

Energy Procedia 63 (2014) 2630 – 2637

Energy Procedia

GHGT-12

Understanding the economic feasibility of ship transport of CO_2 within the CCS chain

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Abstract

An economic model for ship transport of CO_2 is developed and benchmarked against published studies. The costs and benefits of ship transport for several likely CCS scenarios are compared against pipeline transport of CO_2 for offshore injection. The results show that ship transport can be cost competitive with pipelines. The largest shipping cost components are electricity and fuel, each accounting for almost 30 % of the total cost. Capital costs only contribute around 28 % of the total shipping cost, compared to more than 70 % for pipeline transport. Economies of scale can make shipping more cost-effective over long distances.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: CO_2 Transport; CO_2 Shipping; Offshore pipeline; Techno-economic assessment; Carbon Capture and Storage (CCS)

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1. Introduction

Although CCS implementation requires large investments, it plays an important role in the development of climate change mitigation strategies [1]. As the cost of CCS is currently a limiting factor in its deployment, there has been significant interest in exploring alternative methods of CO_2 capture, transport and storage to reduce costs. For example, CO_2 can be used for enhanced oil recovery (EOR) to improve oil production while storing CO_2 [2]. The transport cost of CO_2 often comprises a large portion of the total CCS cost (up to 30%), especially for larger distances [3]. There is therefore a need to understand the drivers of transport costs in order to reduce them.

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Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.285

Nomenclature

CX	Present value of the capital expenses (CAPEX), US\$m
DX	Present value of the decommissioning expenses, US\$m
OX	Present value of the operating expenses (OPEX), US\$m
α_t	Present value of the amount of CO_2 avoided by transport, Mt
$\gamma_{boil\text{-}off}$	Present value of the amount of CO_2 generated and emitted due to boil-off, Mt
γ_{fuel}	Present value of the amount of CO_2 generated and emitted due to fuel consumption, Mt
κ	Present value of the amount of CO_2 captured and loaded to the ship or pipeline, Mt
σ_t	Levelised CO_2 transport cost per tonne of CO_2 avoided, US\$/t

Two widely considered methods for the transport of CO_2 are pipeline transport and ship (marine) transport [4]. While pipeline transport has been well researched and deployed for CCS and EOR projects [5, 6], ship transport is a less developed concept for these applications. Pipeline transport offers significant economies of scale as flow rate increases, but is capital cost intensive [7]. In contrast, ship transport has lower capital requirements and substantial economies of scale with transport distance. Therefore, ship transport of CO_2 could potentially be a cost competitive option for CCS.

Recent studies have shown that ship transport can be more cost-effective than pipeline transport when offshore injection is involved or when transport distances are long [4, 8]. Ship transport is also more flexible than pipeline transport because (a) routes can be changed and (b) injection can be easily switched to a different storage site (e.g. if more injection capacity is required). This makes it ideal during the pilot and ramp-up stages of a project. Further, there are many offshore storage basins or EOR opportunities around the world that are easily accessible by ship (such as in Japan, Australia, the North Sea and the Gulf of Mexico). For these reasons, this study aims to understand the cost competitiveness of CO_2 transport via ship, and to examine the circumstances under which shipping of CO_2 is favourable compared to pipeline transport. While this study is conducted in an Australian context, findings of this study are applicable to CCS projects worldwide.

2. Methodology

Pipeline and ship transport costs for CO_2 are estimated using the Integrated Carbon Capture and Storage Economics Model (ICCSEM) developed by UNSW Australia for the CO2CRC. ICCSEM performs simple mass and energy balance as well as shortcut calculations to estimate process equipment sizes. Further details of the calculations carried out in ICCSEM are provided elsewhere [9]. The pipeline transport cost estimation methodology has been thoroughly validated and benchmarked, and has been found to be in good agreement with other published studies [3]. In this paper, the ship transport cost model is benchmarked against previously published studies [4, 10] (see section 3.1). The model accounts for the costs of compression, liquefaction, onshore storage, ship loading, transport by ship, and ship unloading and recompression prior to injection. However, this paper focuses on transport costs only, so the costs of facilities for unloading the ship (included in platform or subsea completion costs) and injecting CO_2 at the delivery point are not included.

The inputs to the ship transport cost model include the amount of CO_2 captured, transport distance, capture source, electricity and diesel prices. The model accounts for economic factors such as discount rate, CAPEX phasing and project lifetime. Table 1 lists the key assumptions in the model.

Cost estimates obtained from the model are presented in this paper in terms of the levelised CO_2 transport cost per tonne of CO_2 avoided (σ_t), which represents the breakeven carbon price at which transport would be cost-neutral. This should not be confused with the contribution of transport to the specific cost of CO_2 avoided for a CCS chain, as avoidance costs are not additive [3]. The levelised cost of CO_2 avoided is calculated as:

$$\sigma_t = \frac{CX + OX + DX}{\alpha_t} \tag{1}$$

where *CX*, *OX* and *DX* are the present values of the CAPEX, OPEX and decommissioning expenses. The present value of the amount of CO_2 avoided by transport (α_t) is given by:

$$\alpha_t = \kappa - \gamma_{fuel} - \gamma_{boil-off} \tag{2}$$

where κ is the present value of the amount of CO_2 captured and loaded to the ship or pipeline, and γ_{fuel} and $\gamma_{boil\text{-}off}$ are the present values of the amounts of CO_2 generated and emitted due to fuel consumption and boil-off, respectively.

Table 1: Model Assumptions

Parameter	**Value**
Cost base	2012 US dollars
Exchange rate	US$1 = A$1
Project life	25 years
Discount rate	7 %
Construction costs	40 % in year 1, 60 % in year 2
Fixed maintenance and labour costs	4 % of CAPEX
Owner costs	7 % of total Engineering Procurement and Construction (EPC) costs
Contingency costs	10 % of total EPC and owner costs
Decommissioning costs	25 % of compression, liquefaction, storage tank and pipeline CAPEX
Load factor	85 %
Cost of electricity	US$56.8/MWh
Cost of diesel	US$1,385/kL
Cost of cooling water	US$0.02/$m^3$
Electricity emission intensity	0.878 t CO_2/MWh
Diesel emission intensity	2.71 t CO_2/kL
Additional volume for onshore vessels	20 %
On-shore vessel geometry	Flat bottom, hemi-spherical top
On-board vessel geometry	Spherical vessels
Number of on-board vessels per ship:	
Ship size ≤ 50,000 m^3	4
Ship size > 50,000 m^3	5
Compression and liquefaction efficiency	70 %
Ship speed	15 knots
Ship loading time	8 hr
Ship size	1 day of emissions
Ship unloading time	24 hr
Ship gross tonnage	2 × design volume
Boil off	2 % per day
Offshore pipeline depth:	
Shallow	100 m
Deep	1,000 m
Pipeline steel grade	X65
Pipeline flange class	900#

For shipping costs, CAPEX includes the cost of the ship as well as the costs related to the acquisition and installation of compression and liquefaction operations. The OPEX for shipping is comprised of electricity, diesel, harbour, labour and maintenance costs. For the pipeline transport options, CAPEX includes the costs related to pipeline construction, pipelay and compression equipment. Pipeline OPEX only includes electricity, labour and maintenance costs.

The economic model is used to assess the economic viability of ship transport for several likely CCS scenarios with CO_2 mass flow rates ranging from 1 to 12 Mtpa and transport distances from 75 km to 1,000 km. The costs and benefits of each option (pipeline or shipping) are then compared for transporting CO_2 for offshore injection.

3. Results and Discussion

3.1. Validation

In order to validate the techno-economic model for CO_2 shipping, cost estimates for CO_2 transport by ship are obtained using the model and compared to recently published studies [4, 10]. The comparisons are made under the same cost assumptions. In particular, for the comparison against the study of Chiyoda Corporation [4], the diesel price was set to Japanese conditions, and harbour costs were also adjusted to match those in that study. Fig. 1 shows generally good agreement, well within the 30 % uncertainty range of an economic scoping study. The differences in cost estimates can be related to factors not included in our techno-economic model, such as the effect of taxes, or differences in fuel consumption and harbour costs, as our estimates are based on Australian data.

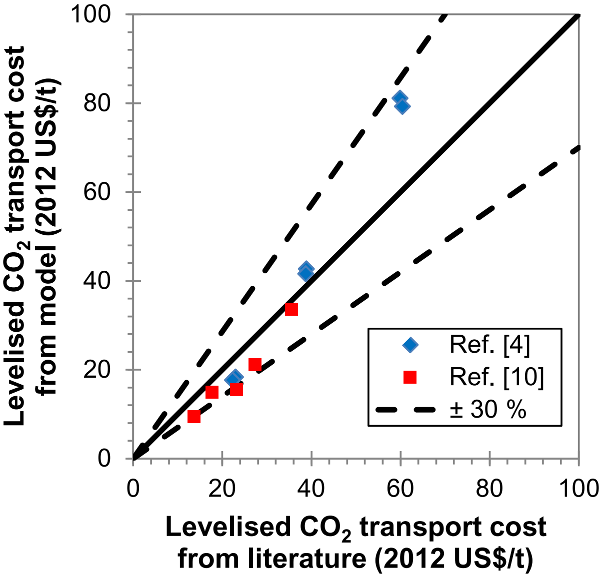

Fig. 1. Comparison of shipping cost model to literature reported cost data [4, 10].

3.2. Cost of shipping pure CO_2

In order to understand the effect of individual components on shipping costs, a breakdown of the costs is evaluated for a base case and two alternative cases. The base case transports 6 Mtpa of CO_2 over 1,000 km. This transport distance is the median of the trade-off points reported in the literature, at which the cost of CO_2 transport by ship and by offshore pipeline are approximately equal [11, 12]. Similarly, the flow rate is the median of baseline flow rates used in the literature to assess ship transport costs [4, 8, 11]. The alternative cases are one case with the same flow rate at double the distance, and another case with double the flow rate at the same distance. Fig. 2a shows the cost breakdown in terms of overall project cost and Fig. 2b presents the breakdown in terms of levelised CO_2 transport cost for the three cases.

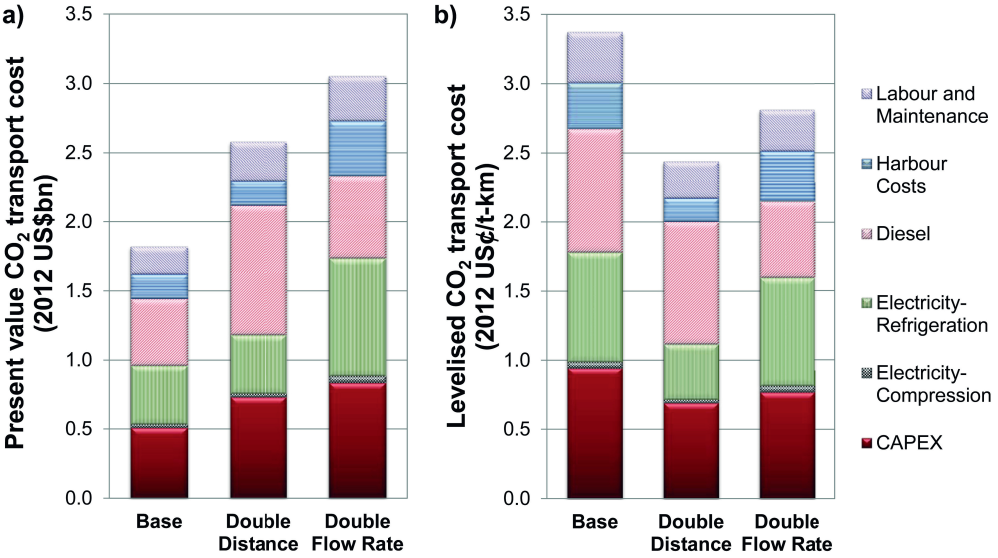

Fig. 2. Effect of distance and amount of CO_2 transported on a) total and b) levelised transport cost.

Based on Fig. 2a, the largest single cost for the base case is CAPEX (contributing 28 %). Operating costs are also significant, especially diesel (27 %) and refrigeration costs (23 %). Hence, shipping is highly sensitive to electricity and diesel prices. Doubling the transport distance causes the total transport cost to increase by around 42 %, mostly due to the increase in diesel consumption. The CAPEX cost also increases when the distance is increased, because the longer trip time requires more ships to be in operation to transport the same amount of CO_2. On the other hand, a doubling of the amount of CO_2 transported leads to a 68 % increase in the total transport cost compared to the base case. This increase is mainly related to the doubling of the refrigeration costs, as well as larger CAPEX and harbour costs which are related to the larger storage tank and ship sizes required.

Fig. 2b shows that, as opposed to the total costs, the levelised transport cost (expressed as cents per tonne-kilometre) are reduced compared to the base case when doubling the transported distance (by 28 %), or when doubling the amount of CO_2 transported (17 % lower). Although doubling the amount of CO_2 transported results in a lower contribution from diesel costs, economies of scale are negligible in electricity and harbour costs. Conversely, doubling the transported distance shows significant economies of scale in electricity and harbour costs, as well as in CAPEX, labour and maintenance costs to some degree. Overall, these results show that shipping has more significant economies of scale with distance than with CO_2 flow rate.

3.3. Comparison to Pipelines

The key aim of this study is to compare the cost of shipping and pipeline transport. For pipeline transport, we compare onshore pipelines, shallow offshore pipelines (at a depth of 100 m) and deep offshore pipelines (at a depth of 1,000 m). The shallow depth of 100 m represents the average depth for continental shelves worldwide, whereas the deep depth of 1,000 m represents the average depth for a potential injection basin located off the continental shelf.

For the base case flow rate and distance, Fig. 3 shows that transport of CO_2 by ship is much less CAPEX intensive (28 %) than transport through pipelines (> 70 %). Pipeline transport costs increase as the water depth at which as the pipeline is located is increased, with onshore pipeline transport resulting in the lowest cost and deep offshore pipelines having the largest cost. This is because pipeline CAPEX increases with water depth (from 70 % onshore to nearly 80 % for deep offshore) due to the larger pipeline thickness required and larger pipelay costs offshore. Although shipping costs are around 7 % higher than onshore pipeline transport costs, shipping costs are slightly lower (~ 2 %) than shallow offshore pipeline transport, and about 10 % lower than deep offshore pipeline transport costs.

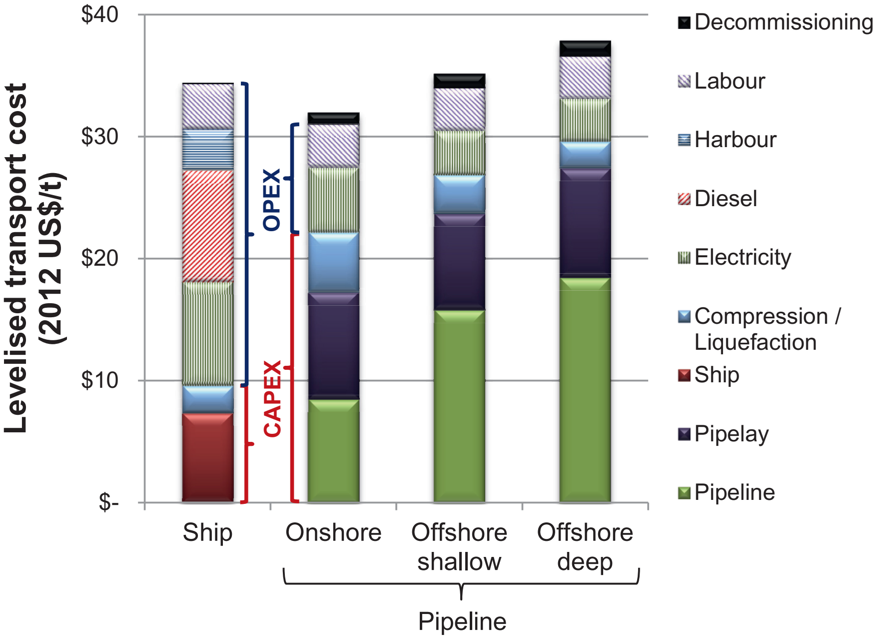

Fig. 3. Comparison of levelised transport costs via ship and pipeline, for 6 Mtpa of CO_2 transported a distance of 1,000 km.

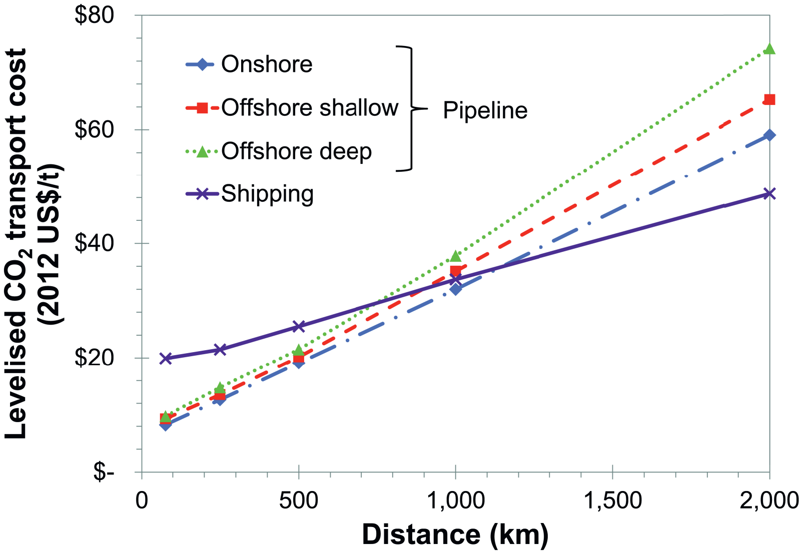

Fig. 4. Effect of transport distance on levelised transport cost, for 6 Mtpa.

The effect of transport distance and flow rate for the four transport options are shown in Fig. 4 and Fig. 5 respectively. Fig. 4 shows that shipping becomes more cost effective than pipelines at longer distances. The trade-off point at which shipping becomes more cost effective than pipeline transport depends on the type of pipeline. For a flow rate of 6 Mtpa, deep offshore pipeline transport reaches the trade-off point at a shorter distance (~ 750 km) than shallow offshore pipelines (~ 900 km), followed by onshore pipeline transport (~ 1,150 km). This trend can be explained by the stronger economies of scale with distance for ship transport compared to pipeline transport, as already seen in Fig. 2 and evidenced by the smaller slope of the shipping line in Fig. 4. Furthermore, the cost of transporting CO_2 via pipelines increases almost linearly with distance, as it is dominated by CAPEX.

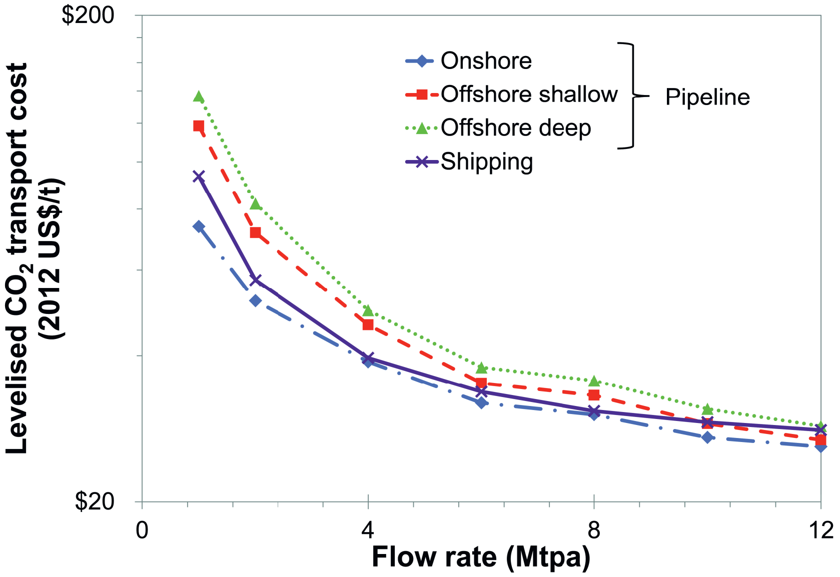

Fig. 5. Effect of CO_2 flow rate on levelised transport cost, for 1,000 km.

It is important to note that the cost of ship transport does not increase linearly with distance. From equation (2) it can be seen that γ_{fuel} and $\gamma_{boil\text{-}off}$ reduce the amount of CO_2 avoided, and can have a significant impact on the levelised transport cost. This is because γ_{fuel} and $\gamma_{boil\text{-}off}$ increase as the distance travelled by the ship increases. For example, for a transport distance of 7,000 km approximately 21 % of the CO_2 loaded onto the ship would be emitted as boil-off under the assumptions used in this paper, resulting in almost a 27 % increase in levelised transport cost due to the reduction in CO_2 avoided alone. The impact of these emissions becomes even larger as the transport distance increases further. Therefore, for long transport distances, boil-off gas re-liquefaction may represent an economically attractive option.

On the other hand, the results in Fig. 5 show that pipeline transport presents stronger economies of scale with flow rate than shipping. For a distance of 1,000 km, onshore pipeline transport of CO_2 always results in the lowest levelised cost. In addition, the cost difference between onshore pipeline and shipping transport increases for flow rates above 8 Mtpa. This is because the cost of CO_2 shipping does not scale well with flow rate. In addition, there may be limits to the size of CO_2 tankers. Although there are proposed designs for ships to carry 100,000 m^3 of CO_2 [13], recent studies [4, 8] have not considered ship sizes above 50,000 m^3 which, under the assumptions of this study, would allow the transport of approximately 15 Mtpa of CO_2. For most smaller flow rates, ship transport is more cost effective than offshore pipelines. Under the assumptions used in this paper, the trade-off point for a distance of 1,000 km is around 9 Mtpa for shallow offshore pipelines and about 12 Mtpa for deep offshore pipelines.

4. Conclusions

In this paper, an economic model for ship transport of CO_2 is developed and incorporated into our in-house techno-economic CCS model (ICCSEM). The ship transport cost model is benchmarked against previously published studies and found to be in good agreement. The largest ship transport cost components are found to be electricity (mostly for refrigeration and, to a lesser extent, for compression) and transport fuel (diesel), each accounting for almost 30 % of the total cost. Capital costs only contribute around 28 % of the total shipping cost, compared to more than 70 % for pipeline transport. This means that while capital costs drive pipeline transport costs, operating costs are the main cost driver for ship transport of CO_2.

The preliminary results presented in this paper show that ship transport can be cost competitive with pipelines. This is particularly the case for smaller CO_2 flow rates and longer transport distances. Furthermore, shipping can be particularly useful for the scale-up stages of a CCS project, or for tapping into smaller capacity injection sites, as it is inherently more flexible in terms of transport routes than pipeline transport.

Although economies of scale can make shipping more cost-effective over long transport distances, the effect of distance on CO_2 emissions from fuel combustion and boil-off should be considered. These emissions reduce the amount of CO_2 injected and avoided, and can have a significant effect on the cost of CO_2 avoidance within the CCS chain.

Acknowledgements

The authors would like to acknowledge the funding provided by the Australian Government through its CRC Program to support this CO2CRC research project. We would also like to acknowledge Ms. Christine Bakewell for her assistance and support in generating the cost data used for this study.

References

[1] IEA. *Carbon Capture and Storage: Progress and Next Steps*. International Energy Agency, 2010.
[2] Global CCS Institute 2012. *The Global Status of CCS: 2012*. Canberra, Australia: 2012.
[3] Fimbres Weihs GA, Wiley DE. Steady-state design of CO_2 pipeline networks for minimal cost per tonne of CO_2 avoided. *International Journal of Greenhouse Gas Control*. 2012;8:150-68.
[4] Chiyoda Corporation. *Preliminary Feasibility Study on CO_2 Carrier for Ship-based CCS*. Global Carbon Capture and Storage Institute, 2011.
[5] IEAGHG. *Development of a global CO_2 pipeline infrastructure*. International Energy Agency Greenhouse Gas R&D Programme, 2010. Report No.: 2010/13.
[6] IEAGHG. *CO_2 Pipeline Infrastructure*. International Energy Agency Greenhouse Gas R&D Programme, 2013. Report No.: 2013/18.
[7] Ozaki M, Ohsumi T. CCS from multiple sources to offshore storage site complex via ship transport. *Energy Procedia*. 2011;4:2992-9.
[8] Roussanaly S, Bureau-Cauchois G, Husebye J. Costs benchmark of CO_2 transport technologies for a group of various size industries. *International Journal of Greenhouse Gas Control*. 2013;12:341-50.
[9] Allison G, Fimbres Weihs G, Ho M, Neal P, Richards M, Wiley D, McKee G. *CO2CRC CCS Economic Methodology and Assumptions*. Canberra, Australia: Cooperative Research Centre for Greenhouse Gas Technologies, 2012. Report No.: RPT12-3490.
[10] IEAGHG. *Impact of Impurities on CO_2 Capture, Transport and Storage*. IEAGHG, 2004.
[11] IEAGHG. *Ship transport of CO_2*. IEAGHG, 2004. Report No.: PH4/30.
[12] IPCC. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change, 2005.
[13] Santos S. CO_2 Transport via Pipeline and Ship. CSLF Workshop on CO_2 Capture; Mexico City: IEAGHG; 2012.