Sensitivity Analysis and Case Studies for CO_2 Transportation Energy Consumption.

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Abstract

The transportation of CO_2 is important to all carbon capture and storage (CCS) projects. Both the infrastructure costs (compressors, pipelines, tanker ships, etc.) and the energy consumed in the compression or liquefaction of CO_2 are significant. Understanding how the size, capacity and energy consumption of transportation alternatives varies between projects is therefore important. Modelling provides a useful insight into the performance of transportation alternatives, but the results are only useful when the basis for comparison is consistent and the impact of model input parameters is well understood. This article presents the results of sensitivity studies made using a transportation model that was developed in earlier work. Several important model parameters are studied using three planned/operating CCS project cases. The results show that while the operating pressure of the storage site is most important in determining the transportation system operating pressure, the temperature of the available cooling utility is the key parameter determining energy consumption.

Keywords: *CO_2, CCS, transportation, modelling*

1 Introduction

All carbon, capture and storage (CCS) projects require the transportation of CO_2 from a source to a storage location. A compressor and a large diameter pipeline is the method often used to achieve this, but as illustrated in Figure 1, the liquefaction of CO_2 to allow ship–based transportation can also form one of the links in the transportation process.

Although identifying the optimum economic case is of key importance to all CCS projects, it is also important to minimize energy consumption because the energy consumed by the process corresponds directly to the efficient consumption of non-renewable resources in fossil-fuel based CCS projects.

Most of the energy consumption associated with CO_2 transportation comprises compression and pumping energy. Compressors are often used to raise the pressure of gaseous CO_2 streams or gaseous refrigerants (in the case of liquefaction) and pumps are used to raise the pressure of liquid CO_2 streams. The pressure-level required for transportation depends on the operating parameters of the storage location, the design of the pipeline and the temperature under which the pipeline operates. Understanding how the combined effect of these parameters affects energy consumption can, therefore, provide an important insight into the relative strengths of different CCS projects.

As part of a project aimed at studying the performance of CCS project alternatives a MATLAB based model for the transportation of CO_2, *CO2TM,* has been developed and is made freely available at UiT Open Research Data (Jackson, 2020a).This model is used as the basis for the present study.

The *CO2TM* takes inputs comprising the source location, transportation type (ship or pipeline) pipeline route, storage reservoir depth and CO_2 mixture type. From these inputs, the model calculates an elevation profile for pipelines and a temperature profile using built-in bathymetry (seabed elevation profile) and sea surface temperature (SST) data. Based on elevation, temperature and CO_2 mixture data, the model estimates the reservoir and wellhead pressure (WHP) and then determines the pressure profile required to ensure

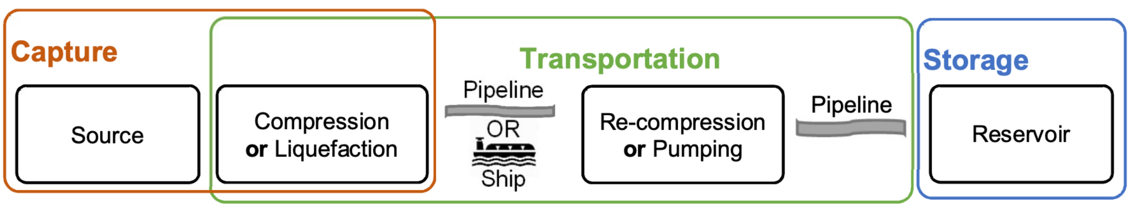

Figure 1. Illustration of the Main Associated with the Transportation of CO_2 (from Jackson, 2020).

single-phase flow in the pipeline. Finally, the energy consumption for transportation processes—comprising either compression or liquefaction—is calculated using the ambient sea temperature in location where each part of the process is situated. The development of this model is described in detail in earlier work (Jackson, 2020b).

The aim of this article is to present results from a study into the sensitivity of the *CO2TM* to various modelling parameters so that the application of this model can be better understood. The study is roughly based on three planned/ operating CCS project cases, which are used to illustrate the impact of the studied parameters on performance.

2 Method

Because the focus of earlier work—including the development of the *CO2TM*— has been the impact of ambient temperature on CO_2 transportation system performance, the main focus for this work is also the study of model sensitivity to seawater temperature. A related modelling parameter, also studied in this work, is the pipeline Heat Transfer Coefficient, HTC. In addition, this article presents results for CO_2 transportation system sensitivity to pipeline roughness, mixture composition and transportation type. The method used in the study of each of these parameters is described in more detail below under several sub-headings.

Although the development of the *CO2TM* is described in earlier work, some modifications to the original model were required to facilitate the present study. The modifications made are also described under the headings set-out below where they are relevant and will be subsequently included in an updated version of the *CO2TM*.

2.1 Sensitivity to Temperature

The *CO2TM* determines SST in the locations defined in the model input parameters using data from JMA (Japan Meteorological Agency). The resulting temperature data is then used as the basis for calculation of the energy consumption of the liquefaction and compression processes along with the temperature profile in the pipeline. For the compression and liquefaction processes, the model applies a margin of 10 °C above the seawater temperature.

Because SST varies annually, the data used in the model is based on two standard deviations above the average of yearly SST, i.e. covering around 95% of all SST measurements. This results in a conservative estimate for the energy consumption of compression and liquefaction processes and the pipeline temperature profile. It is therefore natural to study the sensitivity of the model to seawater temperature with an emphasis on reduced temperatures, which can be interpreted as either the performance during winter months or a less conservative approach to heat exchanger design. To reflect this, a range of temperatures from base -8 ºC to base +4 ºC is used in the sensitivity studies conducted here.

To allow the study of this temperature range, the original *CO2TM* required some modification. The main modification was to allow the user input of seawater temperature to apply to both the liquefaction location and the pipeline location for cases where transport is by ship. This represents an over simplification of reality where the liquefaction location may be a significant distance from the storage location, but it is one way in which sensitivity can be studied.

Another modification required was to implement limits on the minimum sea temperature used in the code to avoid extrapolation of parameters such as density and heat capacity outside of the range of the basis data included in the model. This was done by setting a minimum possible SST of 5 °C within the model.

2.2 Sensitivity to Pipeline Roughness

Pipeline roughness affects pipeline pressure-drop and can vary with both construction material and the age of the pipeline, equating to corrosion and fouling over time. In large diameter gas pipelines a coating is sometimes used to reduce pressure-loss and studies have found that absolute roughness can be as low as 4 μm (Langelandsvik, 2008). However, studies relating to CO_2 pipelines have often used higher values of roughness ranging up to 100 μm (Chandel et al., 2010). The default value of roughness used in the model is 15 μm, but this can be over-ridden using a user-specified roughness input parameter. In the present study, the roughness input parameter was varied from 2 to 100 μm to provide a range of results illustrating sensitivity.

2.3 Sensitivity to Heat Transfer

Subsea pipelines typically loose heat along their length to the surrounding seawater. The HTC, which varies with pipeline design and burial conditions, determines how quickly the pipeline contents approaches the sea temperature. In-turn, the temperature in the pipeline can impact the required operating pressure, which must be maintained at a margin above the bubble point curve of the CO_2 mixture throughout the pipeline.

The default value of the coefficient used in the model is 4 W/m^2 K, but the user can override this using a user-specified model input parameter. Studies of onshore buried pipelines have used HTC in the range 1–6 W/m^2 K (Mazzoccoli et al., 2014; Zhang et al., Massarotto et al., 2006), and for pipelines surrounded by water, up to 45 W/m^2 K (Drescher et al., 2013). The present study uses a range from 1 to 32 W/m^2 K to investigate the impact of this parameter on CO_2 pipelines.

2.4 Sensitivity to CO_2 Mixture Composition

The composition of CO_2 mixtures in transport systems depends on the source of the CO_2 and the entry specifications set for the transportation system. The *CO2TM* has three built-in CO_2 mixture compositions with associated property data representing post, pre and oxyfuel combustion CO_2 sources.

In the previously published version of the *CO2TM,* the post combustion case is the only mixture composition made available for use. To enable the study of the sensitivity to CO_2 mixture composition in the present work, an update was required to make the oxyfuel mixture composition available for use. This work was done on the same basis as the earlier work and, although the details of the method are not described here, the composition used is provide in Table 1.

Table 1. CO_2 Mixture Compositions.

Component	*Post*	*Oxyfuel*
CO_2 mole %	99.99	96.16
N_2 mole %	0.01	2.45
Ar mole %	–	0.96
O_2 mole %	–	0.43

In addition, to provide a consistent basis for comparing energy consumption between post combustion and oxyfuel cases, an update of the *CO2TM* was required to allow the liquefaction energy consumption to be calculated for cases where the feed stream has a pressure of 15 barg— e.g. originating from a low–temperature type oxyfuel purification unit. The reduction in liquefaction energy for these cases was estimated by taking the difference between the compression energy for pipeline transport for the oxyfuel and post combustion capture cases and then deducting this from the energy consumption of the standard liquefaction process, where the feed stream is at low pressure. The updated version of the *CO2TM* will be published subsequent to the completion of the present work.

The sensitivity study conducted in the present work is based on a comparison of the performance of post and oxfuel combustion CO_2 mixture compositions. The basis of this comparison is both the transportation energy consumption and the pipeline inlet pressure. Results are summarized for the *CO2TM* default pipeline size selection: the first pipeline size that results in a pipeline pressure under 180 barg for all operating cases, and for the case where all pipelines have the same diameter.

2.5 Sensitivity to Transportation Method

The transportation cases used in this work are loosely based on three planned/operating CCS projects. Case 1 reflects the planned Norcem/Northern Lights (NL) project , which includes ship-based transport of CO_2 from Norcem in Brevik to the planned NL storage hub in south east Norway. Case 2 reflects the proposed H21 project, which is planned to include the conversion of natural gas to hydrogen with carbon capture in the UK with CO_2 storage in the North Sea[2]. Case 3 reflects the Melkøya CCS project, where CO_2 is removed from natural gas and returned to storage in the Barents Sea. A summary of some of the main modelling parameters associated these cases is provided below in Table 2.

Table 2. Comparison of Case Parameters.

Parameter	*Case 1*	*Case 2*	*Case 3*
Source Location	9,69 E 59,06 N	0,12 E 53,65 N	23,59 E 70,69 N
Liquefaction Loc.	9,69 E 59,06 N	-	-
Compression Loc.	-	0,12 E 53,65 N	23,59 E 70,69 N
Pipeline location	4,89 E 60,56 N	0,12 E 53,65 N	23,59 E 70,69 N
Pipeline length (km)	107	129	151
Reservoir location	3,42 E 60,45 N	2,00 E 54,00 N	4,89 E 60,56 N
Wellhead depth (m)	300	76	318
Reservoir Depth (m)	2000	1300	2500
Sea Temp. (°C)*	15,3	18,0	10,9

* Calculated by the *CO2TM*

In addition to the three cases described above, three alternative cases are also defined: Case 1A is the NL project with pipeline transport of CO_2 directly from the pipeline location; Cases 2A and 3A reflect Cases 2 and 3 with shipping to the NL pipeline as an alternative to pipeline transportation.

The model parameters used to specify the pipeline route for all cases and reservoir details are inferred from openly available data and should not be taken to accurately reflect the details of these projects. Figure 2 provides an illustration of the pipeline route used for the NL cases that was generated using the *CO2TM*.

3 Results & Discussion

The main results of the study are set out below under separate sub-headings.

3.1 Sensitivity to Pipeline Heat Loss

Figure 3 presents results that illustrate the sensitivity of pipeline inlet pressure to the heat transfer coefficient used in the model. For Cases 1A, 2 and 3 a small impact on pressure is visible, but in Case 1 there is almost no impact. This can be explained by the fact that in Case 1

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the CO_2 mixture is very close to the seawater temperature at the point of entry to the pipeline.

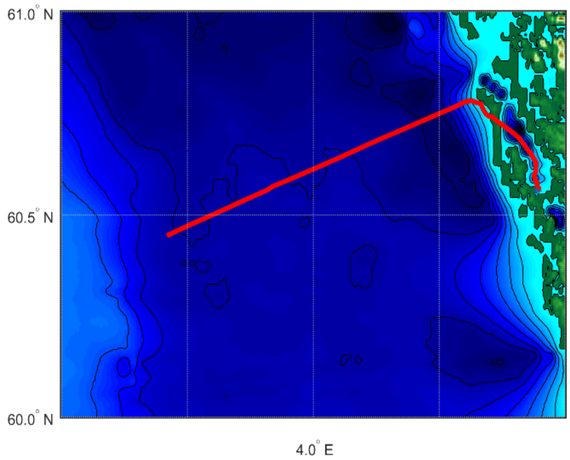

Figure 2. Illustration generated by the *CO2TM* for the Norther Lights (NL) pipeline route used in this work.

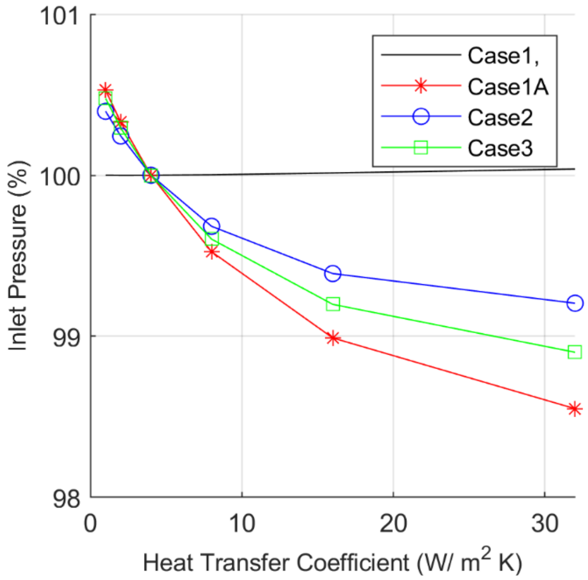

Figure 3. Variation in Pipeline Inlet Pressure with HTC where 100% is the model default basis of 4 W/m^2 K.

Figure 4 shows that the variation in pipeline inlet pressure presented in Figure 3 equates to an even smaller variation in overall energy consumption, reflecting the fact that the dominant part of the system energy consumption is associated with the earlier stages of compression, in the compression cases, and with the liquefaction process in the liquefaction cases.

3.2 Sensitivity to Pipeline Roughness

Figure 5 and Figure 6 present results for the sensitivity of pipeline inlet pressure and energy consumption to pipeline roughness. They show that roughness is a more important factor in transport system design than the HTC, although Figure 6, like Figure 4, shows that the roughness does not play a big role in determining the system energy consumption.

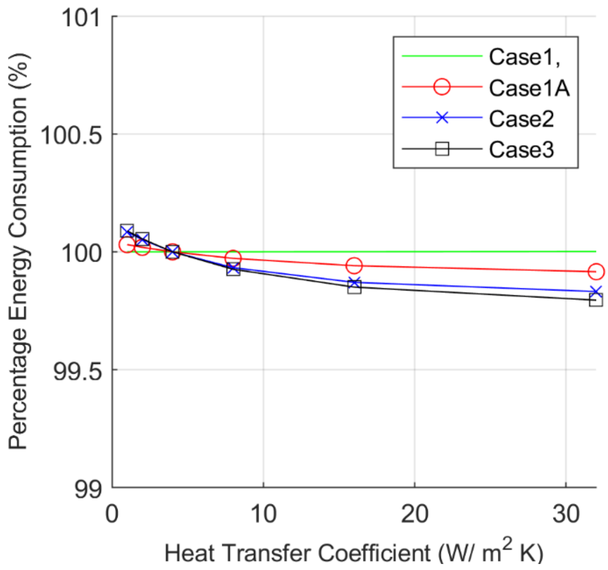

Figure 4. Variation in Energy Consumption with HTC.

However, Figure 5 does show that roughness can have a significant impact on the pipeline operating pressure, which is important to selection of the pipeline size and therefore the economics of CCS projects.

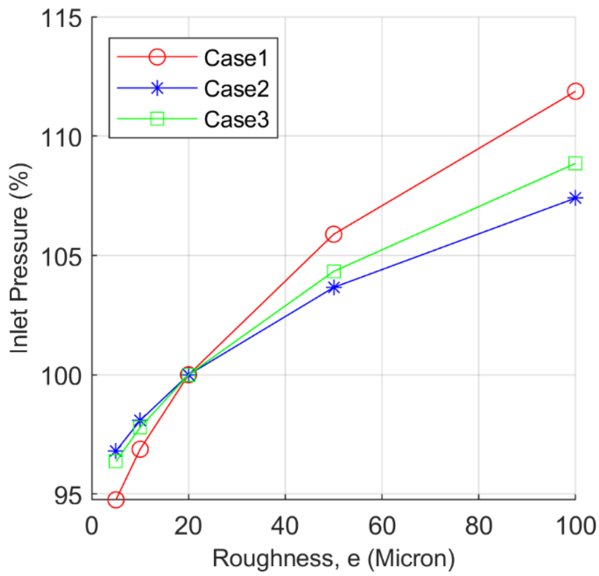

Figure 5. Variation in Percentage Pipeline Inlet Pressure with Pipeline Roughness.

3.3 Sensitivity to Temperature

Figure 7 and Figure 8 show the impact of seawater temperature on pipeline inlet pressure and energy consumption when the default seawater temperature estimated by the model is adjusted in the range – 8 °C to + 4 °C. The results are split into cases with pipeline-based transport (shown in red) and shipping based transport (shown in blue).

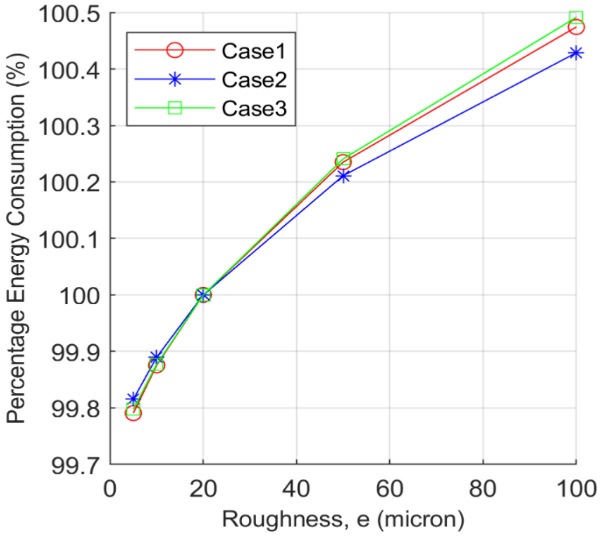

Figure 6. Variation in Percentage Energy Consumption with Pipeline Roughness.

The results show that although the impact of SST on pipeline inlet pressure is not more pronounced than that of roughness, the impact on energy consumption in all cases is much more significant. This is due to the dual impact of sea temperature, i.e. that it both affects the pipeline operating pressure and reduces the energy consumption of the associated compression and liquefaction processes.

The results presented for Case 3, Melkøya in Figure 7 and Figure 8 also show that when the seawater temperature is reduced by 8 °C, the temperature of the pipeline falls below the lowest temperature where compressor energy consumption data is available in the model. In reality, there would be some continued reduction in energy consumption that would gradually reduce towards zero as the sea temperature is also reduced towards zero.

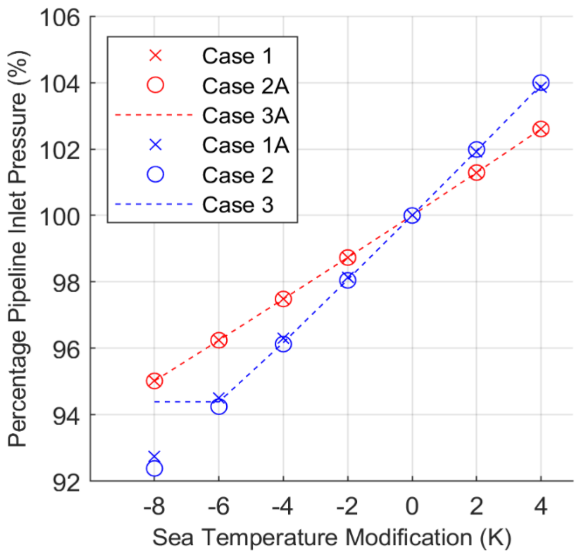

Figure 7. Variation in Energy Consumption with Seawater Temperature for Shipping Cases (in red) and Pipeline Transport (in blue).

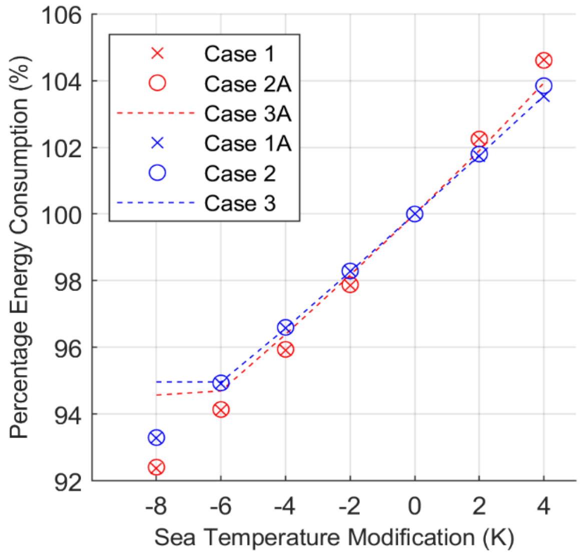

Figure 8. Variation in Energy Consumption with Sea Temperature for Shipping Cases (in red) and Pipeline Transport (in blue)

3.4 Sensitivity to CO_2 Mixture

Figure 9 shows how the pipeline pressure varies with sea temperature for two CO_2 mixture compositions representing post combustion capture and oxyfuel combustion.

All of the results indicate a small increase in operating pressure for the oxyfuel cases. This is due to an increased CO_2 mixture bubble-point pressure, which affects the minimum pipeline operating pressure: in all cases the *CO2TM* enforces a margin between bubble-point pressure and operating pressure. The sensitivity of inlet pressure to seawater temperature is similar for most cases.

Figure 9 shows results for the Norcem/NL case on two different pipeline design basis: a 14-inch pipeline sized based on the model default parameter of 180 bar maximum pipeline operating pressure (red lines), and a 16-inch pipeline sized to match the other two cases (black lines). This comparison highlights an inherent advantage of the NL pipeline that results from a combination of wellhead depth and reservoir depth (see Table 2). The results show that both of these factors have an important influence on the pressure profile calculated by the *CO2TM*.

How the variation in Inlet Pressure translates into a variation in energy consumption is presented for the post combustion cases, which are discussed under the next heading.

3.5 Sensitivity to Transportation Type

Figure 10 shows the variation in energy consumption with seawater temperature modification for a selection of pipeline and ship-based transportation cases.

The results show that in all of these cases, ship based transportation consumes more energy than sending the

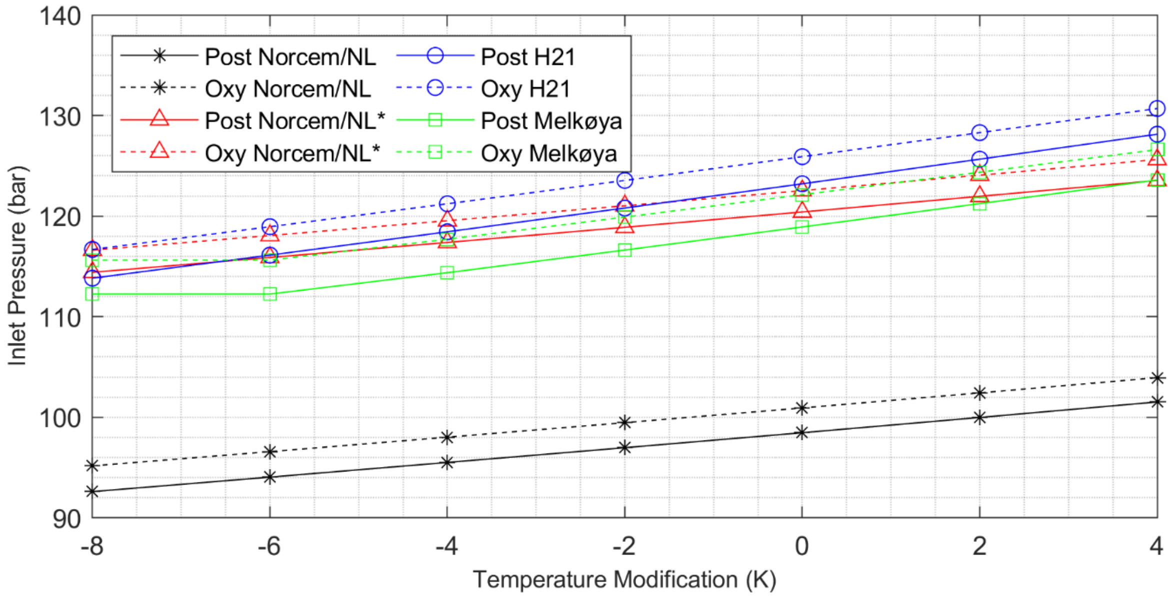

Figure 9. Impact of CO_2 Mixture Composition on Pipeline Operating Pressure.

CO_2 to a pipeline. Although the proportion of additional energy required is seen to vary between cases, the sensitivity of energy consumption to seawater temperature is similar for all cases.

Similar to Figure 9, Figure 10 presents results for both a 14-inch and a 16-inch NL pipeline diameter. However, the results presented in Figure 10 show that the impact of increasing the pipeline size on energy consumption is much smaller than the impact on pipeline operating pressure.

The results presented in Figure 10 also show that, regardless of transportation type, the energy consumption varies significantly between cases: both pipeline transport and shipping CO_2 from Melkøya results in the lowest energy consumption of all cases. This highlights the important role that ambient temperature plays in determining the energy consumption for both transportation alternatives.

4 Conclusions

When pipelines operate close to the temperature of the surrounding medium, the heat transfer coefficient has a low impact on operating pressure and energy consumption.

Pipeline roughness has a small, but potentially important impact on CO_2 pipeline operating pressure and hence the selection of the economic optimum pipeline diameter. The impact of roughness on the

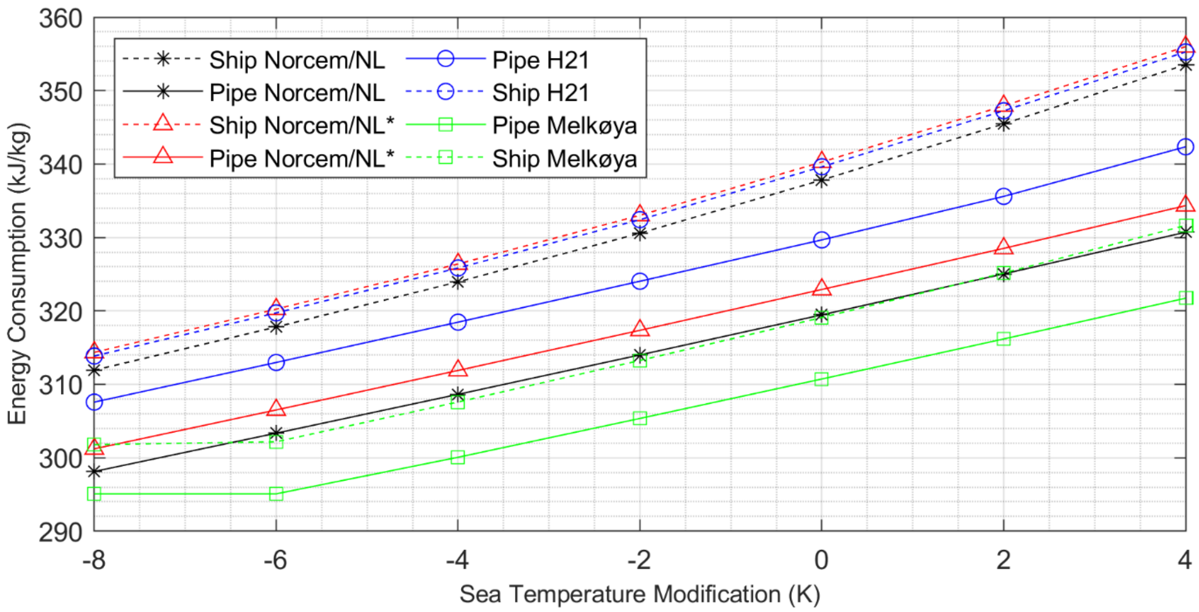

Figure 10. Impact of Transportation Type on Energy Consumption with Varying Sea Temperature

energy consumption associated with transportation of CO_2 is, however, small.

The composition of the CO_2 mixture transported in a pipeline can have an important impact on the transportation pressure.

The operating pressure of the storage reservoir and the wellhead location have the most important impact on CO_2 pipeline operating pressure and potentially the size and economics of CCS projects.

The most important factor influencing the energy consumption of both CO_2 transportation in pipelines and using ships is the temperature of the cooling utility (assumed to be seawater in this study) available in the location where the CO_2 is compressed or liquefied. The results from Figure 10 and Figure 8 show that the impact of temperature is consistent for all cases and equates to around 1 % of overall energy consumption per °C across the range of temperatures and cases studied here.

Compression or liquefaction is always needed at the source of captured CO_2 emissions in CCS projects, and therefore, CCS projects located in low ambient temperature locations can be expected to benefit from lower transportation energy consumption. Figure 10 shows that this advantage can be maximized by returning the captured CO_2 directly to a storage location using compression and pipeline transportation. Interestingly, the advantage associated with a low ambient temperature location such as Melkøya in Northern Norway is also apparent when the captured CO_2 is liquefied and shipped to a storage hub located at some distance.

Allowances for the energy consumption associated with shipping (transportation fuel, re-liquefaction energy, etc.) are not calculated by the *CO2TM* and do not form part of this study. In addition, the design parameters of the pipelines and storage locations used in this study can only be taken to be indicative of the project cases they are based upon. More detailed studies would be required to make an accurate comparison of the relative performance of these different cases. However, the results presented here can provide a guide to the sensitivity of CO_2 transportation energy consumption to some important case–specific and general design parameters.

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