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Optimal pipeline design with increasing CO_2 flow rates

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Abstract

Wide deployment of carbon capture and storage (CCS) will require extensive transportation infrastructure, quite often in the form of pipelines. The rollout of such large-scale infrastructure would undoubtedly require very large investments. In regions with several CO_2 emission sources, it is possible that not all of the major CO_2 sources will implement CCS at the same time. Shared oversized pipeline designs are often proposed in order to form a "cluster" of CO_2 sources and serve as the backbone for an expanding CO_2 transportation infrastructure, to which emission sources will be connected. This paper analyses the economics of using oversized and parallel pipelines for different typical pipeline length and CO_2 flow rate combinations. For new CCS projects, the expansion methodology presented in this paper can identify the optimal pipeline design that minimises the cost per tonne of CO_2 avoided over the life of the project. For existing projects, the expansion methodology identifies the optimal pipeline design change, which may include either using an existing pipeline as CO_2 supply increases or duplicating pipelines.

Keywords: CCS scenario; CCS economics; Optimisation; Oversized CO_2 pipeline

1. Introduction

A single pipeline connecting a static source and a carbon sink is relatively easy to model. The design of a single pipeline between an emission source and an injection location can be done by minimising the cost of CO_2 transport [1, 2]. For many planned CCS projects, significant attention has recently focused on reducing CO_2 transportation costs through the design of pipeline networks that connect several CO_2 emission sources and injection locations.

Most of the existing literature on CCS network design employs a static network model. For example, Fimbres Weihs et al. [3-5] studied the steady-state optimisation of a CCS pipeline network with multiple emission sources and injection sites in Southeast Queensland and East Australia, while Middleton et al. [6, 7] also assumed a static model in their development of an optimisation algorithm for a CO_2 transport network in the United States. One of the major drawbacks of using a static network is that it assumes all

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the CO_2 sources are connected to the network at the same time and ignores the actual expansion of the CO_2 network caused by the gradual uptake of CCS over time.

The optimal design for an expanding network may be different from the optimal solution for a static network case. This is because of the consideration of new sources as the network expands may affect the possibility of temporary over- or under-utilisation of pipelines. A recent study [8] qualitatively analysed the benefit of using oversized pipelines and concluded that the oversized design would take advantage of economies of scale and enable the connection of potential future CO_2 sources in the course of the pipeline life time. However, to date there are no studies that quantitatively analysing the merits of using oversized pipelines in network designs.

This paper aims to quantify the benefits of using oversized CO_2 pipelines under several simplified CCS development scenarios. The analysis considers the transportation of CO_2 from an emission source with an anticipated increase in flow rate during its operating life. The economics of two design methods are compared: (1) independent optimisation of duplicate pipelines constructed before and after the anticipated increase in flow rate, and (2) an "expansion" methodology that allows for the initial installation of an oversized pipeline. The comparison involves calculating the total costs for transportation per tonne of CO_2 avoided based on the Integrated Carbon Capture and Storage Economics Model (ICCSEM) developed by the University of New South Wales (UNSW) for the CO2CRC. The insights gained from this analysis are useful for analysing the use of oversized or parallel pipelines for a CO_2 transport project where the amount of CO_2 to be transported changes over time.

2. Scenarios and assumptions

When developing a CCS transport network with an anticipated increase of CO_2 flow rate over time, one of the design questions is whether an oversized pipeline should be used for a specific pipeline segment. This question can be simplified to the problem of optimising a single pipeline segment, as illustrated in Figure 1.

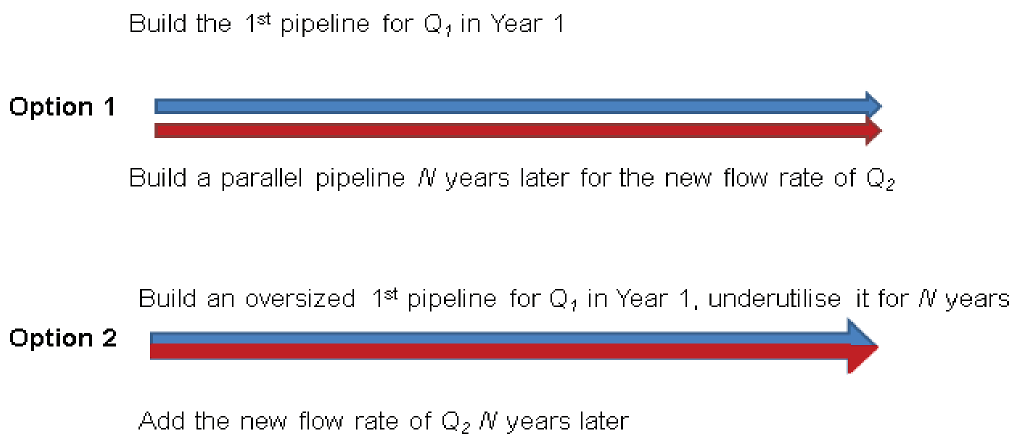

Figure 1. Two possible design options (parallel and oversized design) for an anticipated flow rate increase in a CO_2 pipeline.

At the beginning of the project, there is an initial flow rate Q_1. After N years, the CO_2 flow rate increases by Q_2. This flow increase is representative of an increase in the supply of CO_2 and may be caused by an increase in the flow rate from the existing sources, or by the connection of new sources to the existing pipeline. Two design options available are:

- Option 1 – Parallel design: independent optimisation of duplicate pipelines constructed before and after the anticipated increase in flow rate, and
- Option 2 – Oversized design: initial installation of an oversized pipeline, which is underutilised for N years for the initial flow rate Q_1 but becomes fully utilised when the anticipated flow with rate Q_2 is connected to the pipeline.

There is an inherent trade-off point for the above two options. For Option 1, because the first pipeline is an optimal design for the initial CO_2 flow rate, its diameter is smaller compared to the oversized design. This means that Option 1 has a relatively smaller upfront capital cost at the beginning of the project. On the other hand, for Option 2, the underutilized and oversized design will have a lower compression cost for the initial flow rate.

The main assumptions used in the calculations are:

- The cost basis is 2011 Australian dollars.
- A real discount rate of 7 % is used.
- The initial flow rate Q_1 ranges from 1.5 to 8 Mtpa.
- The final flow rate (Q_1+Q_2) ranges from 2.25 to 36 Mtpa.
- The flow rate ratio (Q_1+Q_2)/Q_1 ranges from 1.5 to 4.5.
- The initial and final CO_2 flows are introduced to the pipeline at approximately the same geographical location.
- The pipeline transport distance investigated ranges from 75 km to 1,000 km.
- The total project duration for both design options is 25 years. For Option 1, the second pipeline is decommissioned 25 years after the first pipeline begins operation. For Option 2, the oversized pipeline will have a total life of 25 years.

3. Cost trends

Figure 2 illustrates the trade-off point for a 500 km pipeline with an initial CO_2 flow rate (Q_1) of 3 Mtpa and an anticipated increase in the CO_2 flow rate (Q_2) of 3 Mtpa after N years, where N ranges from 1 to 12 years. The calculation applies a similar methodology to that used by Fimbres Weihs et al. [3-5] to minimise the cost per tonne of CO_2 transported (reported here as Ac/t-km), based on the levelised cost of CO_2 transportation.

As the time gap N increases, the transportation cost for the parallel pipeline design will decrease because the capital cost of the second pipeline is more heavily discounted. On the other hand, for oversized designs, the costs will increase as the time gap increases because the oversized pipeline would be underutilised for a longer period of time. Effectively this translates to an increase in an underutilisation of the capital for installation that increases as the time gap increases. For this case with a 500 km pipeline and the designated flow rates, the oversized design results in lower costs when *N* is less than 5 years, but when *N* is more than 6 years the parallel pipeline design is cheaper. The crossover in Figure 2 can be regarded as the trade-off point for decision making. Oversized designs are preferred when the time gap is smaller than the trade-off point.

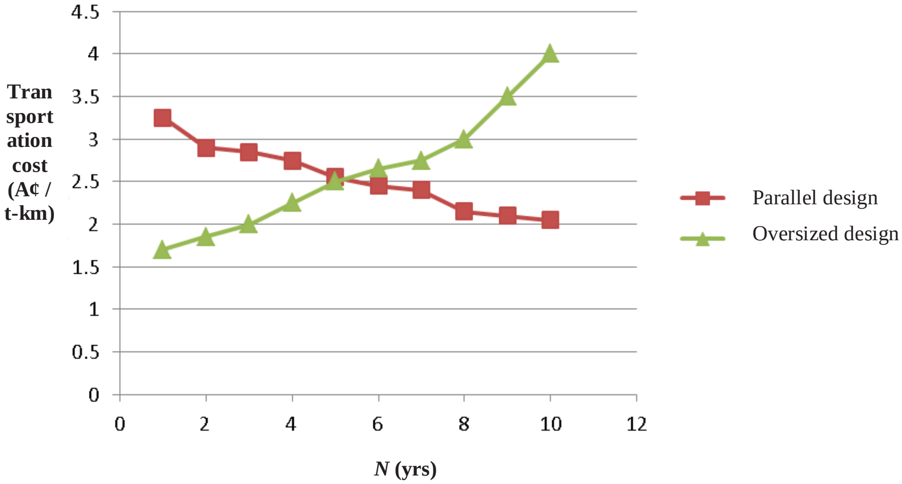

Figure 2. The transportation cost of using parallel and oversized pipeline for a 500 km pipeline, Q_1 = 3 Mtpa, Q_2 = 3 Mtpa.

4. Applying the methodology to typical flow rate changes and pipeline lengths

A contour plot is generated to illustrate the trade-off point for any combination of initial flow rate Q_1, final flow rate ratio $(Q_1+Q_2)/Q_1$ and pipeline length. Figure 3 and Figure 4 show contour plots of the trade-off points for all the flow rate combinations, for 1,000 km and 750 km pipelines respectively. As the pipeline length increases, the time to the trade-off point is reduced. This is because the larger capital cost of the longer pipelines makes the oversized designs less economically attractive. Following this method, similar contour plots can be generated for different pipeline length.

Figure 3 and Figure 4 can be used to assist in deciding whether to design an oversized pipeline or parallel pipelines. For example, suppose a particular CO_2 pipeline development under consideration has a transport distance of 1,000 km CO_2 and that the time gap between the introductions of the two flow rates to the pipeline is 7 years. If the initial flow rate Q_1 is 3 Mtpa and the final flow rate (Q_1+Q_2) is 9 Mtpa, Figure 3 shows that the trade off point is 6 years. Since the gap for this particular example is larger than the trade-off point, this suggests that it would be more economical to design parallel pipelines and to build them as required to match the transportation needs of each flow.

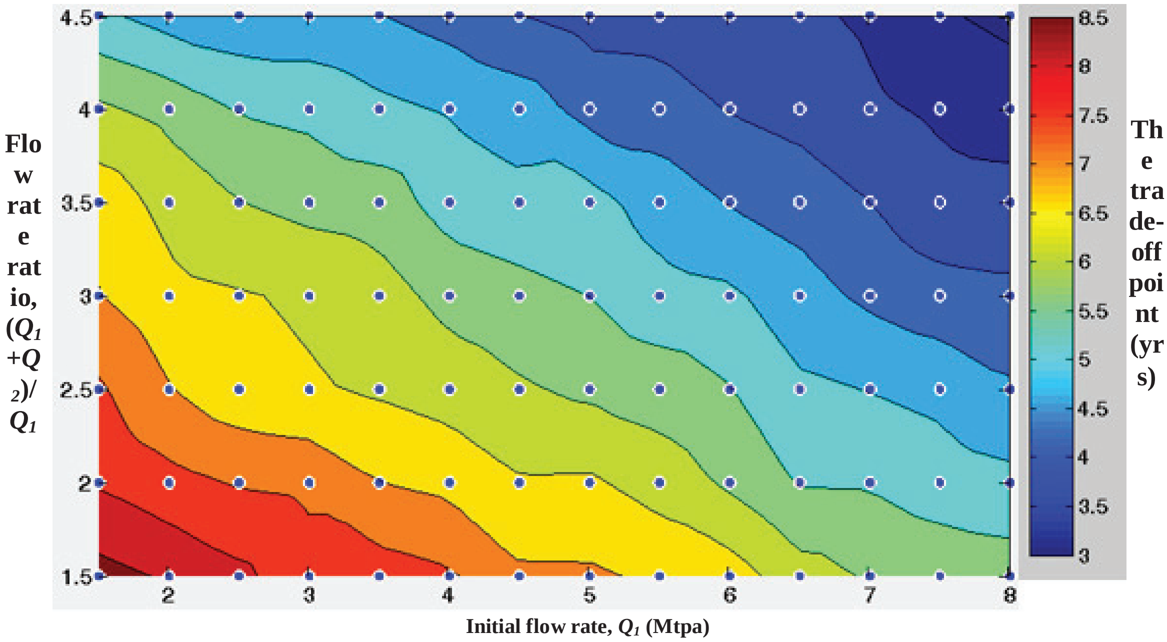

Figure 3. Contour plot of the trade-off points for different flow rate combinations for a 1,000 km pipeline.

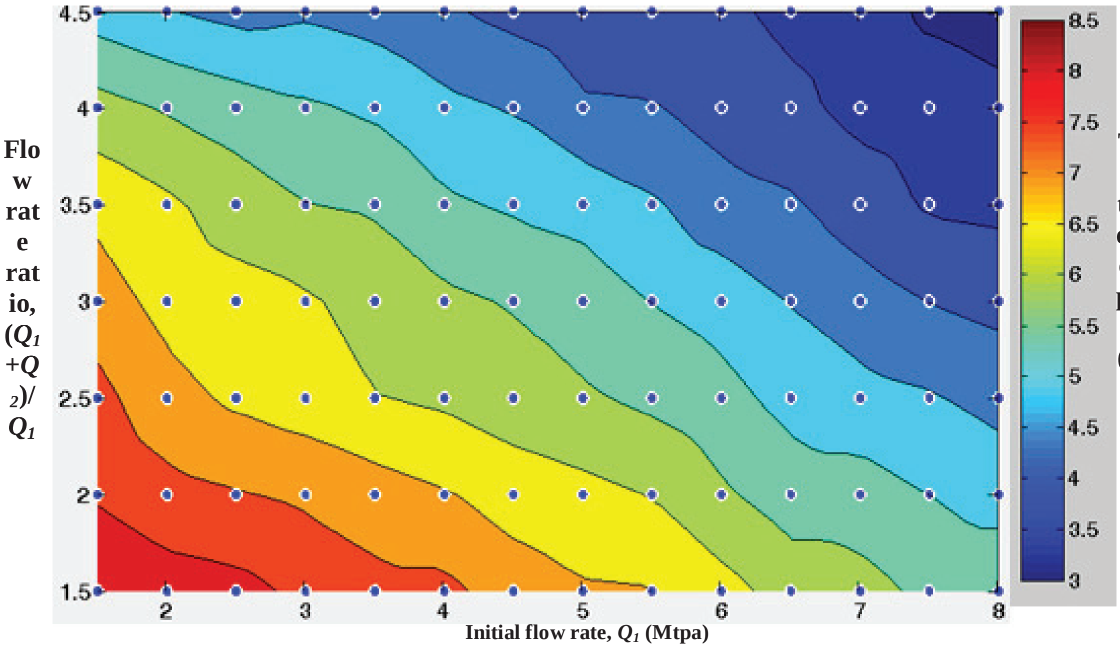

Figure 4. Contour plot of the trade-off points for different flow rate combinations for a 750 km pipeline.

5. Pipeline diameter for oversized designs

After a decision has been made on whether to use an oversized or parallel design, the next step in the pipeline design process is to determine the pipeline diameter that minimises the levelised cost of CO_2 transported. For the case where a parallel design is preferred, the choice of diameter can be carried out independently for each of the parallel pipelines using a shortcut method [3]. If the flow rate is kept constant over the operating life, the choice of optimal diameter is determined mainly by the flow rate.

However, for projects where the opportunity to use oversized pipelines may be more cost effective, shortcut methods such as the correlation in [3] are not applicable. This is because the optimal diameter would be neither the optimum for the initial flow rate (Q_1) nor for the final flow rate (Q_1+Q_2), but somewhere in between (depending on the time gap). Hence, understanding the factors that determine the optimal diameter for the oversized pipeline for a particular transport project would be beneficial.

In this section, we evaluate the effect of flow rate on the optimal oversized diameter. This is achieved by computing the ratio of the diameter for the oversized design (D_{os}) over the diameter of the first pipeline in the parallel design (D_1). Both D_{os} and D_1 are optimal diameters for a time gap equal to the trade-off point.

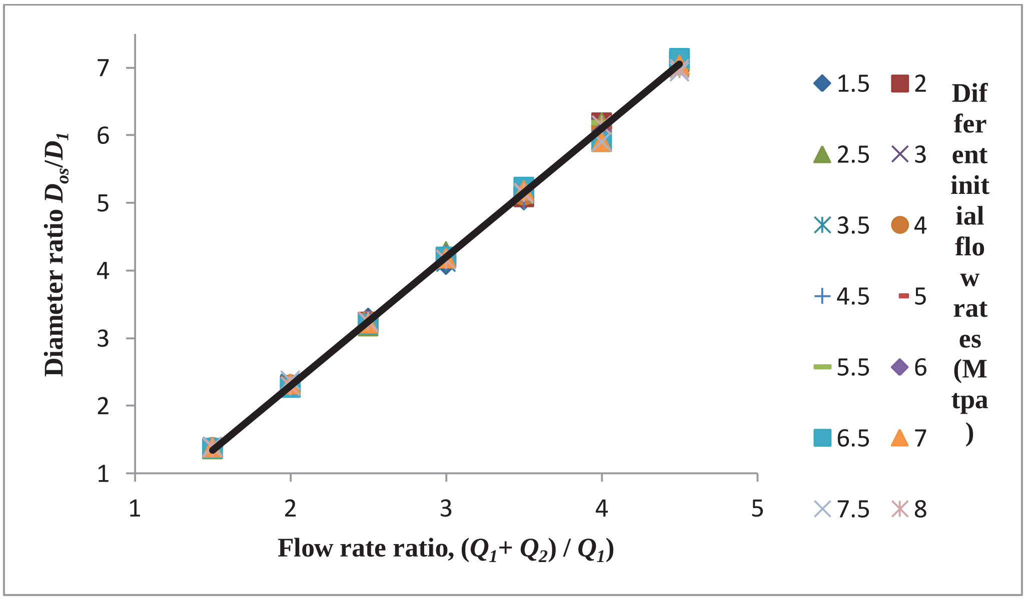

Figure 5. Relationship between the ratio of diameter for design option 1 and the diameter of the first pipeline at the trade-off point, for a 1,000 km pipeline.

As shown in Figure 5, the diameter ratio D_{os}/D_1 is linearly related to the flow rate ratio $(Q_1+Q_2)/Q_1$, with a high correlation value of R^2 = 0.935. This relationship does not appear to depend on the initial flow rate. Although Figure 5 only presents data for a pipeline length of 1,000 km, the relationship at different pipeline lengths also appears to be linear. The line plotted in Figure 5 can therefore be used to determine the required level of pipeline oversizing, once it is known that oversizing is the preferred design option. For example, for a CO_2 pipeline development with a transport distance of 1,000 km and with Q_1 = 3 Mtpa and Q_2 = 6 Mtpa, the flow rate ratio $(Q_1+Q_2)/Q_1$ =3 and the trade-off point (from Figure 3) is approximately 6 years. If the optimal diameter for the first parallel pipeline D_1 = 340 mm, Figure 5 can be used to determine that the optimal diameter for the oversized pipeline would be about 4.2 times larger, that is, D_{os} = 1400 mm.

From Figure 5, several insights into the design of pipeline networks for CO_2 transport can be gained:

- Pipeline length:
  - Oversized pipelines are more attractive for shorter pipeline lengths.

- Flow rate increase ratio $(Q_1+Q_2)/Q_1$:
  - Oversized pipelines are less attractive for larger flow rate ratios.

- Time gap:
  - Oversized designs are less attractive when the time gap between the initial flow rate and the flow rate increase is large
  - This is because the cost of the second pipeline in a duplicate pipeline design is moved further into the future and hence is more heavily discounted.

- Diameter ratio:
  - For the analyses completed to date, the ratio of the oversized diameter D_{os} and the diameter of the first parallel pipeline D_1 at the trade-off point appears to follow a linear dependence with flow rate ratio $(Q_1+Q_2)/Q_1$ regardless of the initial flow rate Q_1 or the pipeline length.
  - This means that for larger increases in CO_2 flow rates, proportionally larger diameters are required for the oversized pipeline design option.

It should be mentioned that the results presented here may change if a different discount rate is used. A higher discount rate will make oversizing of pipelines less economically attractive. The parallel pipeline design, which requires less capital cost at the beginning of the project, will be more attractive because the present value of the cost of building a second pipeline will be lower after discounting.

6. Conclusion and future work

This study uses a preliminary optimisation methodology with simplified scenarios for pipeline planning. For a new CCS project with anticipated expansion in the near future, the results presented in this paper can help identify the optimal pipeline design that minimises the levelised cost of transport. The key parameters in the pipeline design, including pipeline length, flow rates, flow ratio and the time gap between the increases in flow rate are analysed. A contour plot is presented to assist with the decision of whether to design an oversized pipeline or parallel pipelines for a range of flow rates and transport distances.

This study is limited to the pipeline design for two CO_2 sources located in close proximity. Future studies should analyse more generalised scenarios, such as the optimisation of pipeline designs for 3 or more emission sources successively connected to a CO_2 pipeline. Moreover, expanding pipeline networks should also be investigated.

Acknowledgements

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