Techno-economic evaluation of CO_2 transport from a lignite-fired IGCC plant in the Czech Republic

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Abstract

This paper investigates different strategies for CO_2 conditioning and transport options for the CO_2 to be captured at a lignite-fired IGCC in the Czech Republic, including the impact of impurities present in the captured CO_2 streams. Four transport cases, combining two transport delivery location scenarios (Czech storage and European transport hub) and two transport technology options (pipeline-based and train-based transport), are designed and evaluated. For the Czech storage case, the cost evaluation of the CO_2 conditioning and transport results in costs of 10.5 and 18.3 €/t_{CO2} for the pipeline and train options respectively. In the European hub scenario, the CO_2 conditioning and transport costs are estimated at 15.4 and 24.9 €/t_{CO2}. These results clearly identify the pipeline transport options as the cost-optimal solutions for CO_2 transport in both delivery location scenarios, due to the longer transport distances and higher conditioning costs involved for train-based export. Moreover, the comparison of transport delivery location scenarios also shows that if CO_2 storage is not possible at the Czech storage location and the CO_2 has to pass through the European hub, this would result in an increase of at least 4.9 €/t_{CO2}, plus the additional transport and storage costs after the European hub stage.

In addition, further assessments are performed to evaluate the impact of impurities in the CO_2 streams from the capture plant on the CO_2 conditioning and transport costs for the four combinations of transport scenarios and technology options. The results show that the impurities present in the CO_2 streams lead to increases in CO_2 conditioning and transport costs ranging from 1.6 to 11.4% (0.2-1.9 €/t_{CO2}). However, the energy and cost impacts associated with the impurities are highly dependent on the transport technology and transport delivery location scenario considered. Furthermore, the process energy and cost performances of two alternative CO_2 liquefaction processes, designed to reduce CO_2 losses through the purged gas, are also evaluated. These two alternative processes result in higher CO_2 conditioning cost than the base case process, which suggests that reducing the CO_2 losses compared to the base case would not be a good strategy, unless high costs (70-110 €/t_{CO2}) were spent to capture the CO_2 that is purged. Finally, the potential of train-based transport is evaluated beyond the four cases considered by comparing the CO_2 conditioning and transport costs of pipeline and train transports as a function of the distance for different train conditioning cost scenarios and different project economic valuation periods. The results show that train-based transport could potentially be a cost-optimal alternative to pipeline-based transport for medium to long distances especially in cases where the additional conditioning costs of train-based transport compared to pipeline are limited, or in cases of financial risk-averse decisions.

Keywords: Carbon Capture and Storage (CCS); CO_2 transport; Pipeline transport; Train-based transport; Techno-economic comparison; lignite-fired IGCC.

Abbreviations: 2DS, 2 degrees scenario; API, American Petroleum Institute; CAPEX, capital expenditure; CCS, carbon capture and storage; CEPCI, chemical engineering plant cost index; EOR, enhanced oil recovery; IEA, International Energy Agency; IGCC, integrated gasification combined cycle; ROW, right of way.

1 Introduction

Carbon Capture and Storage (CCS) will be an essential technology to ensure that the commitment of COP-21 to limit global temperature increase caused by anthropogenic climate change to 1.5°C can be met at relatively low cost. Indeed, the International Energy Agency (IEA) (International Energy Agency, 2013) evaluated that CCS should account for 14% of the reduction in CO_2 emissions in the two degrees scenario (2DS). The IEA has also stated that, without CCS, the power sector alone would require additional investments in power generation capacity of at least USD 3.5 trillion (without the additional electricity storage and network requirements) compared to the 2DS scenario (International Energy Agency, 2016). While this emphasizes the importance of accelerating CCS deployment, large-scale implementation has fallen behind. Since the first CCS with enhanced oil recovery (EOR) project in 1972, only 15 large-scale CCS projects have come into operation, with a further six CCS facilities due to become operational by the end of 2017 (Global CCS Institute, 2015). One of the main obstacles to large-scale implementation of CCS is the current high costs and financial risks associated with demonstration projects. These costs are expected to be reduced through experience gain on unnecessary overdesigns and overspecification in demonstration projects, the development of new and more efficient technologies and materials (Berstad et al., 2014a; Berstad et al., 2014b; He et al., 2015; Lindqvist et al., 2014; Riboldi and Bolland, 2015; Roussanaly et al., 2016), economies of scale (Herzog, 2011), better understanding of the behaviour and integration of the whole chain (Anantharaman et al., 2013; Corsten et al., 2013; Jakobsen et al., 2017; Koornneef et al., 2012; Roussanaly and Anantharaman; Roussanaly and Grimstad, 2014), and so on. While a significant part of the literature focuses on CO_2 capture and CO_2 storage, less efforts have been put into CO_2 transport as due to its thought high maturity.

In practice, CO_2 can be transported via pipeline, ship, train or truck (Metz et al., 2005). CO_2 transport is often considered to be the most mature part of the CCS chain as more than 6500 km of CO_2 transport pipelines are currently in operation around the world (Noothout et al., 2013). However, only a few small ships for transport of food-grade CO_2 are currently in operation around the world (Yara, 2015). Even if further research and development is required for tanked transport of CO_2 (ship, truck and train), many important aspects of CO_2 transport have been extensively studied in the literature. As most existing CO_2 pipelines are located in sparsely populated areas, while future infrastructure may pass close to more densely populated areas, significant efforts described in the literature have been put into safety-related aspects of CO_2 transport (Koornneef et al., 2010) such as crack modeling and prevention (Aursand et al., 2016b; Joshi et al., 2016; Xie et al., 2014), corrosion (Halseid et al., 2014; Sim et al., 2014), failure probabilities (Ha-Duong and Loisel, 2011). Techno-economic assessment and comparisons of pipeline and shipping transport have been extensively reported in the literature, based on evaluations of defined cases without uncertainties (Aspelund et al., 2006; European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2011b; Gao et al., 2011; Jakobsen et al., 2017; Jung et al., 2013; McCoy and Rubin, 2008; Roussanaly et al., 2013a), but also with uncertainties (Knoope et al., 2015a, b), on more generic notes to understand when pipeline and shipping are respectively the cost-optimal technology (Geske et al., 2015; Metz et al., 2005; Roussanaly et al., 2014; Roussanaly et al., 2013b), and even from a network perspective (Coussy et al., 2013; Fimbres Weihs et al., 2011; Morbee et al., 2012). More recently, the impact of impurities in the CO_2 streams on the technical design and cost performances has gained a stronger focus with especially two H2020 EU projects: IMPACTS and CO_2 QUEST. In addition to providing overall recommendations regarding the evaluation of the impact of impurities on CO_2 transport and storage (Brunsvold et al., 2016; Porter et al., 2016; Rütters et al., 2016; Skaugen et al., 2016), these projects addressed the impact of impurities on pipeline decompression (Aursand et al., 2016a) and fracture (Talemi et al., 2016), on the dispersion of CO_2 in the case of leakage (Wareing et al., 2016), and even on CO_2 injection and storage (De Dios et al., 2016; Waldmann et al., 2016; Wolf et al., 2016). Finally, while the technical and cost performances of CO_2 conditioning and transport have been studied for pipeline transport, the results show that their impact is very much case-specific, depending particularly on the type and level of impurities, as well as the transport characteristics (Martynov et al., 2016; Porter et al., 2016; Skaugen et al., 2016).

This paper investigates strategies for conditioning and transport of CO_2 captured from a lignite-fired integrated gasification combined cycle (IGCC) power plant in Czech Republic. The analyses consider the design, evaluation and comparison of transport to different delivery locations and by different modes of transport (pipeline versus train), taking also into account the impact of impurities present in the CO_2 captured streams. In addition, this paper also evaluates and discusses the impact of the present impurities on the design and cost performances of CO_2 conditioning and transport, as well as the impact of alternative CO_2 liquefaction process designs on the cost of conditioning. Finally, the potential of train-based CO_2 transport is further evaluated.

2 Methodology

2.1 Study concept and case definition

The study concept is based on CO_2 capture, transport and storage from an IGCC plant similar to the Vřesová power plant in the Czech Republic. While the techno-economic modelling and evaluation of the IGCC plant with different CO_2 capture technologies (rectisol, low-temperature and membranes) are presented in Roussanaly et al. (Roussanaly et al., 2017), this study aims at the comparison of CO_2 conditioning and transport options for the CO_2 to be captured at the lignite-fired IGCC, including the impact of impurities present in the captured CO_2 streams.

Based on the location of the IGCC plant, two transport scenarios are considered: 1) the CO_2 captured is conditioned and transported to storage located in the Zatec Basin (Czech Republic) 2) the CO_2 captured is conditioned and transported to an hypothetical European transport hub, located near Dresden (Germany), with the aim of subsequent large-scale pipeline transport to a storage site in the North Sea. Besides these two destination options, two technologies are considered for the transport of CO_2: pipeline-based transport and train-based transport. While the first technology is quite mature (Metz et al., 2005; Miller, 2016), train-based transport (Gao et al., 2011; Global CCS Institute) is less mature but is thought to be similar to existing ship- and truck-based transport solutions (Metz et al., 2005). Considering the combination of transport scenarios and transport technologies, four transport cases, presented in Figure 1(a) and (b), are considered in this study. It is worth noting that the train-based CO_2 transport is based on existing railroad infrastructure in order to avoid prohibitive railroad installation costs. However, in practice this leads to longer transport distances than for pipeline transport. Finally, for both transport scenarios, the pipeline transport is assumed to deliver the CO_2 at the same location than the hypothetical train unloading station for consistency, while the remaining short pipeline connections to storage or the hub are not here included.

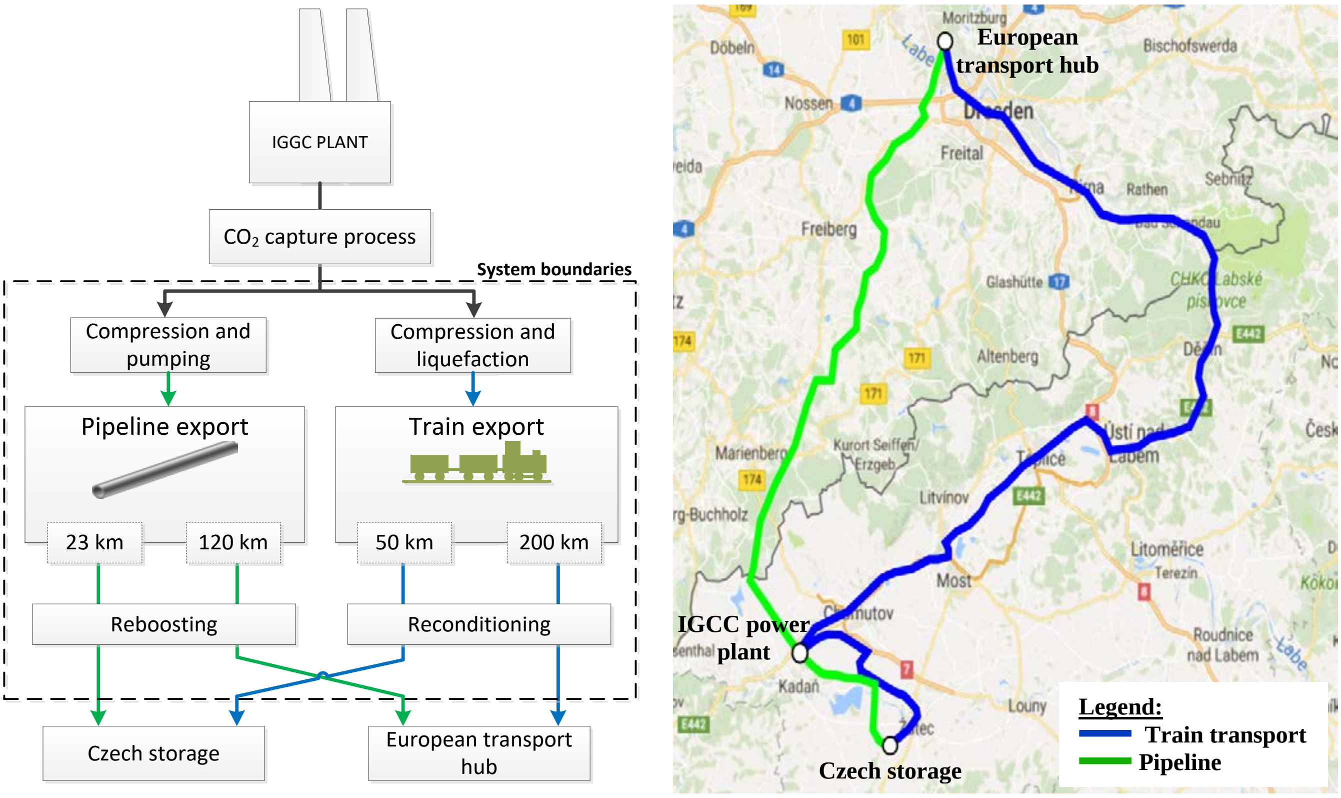

Figure 1: (a) Schematic diagram and system boundaries of the four CO_2 conditioning and transport cases (b) Map of the considered pipeline and train transport corridors

The system boundaries comprise CO_2 conditioning, transport and reconditioning (if necessary). For the pipeline transport chain, the captured CO_2 is conditioned to 150 bar and then transported by pipeline with reboosting along the pipeline, and if necessary also at the exit in order to ensure that storage (90 bar) or transport hub (150 bar) pressure requirements are satisfied (Roussanaly et al., 2013b). In the case of the train transport, the captured CO_2 is liquefied to 6.5 bar and -50.3 ºC, followed by train transport and

finally a reconditioning step to ensure that storage and transport hub pressure and ambient temperature requirements are met.
The CO_2 to be conditioned and transported is assumed to be obtained from a Rectisol-based CO_2 capture resulting in four CO_2 streams with impurities as shown in Figure 2. The compositions and characteristics of the corresponding CO_2 streams are shown in Table 1. It is worth noting that the CO_2 streams from the Rectisol capture contain significant amount of impurities (mainly methanol, hydrogen and nitrogen). These impurities may have a significant impact on the CO_2 conditioning and transport design and performances (Porter et al., 2016; Skaugen et al., 2016) and are thus included in the evaluations performed. It is worth noting that the water initially present in the syngas is removed within the Rectisol-based capture process as show in Figure 2, thus the CO_2 streams sent for conditioning are already dehydrated.
In all four CO_2 conditioning and transport cases considered, the CO_2 stream transported fulfil the transport impurities specification considered in recent IEAGHG studies (IEAGHG, April 2017). Although stronger requirements on impurity level may be required in the case of connection to a hub, such requirements are expected to be case specific to the hub (other CO_2 sources, type and level impurities, volume, etc.) and are thus not considered in the present study.

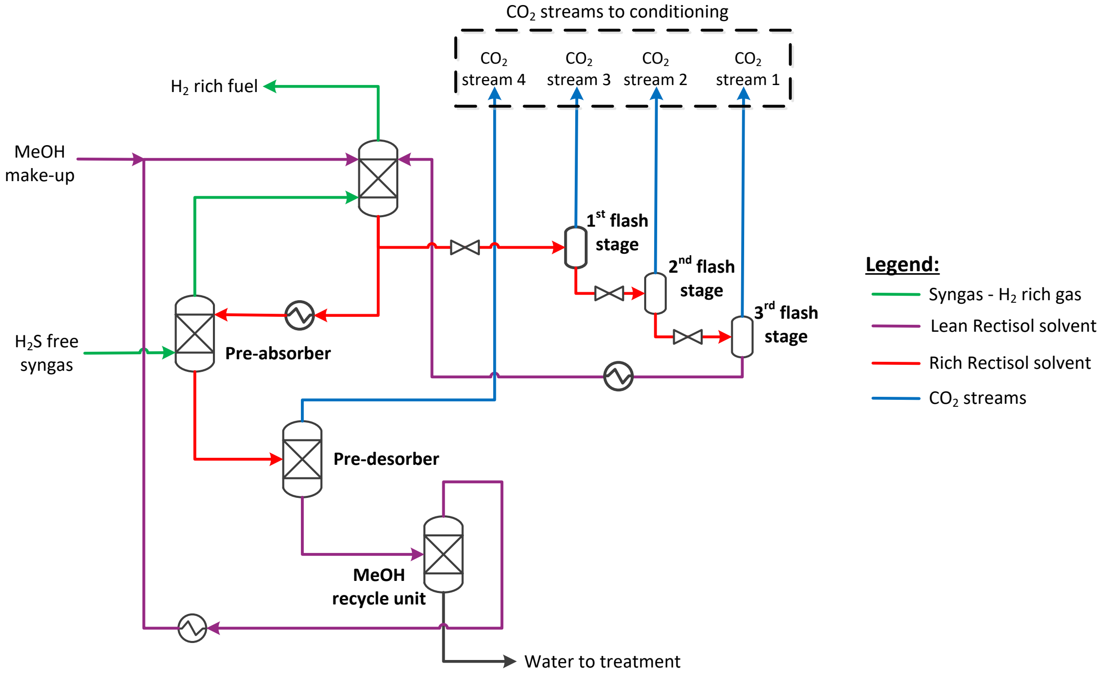

Figure 2: Simplified Process Flow Diagram of Rectisol-based CO_2 capture with the stream sent to conditioning

Table 1: Composition and characteristics of the four CO_2 streams obtained from the Rectisol capture process

Composition (%mol)	Stream 1	Stream 2	Stream 3	Stream 4
Carbon Dioxide	99.01	99.36	91.72	98.08
Methanol	0.979	0.435	0.318	0.846
Nitrogen	0.004	0.143	3.203	0.445
Hydrogen	-	0.019	3.916	0.497
Carbon Monoxide	-	0.004	0.253	0.032
Hydrogen Sulphide	0.001	0.001	-	0.004
Argon	0.002	0.039	0.589	0.094
Temperature (°C)	-17.5	-12.9	-3.8	11.1
Pressure (bar)	1	3.3	9.5	9.5
Flow rate (kg/s)	14.22	31.22	5.40	0.13
Accumulated flow rate (kg/s)	14.22	45.44	50.84	50.97

2.2 Technical modelling

The following sections describe the technical modelling of the conditioning and export system for both pipeline and train transports.

2.2.1 Conditioning and export system based on pipeline transport

Prior to pipeline export, the streams from the Rectisol capture process need to be conditioned in order to meet the required pipeline transport pressure (traditionally from 110 to 150 bar (Anantharaman et al., 2011; European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2011b)). Here, similarly to the literature (European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2011b; Roussanaly et al., 2013a), these streams are conditioned via a series of five compression stages (with mixing and cooling steps when required) up to 85 bar and finalised by pumping to the inlet export transport pressure (150 bar) and temperature requirements (40 ºC), as shown in Figure 3. It is worth noting that, in practice, for very short transport distances as considered in the Czech storage scenario, a lower inlet export transport pressure could be considered as the pipeline pressure drops remain limited (depending on the diameter). As shown in Appendix A, such consideration would reduce the conditioning and transport cost only marginally (less than 4%) for the Czech storage and are therefore not included to ensure consistency between cases.

Due to the stream compositions considered, flashing to remove condensable components is not required along the compression train, and therefore the streams remain as single-phase vapour throughout the compression train. A pressure-enthalpy diagram of the compression cycle from 1 bar to the final discharge pressure of 85 bar (via intermediate pressures of 3.3, 9.5, 15 and 28 bar) is illustrated in Figure 4(a). The phase envelope shown in the figure is given for the final transported composition[1]. The diagram also plots the constant temperature line of 25°C and shows that external cooling to 25°C after compression is required at 15 and 28 bar, while no cooling is required after the other compression stages due to the addition of the cold CO_2 streams.

Finally, it is worth noting that the power consumption for each compression and pumping stage is calculated as isentropic compression or pumping with efficiencies of 80%.

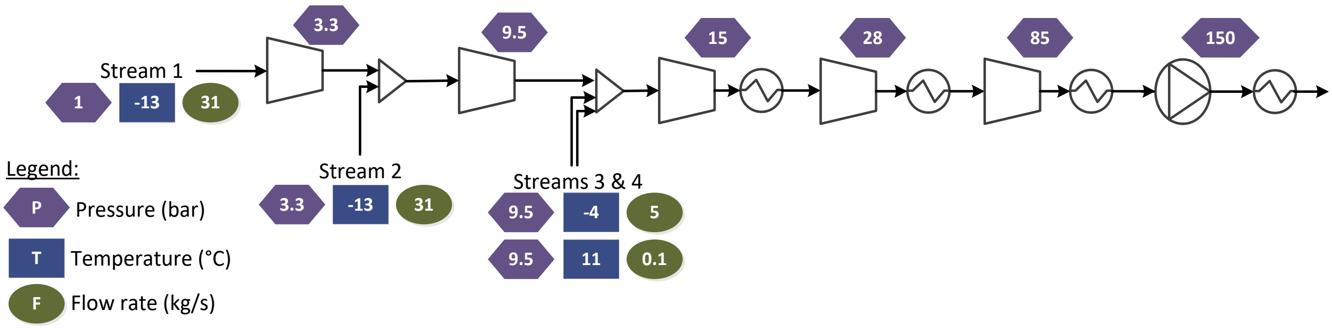

Figure 3: CO_2 conditioning process flow diagram modified for a Rectisol based capture

[1] Carbon Dioxide: 98.42%$_{vol}$, Nitrogen: 0.44%$_{vol}$, Hydrogen: 0.45%$_{vol}$, Methanol: 0.57%$_{vol}$, Carbon Monoxide: 0.03%$_{vol}$, Argon: 0.09%$_{vol}$, and Hydrogen Sulphide: 0.0005%$_{vol}$.

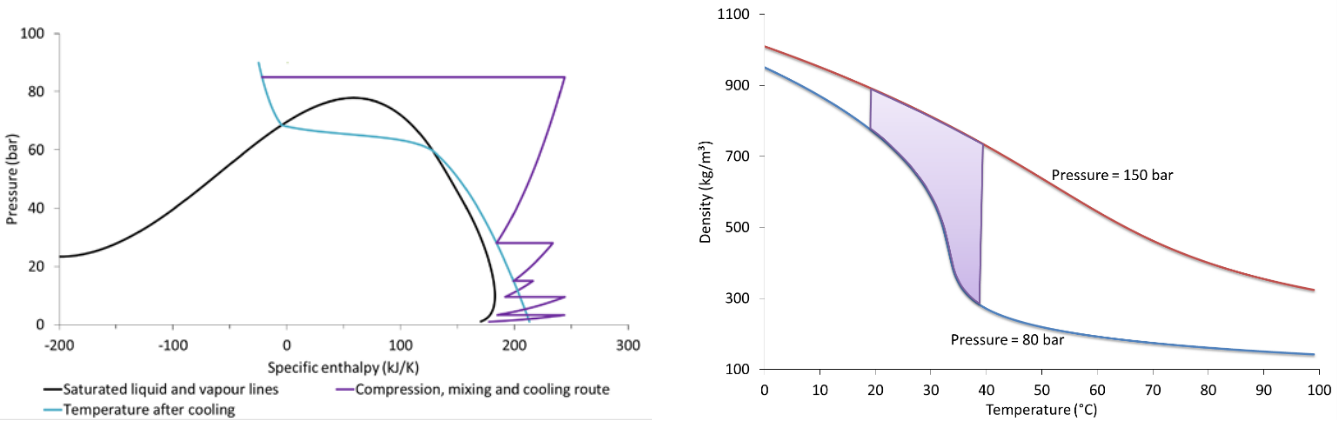

Figure 4: (a) Compression, mixing and cooling route in a pressure-enthalpy diagram for 5 compression stages 3.3, 9.5, 15, 28 and 85 bar and the 25°C cooling isotherm (b) Range of densities of the transported CO_2 mixture for the pipeline operational envelope (purple shaded area) for varying temperature between 80 and 150 bar

Pipeline export is a rather simple process that comprises pipeline sections linked by pumping stations that are required to overcome the pressure drops along the transport distance and maintain a minimum pressure of 85 bar throughout the pipeline and to ensure the desired pressure at the point of delivery (90 bar for the Czech storage case and 150 bar for the European hub case). The technical modelling is performed based on the methodology described in detail by Skaugen et al. (Skaugen et al., 2016). While the optimal diameter is selected based on costs after the technical evaluation, the model assesses the technical characteristics of the pipeline transport (pipeline thickness, heat transfer along the pipeline, pressure drops, electrical consumption, number of pumping stations, etc.) for each of the pipeline diameters evaluated.

In this model, the thermodynamic and transport properties of the fluids along the pipeline and the effects of residual components on transport energy consumption and pipeline design are based on the following models. The Peng-Robinson equation of state (Peng and Robinson, 1976) is used to calculate thermodynamic properties and vapour-liquid equilibrium, while corresponding state methods (Huber and Ely, 1992; Huber et al., 1992) are used for transport properties such as viscosity and thermal conductivity. Heat transfer between the fluid temperature and the ambient air includes all thermal resistances, where the soil thermal conductivity is one of the most influential parameters. The pressure and specific enthalpy are integrated numerically from the calculated local heat transfer rate and frictional pressure losses are based on the pipeline surface roughness. The minimum pressure in the pipeline also needs to be above the two-phase region, which means above the cricondenbar (i.e. the maximum pressure on the phase envelope in Figure 4(b)). Recompression takes place if the pressure falls below a specified margin to the cricondenbar. As density is one of the most important parameters for the pressure drop calculation, the variation in density within the approximate operating temperature and pressure is shown in Figure 4(b). In the pipeline model, the minimum wall thickness is calculated according to the proposed ISO standard (International Organization for Standardization, 2016) and the method recommended by DNV-GL (Det Norsk Veritas, 2010). A summary of the characteristics and parameters considered for the conditioning and pipeline export is presented in Table 2.

As specific pipeline routes are here considered, the pipeline elevation profiles are included when assessing the pipeline transport (pressure drops, thicknesses, etc.). In these cases, the gravitational term in the pressure loss model is used to locate pipeline sections where the highest fluid pressure appears and where a thicker pipeline is required. While the pipeline characteristics (diameter and thickness) can be varied along the transport in order to minimize system costs and satisfy safety requirements, this study considers a single diameter and thickness throughout the pipeline[2], based on the point of greatest constraint.

[2] It is worth noting that in practice, the pipeline thickness could be modified across the pipeline length to reduce the investment cost of the pipeline. However, overdesign is here considered in order to avoid public acceptance challenges as such a project would be the first in Czech Republic.

Table 2: Characteristics and parameters considered for the conditioning and pipeline assessment

Element	Parameter	Value
Pipeline design	Pipeline classification for design [-]	4
	Pipeline maximum operating pressure [bar]	150
	Minimum pipeline pressure allowed [bar]	85
	Wall thickness standard source	API
Pipeline material properties	Pipeline material	X70
	Pipe thermal conductivity [$W.m^{-1}.K^{-1}$]	55
	Pipe material density [kg/m^3]	7700
	Pipeline roughness [µm]	47.5
Soil and ambient conditions	Ambient temperature [°C]	15
	Ambient heat transfer coefficient [$W.m^{-2}.K^{-1}$]	5
	Soil thermal conductivity [$W.m^{-1}.K^{-1}$]	2.4
	Depth of the pipeline centre [m]	1
Rotating equipment	Compressor isentropic efficiency [-]	0.8
	Pump isentropic efficiency [-]	0.8

2.2.2 Conditioning and export system based on train transport

Similarly to ship-based transport, CO_2 can be transported by train under a wide range of conditions, ranging from cold liquid CO_2 at sub-zero temperatures and low pressures to dense phase at high pressures and ambient temperature (Seo et al., 2016). As in most of the recent studies on ship-based CO_2 transport (Alabdulkarem et al., 2012; Knoope et al., 2015b; Roussanaly et al., 2014; Roussanaly et al., 2013a; Vermeulen, 2011), the CO_2 is assumed to be transported in liquid form at 6.5 bar and about -50.3 °C.

To meet train-based transport temperature and pressure specifications, the CO_2 streams from the capture process need to be conditioned. The conditioning process is based on the compression stages followed by liquefaction, using the two-stage ammonia cooling cycle process suggested by Alabdulkarem et al. (Alabdulkarem et al., 2012), which has been determined to be an energy- and cost-efficient CO_2 liquefaction cycle (Roussanaly et al., 2013a). However, the conditioning process is here modified as shown in Figure 5; first, in order to take into account the pressure and temperature levels of the CO_2 streams from the capture process, which result in a compression, mixing and cooling route that is identical to the first three stages of the pipeline conditioning process. Secondly, in order to avoid the accumulation of impurities, the gas is then compressed to the selected liquefaction pressure (30 bar) and then partially condensed by the ammonia cycle at about -30°C before going to a separator. The flash gas from this first separator contains light components such as hydrogen and nitrogen, and is purged to avoid the accumulation of impurities through the recycle process. The liquid is expanded through a valve to a second separator where the flash gas is re-compressed and mixed with the main flow while the purified CO_2 liquid is pumped for (intermediate) storage. Although not included here[3], the purged stream would in practice be sent for combustion along with the hydrogen rich fuel in order to value the associated hydrogen and carbon monoxide, as well as avoid release of methanol and hydrogen sulphite to air.

It is worth noting that the liquefaction pressure and the temperature after the partial condensation will directly influence the amount and compositions of purged gas and recirculation gas, the required cooling capacity and ammonia refrigeration cycle power consumption, as well as the purity of the liquid CO_2 product, and that all elements should in practice be considered in a techno-economic comparison.

The thermodynamic data are generated using an in-house thermodynamic library that employs the Peng-Robinson equation of state, with freezing point calculations as discussed by Wilhelmsen et al. (Wilhelmsen et al., 2017).

[3] This would require the full evaluation of the power plant with CO_2 capture, transport and conditioning which is beyond the scope of the paper.

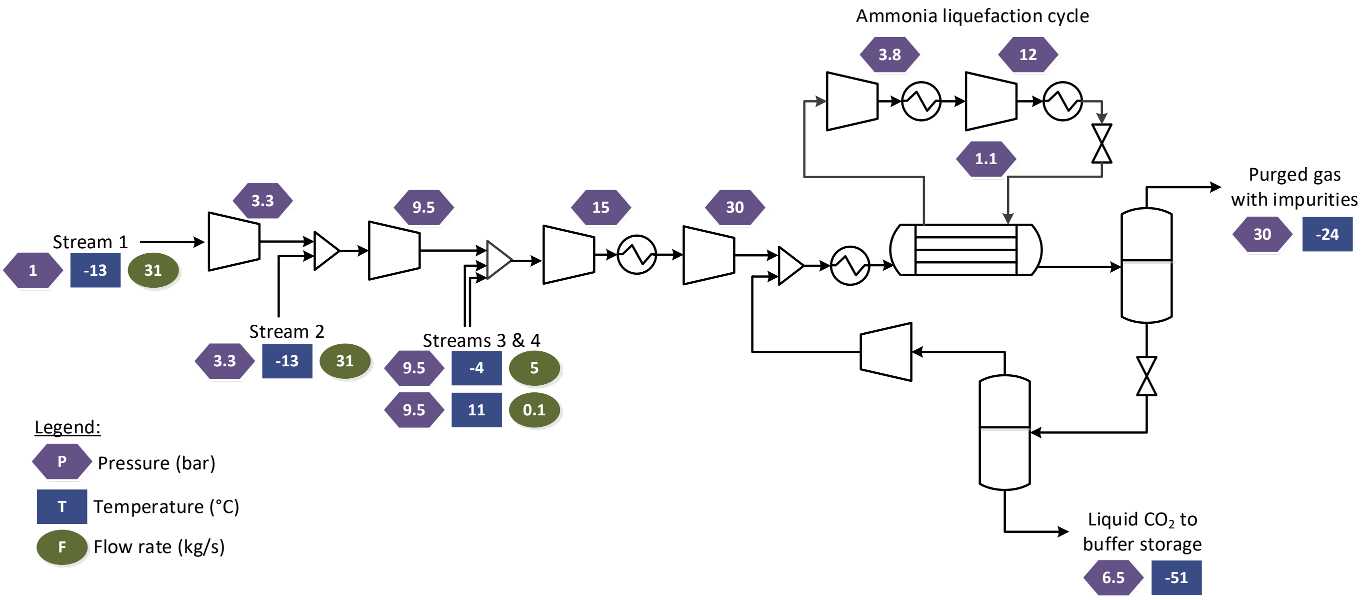

Figure 5: CO_2 liquefaction process flow diagram modified for Rectisol-based capture

After the liquefaction process, the CO_2 is exported on a batch basis between the power plant and the storage site. Low-temperature buffer storages are used both before and after the train export as the CO_2 liquefaction and injection are continuous processes, while the train transport is a batch-based system. A schematic representation of the train export system is presented in Figure 6.
The low-temperature buffer storage before the train transport is designed to accommodate 150% of the train transport capacity or at least 24h[4] of the CO_2 stream in case of problems in the train transport operations. In order to overcome the pressure drops and provide the head necessary to transport the CO_2 from the buffer storage to the train tanks, a pump providing a pressure increase of 1.5 bar is located after the buffer storage at the power plant.
While the train supply chain (including number of trains, wagons) is optimised in order to minimise the transport cost, the dimensions of the wagon tanks are assumed to be 3m x 3.5m in section and 21m in length, based on the CMGV 11-9733 model wagon (Eurofire, 2016.). Assuming that 90% of the available transport volume is used, each wagon has a capacity of 240 t_{CO2}. The maximum number of wagons per train is here assumed to be 20 in order to keep to a maximum train length of 600 m including locomotive. The train is assumed to travel at an average speed of 60 km/h, in accordance with average freight train transport speed. The arrival/loading/departure at the power plant and the arrival/unloading/departure at the storage site are each assumed to take place within 5 h (Roussanaly et al., 2014; Roussanaly et al., 2013b)[5].
At the unloading site, low-temperature buffer storage with a volume 150% higher than the train transport capacity is present in order to ensure continuous injection at the storage site. In order to reach the storage or hub pressure and temperature requirements, reconditioning takes place after the buffer storage. The reconditioning involves repumping to 150 bar in the European hub case and 90 bar in the Czech storage case, which is adequate for a saline aquifer injection, followed by heating to 4 ºC. Since frigories have an economic value , the costs of the reconditioning heating operation are not considered here.

[4] This results in more constraining buffer storage overdesign for transport over "short" distances.
[5] In comparison, around 12 h has been estimated for ship-based transport, but ship transport includes additional and longer operations such as mooring, docking, etc. as well as larger volumes.

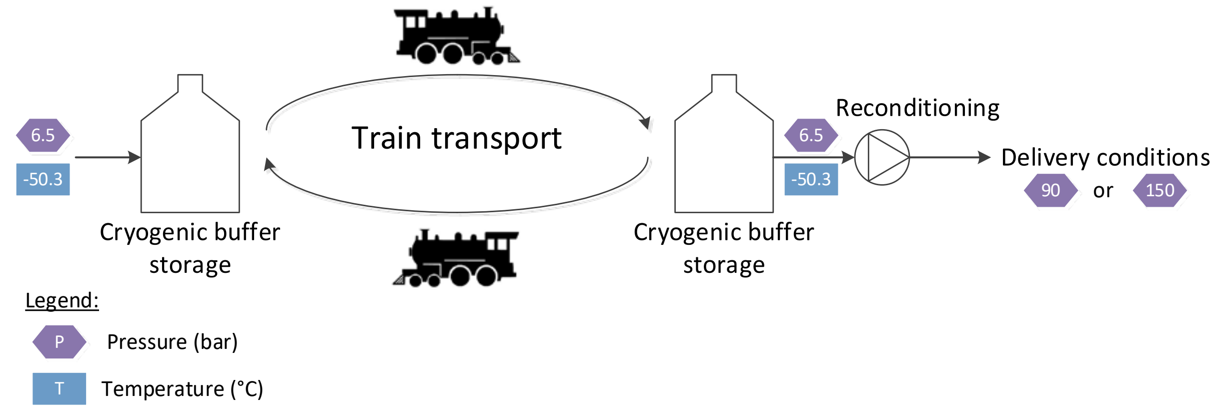

Figure 6: Schematic representation of train-based CO_2 transport

2.3 Cost assessment methodology

Investment and operating costs are given in 2015 Euro prices for a plant located in Czech Republic. When necessary, investment costs are updated according to the Chemical Engineering Plant Cost Index (CEPCI) (Chemical Engineering, 2016), while relevant utilities costs are corrected according to an average yearly inflation of 1.7% (Trading Economics, 2011).

2.3.1 Investment costs

2.3.1.1 Process units investment cost

While the costs of the pipeline and train are based on the literature, the costs of CO_2 conditioning and reconditioning processes are assessed on the basis of a “bottom up” approach. In this approach, the direct costs without process contingencies are evaluated using Aspen Process Economic Analyzer® for a Dutch location. However, it is worth noting that, due to their specificity, some process units such as the low-temperature buffer storage and CO_2 pump are evaluated based on the literature (Roussanaly et al., 2013a). The total plant cost is assessed by adding direct costs, process contingencies, indirect costs, owner's costs and project contingencies. In view of the high maturity of CO_2 conditioning, process contingencies are considered to be 10% of the process cost without contingencies, while the indirect costs, the owner's costs and the project contingencies are assumed to represent 34%[6] (Roussanaly et al., 2017) of the total direct cost, including process contingencies. The overall plant cost are updated to reflect the costs of a plant located in Czech Republic (Humphreys, 2004; Richardson Engineering, 2007).

2.3.1.2 Pipeline investment cost

For pipeline transport, the pipeline investment costs are assessed following the cost model proposed by Knoope et al. (Knoope et al., 2014). This cost model, adapted to onshore pipelines, is based on the evaluation of material costs, labour costs, right-of-way costs, and miscellaneous costs. The cost suggested by Knoope et al. (Knoope et al., 2014) are here considered after being updated with the CEPCI.

$$I_{\text{pipeline}} = I_{\text{material}} + I_{\text{labor cost}} + I_{ROW} + I_{\text{Miscellaneous}}$$
$$I_{\text{material}} = \frac{\pi}{4} \cdot (D^2 - (D - 2t)^2) \cdot L \cdot \rho_{\text{steel}} \cdot C_{\text{steel}}$$
$$I_{\text{labour cost}} = C_{\text{labour}} \cdot D \cdot L \cdot \text{Terrain factor}$$
$$I_{ROW} = C_{ROW} \cdot L$$
$$I_{\text{Miscellaneous}} = 25\% \cdot (I_{labour\ cost} + I_{\text{Materials}})$$

where:

I_{pipeline} is the pipeline investment cost combining the costs of materials, labour, rights of way and miscellaneous costs.

I_{material} is the pipeline materials cost, based on its external diameter (D), thickness (t) and length (L), the steel density (ρ_{steel}) equal to 7900 kg/m^3, and the steel cost (C_{steel}) equal to 1.57 €$_{2014}$/kg.

[6] Following the AACE 16R-90 guidelines for AACE Class 4 budget estimates.

$I_{\text{labour cost}}$ is the pipeline labour cost calculated on the basis of a unitary labour cost (C_{labor}) of 22.1 €$_{2014}$/in/m, combined with the pipeline external diameter, length, and a terrain factor of 1.1 (Bureau et al., 2011; IEAGHG, 2002). In the case of the transport to the Czech storage, the labour investment cost are further increased by 50% to take into account the impact of the short transport distance (Bureau et al., 2011; IEAGHG, 2002).
I_{ROW} is the pipeline right-of-way (ROW) cost, estimated on the basis of a unitary ROW (C_{ROW}) equal to 87.4 €$_{2014}$/m and combined with the pipeline length. Due to the limited public data on right-of-way cost for Czech Republic, the right-of way cost are adapted specifically for a Czech location but using the generic estimates from Knoope et al.
$I_{\text{Miscellaneous}}$ includes other costs and margins, and is estimated at 25% of total materials and investment costs.

2.3.1.3 Train investment cost

While the cryogenic buffer storages are assessed based on an investment cost of 1590 €/m^3 (European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2011a)[7], the train investment costs are based on the estimated costs of the locomotive and wagons respectively. The cost of the locomotive is scaled, with a power factor of 0.85, from a reference locomotive able to transport 1250 ton of freight and which cost of 3530 k€ (Andersson et al., 2011). The investment cost of the wagons is assumed to be proportional to their transport capacity and based on a cost of 3.89 k€/t$_{CO2}$. This wagons investment cost was estimated considering a conventional wagons cost of 2.3 k€/t$_{\text{freight}}$ (Andersson et al., 2011) combined with an addition cost of 1.6[8] k€/t$_{CO2}$ for the cryogenic CO_2 tanks and their integration within the wagons.

$$\text{Train transport (k€)} = 3530 \cdot \left(\frac{\text{Train capacity } (\text{t}_{\text{CO2}})}{1250}\right)^{0.85} + 3.89 \cdot \text{Train capacity } (\text{t}_{\text{CO2}}) \qquad (1)$$

It is worth noting that no data specific to train-based CO_2 transport is available in the literature and that the uncertainties on train investment costs are higher than for the pipeline transport alternative.

2.3.2 Maintenance and operating costs

Annual fixed operating costs include maintenance, insurance and labour costs. For process units, the costs of maintenance, insurance and local property taxes are considered to represent 4.5% of the total direct costs (Anantharaman et al., 2011), and 1.5% of CAPEX for the pipeline. Meanwhile, the operating labour cost is based on the estimated overall number of employees and a "fully burdened" labour cost of 40 k€/y, while administrative and support labour costs are assumed to be 30% of the operating labour cost ,combined with 12% of the maintenance cost, insurance and local property taxes (IEAGHG, 2013).
The variable operating costs include consumption of electricity and cooling water. The variable operating costs are evaluated based on estimated utilities consumption and the costs presented in Table 3. The cost of electricity considered is based on the previously estimated cost of the IGCC plant with Rectisol-based CO_2 capture and conditioning for pipeline export (Roussanaly et al., 2017).
Due to their specificity, the train operating costs are calculated differently. For the train operation, the annual fixed and variable operating cost is built up as a linear function of freight weight and travel distance (0.026 €$_{2014}$/t/km (Andersson et al., 2011)) when the train is going to the storage location. When it is travelling as empty freight (return to power plant), the operating cost is assumed to be halved.
Finally, a penalty cost of 36 €/t is considered for the CO_2 purged in the conditioning process before train export. This penalty is meant to take into account the cost that was previously spent to capture this purged CO_2 (Roussanaly et al., 2017).

[7] A direct cost of 1000 €$_{2009}$/m^3 is considered by the Zero Emission platform and result in an investment cost of 1480 €$_{2014}$/m^3 once updated with the CEPCI and including process contingencies, indirect costs, owner's costs and project contingencies
[8] This cost is based on a cryogenic storage investment cost of 1590 €/m^3 and an additional integration cost of 40%.

Table 3: Cost of main utilities

Utilities	Cost
Electricity (€/MWh) (Roussanaly et al., 2017)	95
Cooling water (€/m^3) (Dlouhy et al., 2012)	0.15

2.3.3 Key performance indicators

The CO_2 conditioning and transport cost (Skaugen et al., 2016) is used to compare the different transport technologies and delivery site scenarios. This key performance indicator approximates the average discounted cost of CO_2 conditioning and transport based on equation 1. The CO_2 conditioning and transport costs are calculated based on a real discount rate of 8% and an economic lifetime of 25 years (Anantharaman et al., 2011).

Finally, investment costs are assumed to take place over three years with a 40/30/30 cost allocation, and the power plant is assumed to operate at 40 and 65% of capacity during the two first years of operation, in order to take into account potential technical issues, followed by a stable 85% afterwards (Anantharaman et al., 2011).

$$\mathrm{CO_2\ conditioning\ and\ transport\ cost} = \frac{\mathrm{Annualized\ investment + Annual\ OPEX}}{\mathrm{Annual\ amount\ of\ CO_2\ transported}} \qquad (2)$$

3 Results

The following sections present the results of the technical and cost evaluation of the CO_2 conditioning, CO_2 transport, and the overall conditioning and transport system for the four cases evaluated.

3.1 CO_2 conditioning

As previously explained, the conditioning for pipeline and train transports share the same mixing, compression and cooling strategy for the first compression stages (up to 15 bar). For the pipeline conditioning, this route is followed by further compression of the CO_2 to 85 bar and subsequent pumping to 150 bar. However, for train-based conditioning, this route is followed by compression to 30 bar and partial liquefaction through an ammonia liquefaction cycle. The vapour from this partial liquefaction is purged directly to remove the impurities, while the liquid is throttled through a valve. After throttling the stream is flashed, where the resulting liquid is ready for transport and sent to temporary buffer storage, while the recovered vapour is recycled to the compression train.

The resulting compositions and conditions of some of the streams of both the pipeline and train-based conditioning processes are presented in Table 4. In the pipeline conditioning process, the composition of the CO_2 delivered remains is unchanged after mixing, as the stream stay in a single vapour phase throughout the conditioning process. However, in the case of the train-based conditioning, the CO_2 product purity increases by almost one percentage point, as most of the impurities (except for methanol) have very low solubility in the liquid CO_2 streams. As explained above, these impurities are purged in order to prevent their accumulation over time. As Table 4 shows, the impurities represent 35%mol of the purged streams while the process is designed to limit the purge of large amounts of CO_2. In the case of the conditioning for train-based export, the CO_2 is delivered at -53.2 °C and 6.5 bar, which provides a 3.6 °C margin above the CO_2 freeze-out temperature.

Table 4: Mole fraction compositions of the various process streams after compression and conditioning

	Common	Pipeline system	Train system				
Composition ($\%_{mol}$)	Feed after mixing and conditioning to 15 bar	Pipeline export	Stream after mixing with the recycle	Purged gas	Liquid for expansion	Recycle	Train export
Carbon Dioxide	98.42	98.42	97.19	64.24	97.90	91.52	99.32
Methanol	0.57	0.57	0.47	0.002	0.478	0.0002	0.58
Nitrogen	0.44	0.44	1.26	14.93	0.96	5.00	0.06
Hydrogen	0.45	0.45	0.71	17.16	0.36	1.94	0.004
Carbon Monoxide	0.03	0.03	0.09	0.94	0.08	0.39	0.01
Hydrogen Sulphide	0.0005	0.0005	0.0005	0.0003	0.005	0.0004	0.0005
Argon	0.09	0.09	0.28	2.73	0.23	1.15	0.02
Temperature (°C)	21.9	37.0	25	-24.0	-24.0	-53.3	-53.3[9]
Pressure (bar)	15	150	30	30	30	6.5	6.5
Flow rate (kg/s)	50.85	50.85	61.57	1.09	60.48	10.72	49.75

Figure 7 shows power consumptions for the various compressor stages (a), the heat-exchanger duties for the compressor after-coolers, the main liquefier and the refrigeration main condenser (b) and the cooling water consumption (b). For the pipeline conditioning, the five compression stages and pumping from 85 to 150 bars require a total of 12.8 MW, which represent a specific energy consumption of 68.5 kWh/t_{CO2}. Meanwhile, for the train conditioning alternative, the five compression stages, the recycle compressor and the ammonia compressor stages require a total power consumption of 18.7 MW, representing an energy consumption of 105.1 kWh/t_{CO2}. This increase is mainly due to the additional power consumption associated with the ammonia compression in the refrigeration cycle.

In terms of heat exchanger cooling and liquefaction duties, the evaluation shows that conditioning prior to train transport results in heat exchanger cooling duty and cooling water consumption that are almost three times as large as conditioning for pipeline transport (21.6 versus 56.9 MW for the cooling duty and 13.8 versus 36.4 Mm^3/y for the cooling water consumption). In this case, the major increase in duty is linked to both the partial liquefaction heat exchanger and the ammonia condenser (i.e. the cooler following the ammonia second compression stage) which results in heat exchanger duties of respectively 19.8 and 25.9 MW respectively.

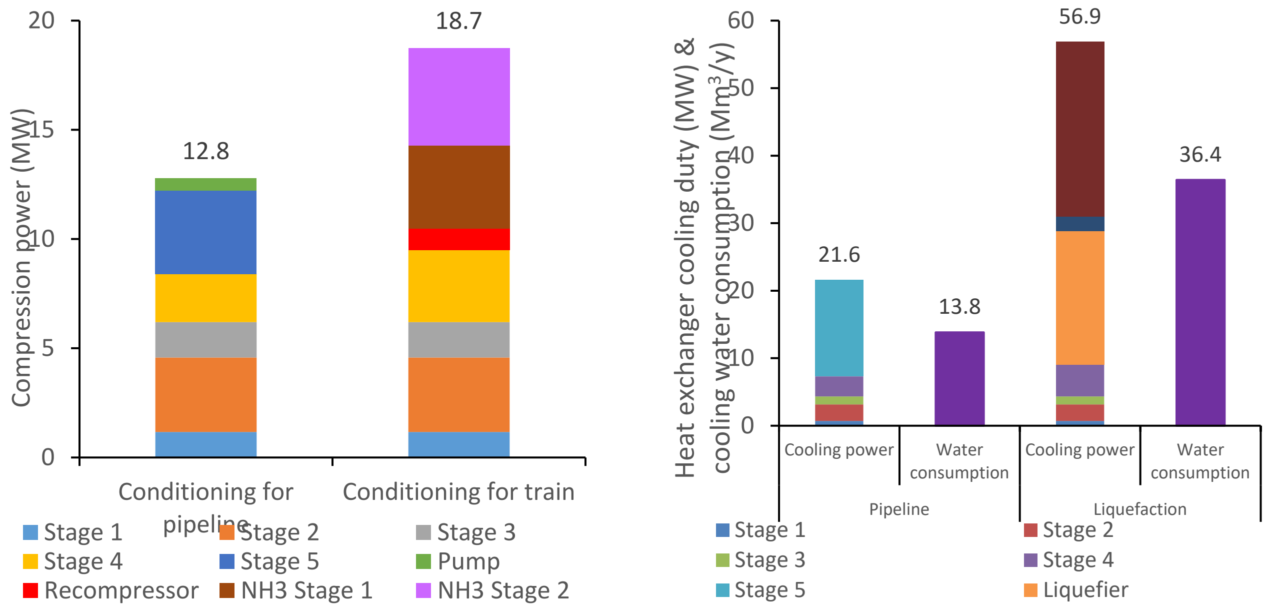

Figure 7: (a) Power consumptions, (b) heat exchanger duty and cooling water consumption for the conditioning compression and liquefaction for pipeline and train transport.

[9] A 3 °C margin is provided in order to take later potential heat-up during pumping and buffer storage prior to transport into account.

As Figure 8 shows, the cost evaluation shows that CO_2 conditioning for pipeline-based transport leads to a cost of 9.3 €/t_{CO2} while conditioning for train transport results in a cost of 14.7 €/t_{CO2}. Conditioning for the train-based system is therefore 50% higher than for the pipeline case, which follows the same trend as the energy consumption results. This similarity in trends is due to the strong relation between the conditioning power and cost. Indeed, the cost of electricity consumption represent 70% of total conditioning cost while the remaining part of the cost is also closely related to the system power consumption through the investment cost.
Finally, it is also worth noting that water consumption in the case of train-based transport is significantly higher than for the pipeline transport alternative, due to the cooling requirement of the ammonia cycle. Although the cost contribution of this consumption is small, the relatively high water consumption could be a limiting factor in the case of retrofitting in an existing power plant with water consumption constraints.

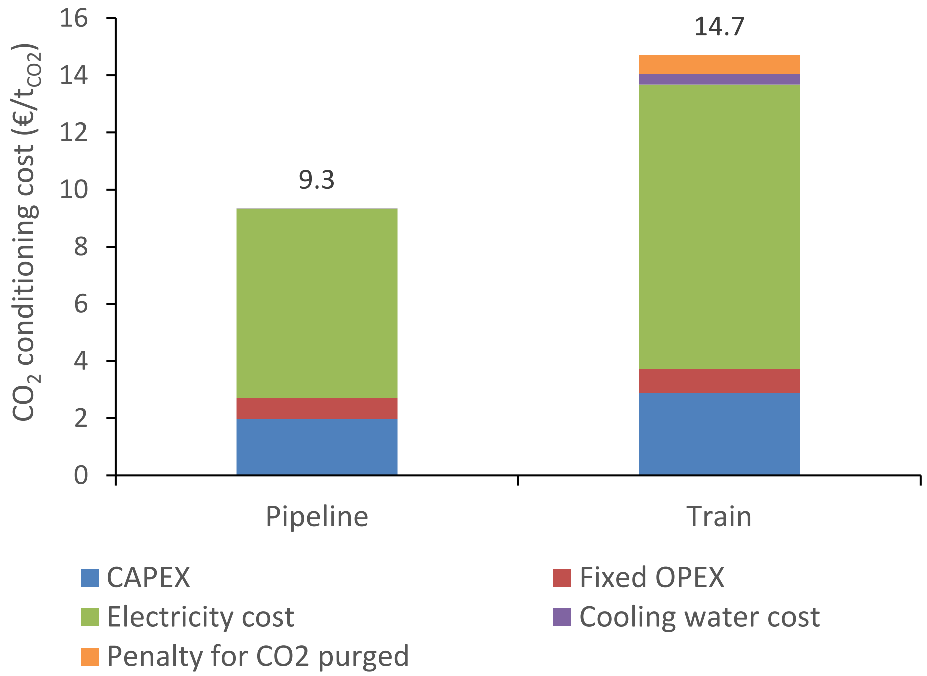

Figure 8: CO_2 conditioning costs for pipeline and train export

3.2 CO_2 transport

3.2.1 Pipeline export system

First, the required pipeline thicknesses, evaluated on the basis of the methodology discussed above, leads to the values presented in Table 5 considering the American Petroleum Institute (API) 5L standard (American Petroleum Institute, 1990). The maximum saturation pressure for the given temperature-pressure "envelope" is the cricondenbar for the CO_2 mixture. For the composition shown in Table 4, this corresponds to 78.6 bar and is therefore 4 bar above the critical pressure of pure CO_2.
The required energy consumption and the number of repumping stations for transporting the captured CO_2 over 23 and 120 km are shown in Figure 9 (a) and (b). Depending on the pipeline diameter, the repumping power ranges between 0 and 0.38 MW for the Czech storage case and 0.15 and 4.7 MW for the European hub case, while the number of repumping stations ranges from zero to one for the Czech storage option and one to nine for the European hub case. It worth noting that in the Czech storage case, no repumping is required for most of the diameters considered as the pressure drops remain low enough to ensure the minimum pipeline outlet pressure requirement without repumping. As previously presented (Morbee et al., 2012; Serpa et al., 2011), Figure 9(b) the pressure drops increase non-linearly when the pipeline diameter decreases, leading therefore to higher electricity consumption and a larger number of repumping stations. The inclusion of additional booster stations will also increase the temperature of the compressed fluid and thus increase the wall frictions due to lower density as seen in Figure 4(b).

Table 5: Calculated pipeline wall thicknesses and inside diameters for 150 bar transport pressure

Outside diameter (in)	6.625	8.625	10.75	12.75	14
Wall thickness (mm)	7.9	10.3	12.7	15.9	15.9
Inside diameter (mm)	152.4	198.4	247.7	292.1	323.9

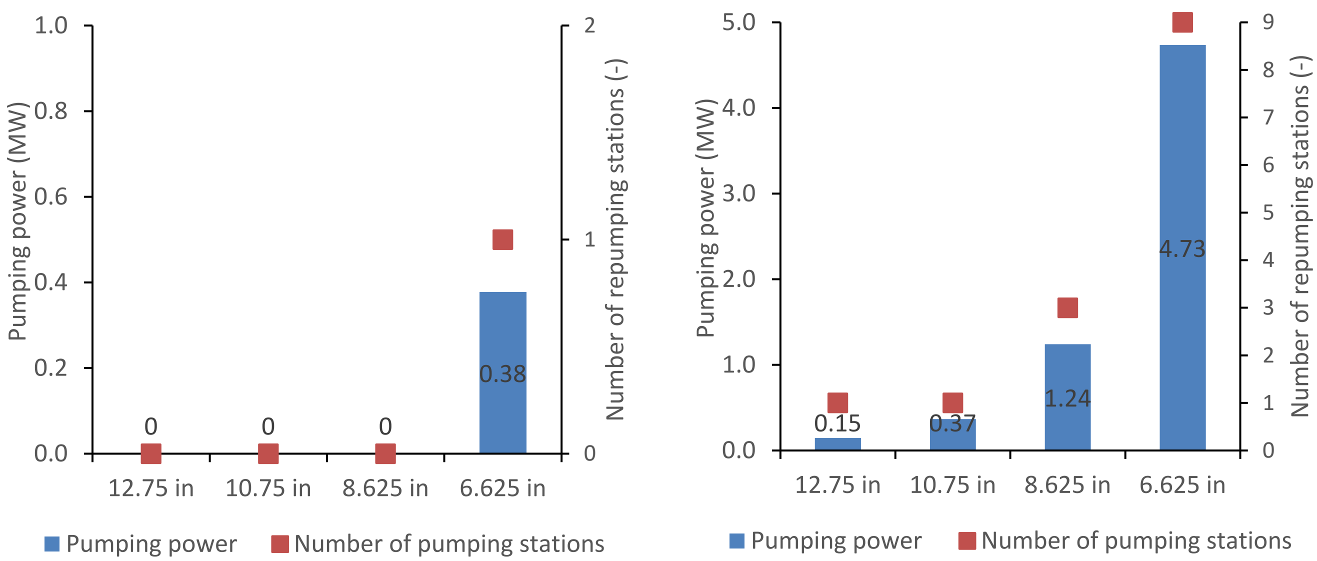

Figure 9: Transport power consumption and number of booster stations for pipeline transport over (a) 23 km and (b) 120 km

The CO_2 transport costs for both pipeline transport cases are presented in Figure 10 (a) and (b) for different pipeline diameter options (from 6.625 in to 12.75 in). Indeed, as previously illustrated in the literature (McCoy, 2009; Roussanaly et al., 2013a; Skaugen et al., 2016), there is a trade-off between pipeline investment cost and costs associated with pressure drop leading to a cost-optimal diameter that will depend on the system characteristics and especially the pipeline mass flow. The results show that a pipeline diameter of 8.625 in is cost-optimal[10] and selected in both cases considered here.
For the optimal pipeline diameter, the CO_2 transport cost evaluation results in costs of 1.2 and 6 €/t_{CO2} for the Czech storage case (23 km transport) and European hub (120 km transport). Once these values are normalized per 100km of transport distance, the average CO_2 transport cost is estimated to be 5-5.2 €/t_{CO2}/100km, a figure that is primarily dominated by the pipeline investment costs. These values are a fairly linear function of transport distance as pipeline investments and maintenance, and pressure drops are individually rather linear functions of transport distance (Roussanaly et al., 2013b). However, small divergences from the average value are observed due to the cost steps introduced by adding repumping stations.
The cost of CO_2 transport normalized to the distance can appear to be somewhat higher than figures presented in the literature for large-scale transport of CO_2 (Coussy et al., 2013; European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2011b; Skaugen et al., 2016). However, it is important to bear in mind that the numbers obtained here are for a rather small transport volume (around 1.34 Mt_{CO2}/y) and that CO_2 transport costs decrease significantly with volume, as a number of studies have demonstrated[11] (Jakobsen et al., 2017; McCoy, 2009).

[10] It is worth nothing that while a 10.75 in diameter pipeline leads to slightly higher CO_2 transport cost, a pipeline diameter of 8.625 in also lowers the pipeline investment cost and therefore the associated financial risk.
[11] For a 300 km offshore pipeline, Jakobsen et al. showed that the pipeline transport cost normalised to the capacity (€/t_{CO2}) is divided by three when the capacity increases from 1 to 5 Mt_{CO2}/y.

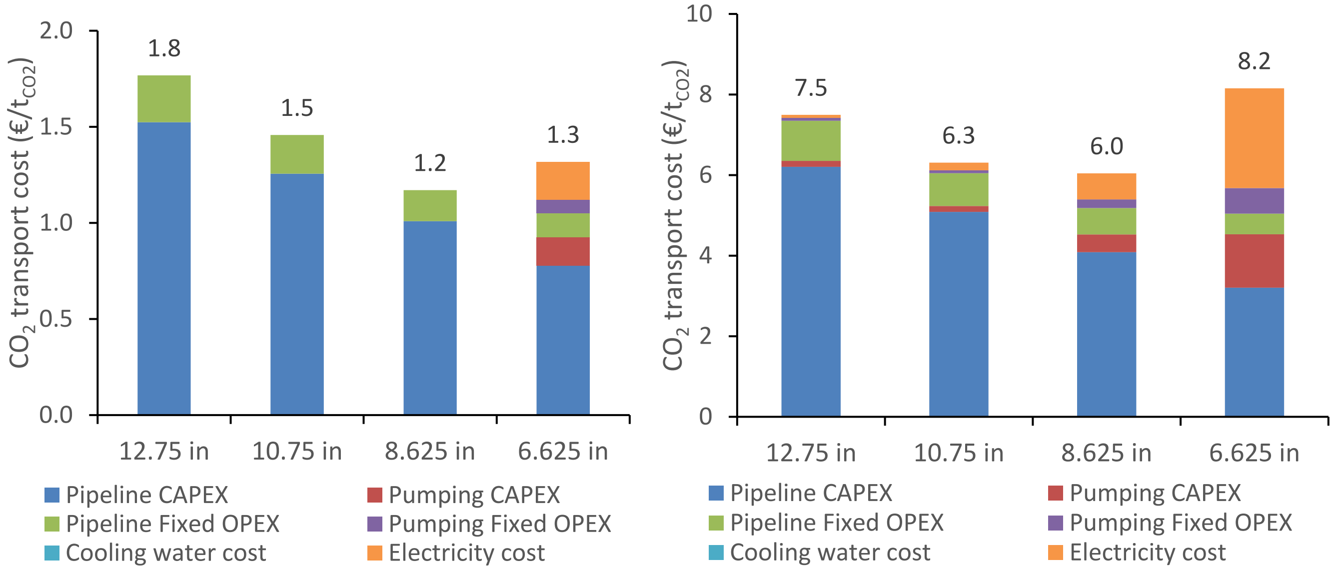

Figure 10: CO_2 transport cost for pipeline export to (a) the Czech storage and (b) the European hub, for different pipeline diameters

3.2.2 Train-based export system

Based on the case conditions, the cost-optimal number of wagons per train and the associated characteristics of the export system for each of the distance scenario are shown in Table 6. In both of the scenarios, the optimal number of wagons corresponds to the smallest number of wagons (9 and 13) leading to a single train in the export infrastructure. It is also worth noting that due to the short distances involved, the contribution of actual transport time to the duration of the transport cycle (which also includes arrivals, loading, unloading, and departures) is relatively small (15 to 40%). This leads to a limited increase in the number of wagons required in the two scenarios, despite a large increase in the transport distance.
Finally, regarding the loading and unloading operations, the assessment evaluates an overall buffer storage capacity of 6400 and 7800 m^3 depending on the case, while relatively modest power consumption for these operations (between 419 and 713 kW) is required.

Table 6: Technical characteristics of the optimal train supply chain system

	Czech storage	European hub
Transport distance [km]	50	200
Number of trains [-]	1	1
Number of wagons per train [-/train]	9	13
Train length [m]	273	382
Capacity per train [t_{CO2}/train]	2,157	3,116
Transport cycle duration [h]	11.7	16.7
Number of travels per year [-/year]	751	526
Loading power [kW]	9	9
Buffer storage before train [m^3]	3,700	3,900
Buffer overdesign compare to train capacity [%]	105	50
Pressure after reconditioning [bar]	90	150
Unloading power [kW]	410	704
Buffer storage after train [m^3]	2,700	3,900
Buffer overdesign compare to train capacity [%]	50	50

The cost of transport for both train-based scenarios is shown in Figure 11 for the cost-optimal number of wagons per train in each case. The cost evaluation leads to a cost of 4.1 €/t_{CO2} for the Czech storage case (50 km) as against 10.8 €/t_{CO2} in the European hub case (200 km). Once normalised to the distance

involved, these numbers correspond to a cost of 8.2 €/t_{CO2}/100km in the first case and 5.4 €/t_{CO2}/100km in the second one. Compared to pipeline transport, a significant cost reduction (34%) is observed when the transport distance increases from 50 to 200 km. When looking at the cost breakdown, this cost reduction appears to be due to an increase in investment cost (around 35% increase for a distance four times as long) while the operating costs of the system are linear with the distance. Indeed, for short distances, the train spends most of its time loading and unloading at the power plant or the storage sites, resulting in a low utilisation factor. However, the longer the transport distance, the higher is the train utilisation rate[12], resulting in significant economies of scale with transport distance.
However, similarly to ship-based transport and in contrast to pipeline transport, the costs of train-based transport may be expected to be a fairly linear function of the transported volume.

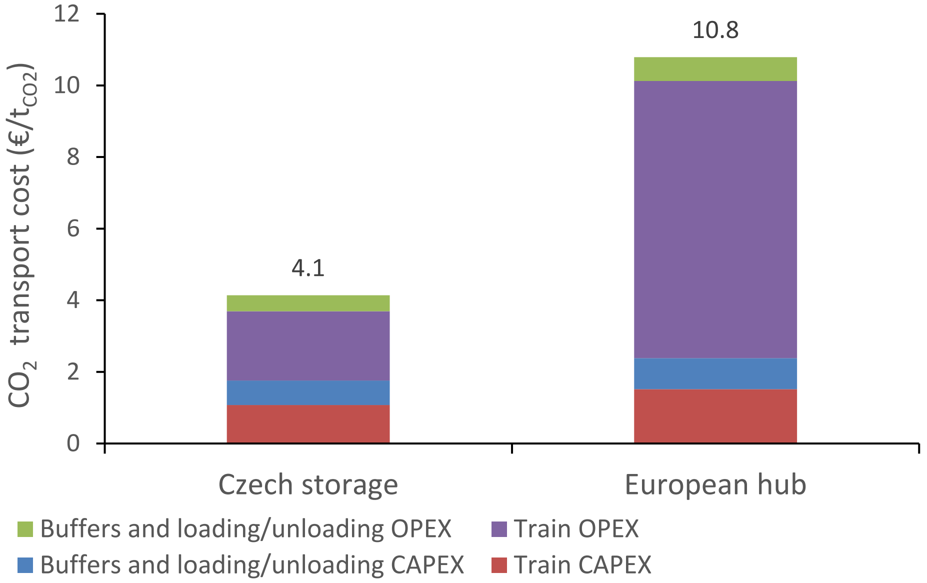

Figure 11: CO_2 transport cost for train-based export to the Czech storage (50km) and European hub sites (200km)

3.3 Overall comparison

The costs associated with CO_2 conditioning and transport for both transport destination scenarios are presented in Figure 12 considering both CO_2 transport methods. In the Czech storage scenario, the evaluation of CO_2 conditioning and transport costs result in an overall figures of 10.5 and 18.3 €/t_{CO2} for the pipeline and train options respectively. In the European hub scenario, these costs are estimated at 15.4 and 24.9 €/t_{CO2}. This means that, for both destination scenarios, pipeline is the most cost-efficient transport option, as it is around 40% cheaper than train-based transport. Based on the previous sections, two main reasons can be adduced to explain these major differences. First, as mentioned above, the cost of CO_2 conditioning is around 5 €/t_{CO2} higher for train export than for pipeline export. Secondly, the transport distances are here significantly longer for the train-based export than in the case of pipeline-based export.
Furthermore, the cost evaluation shows that for both transport options, the costs of CO_2 conditioning and transport cost increase of around 40% between the Czech storage and European hub scenarios. This means in practice that if storage is not possible at the Czech storage site and the CO_2 needs to pass by the European hub, this would result in an increase of at least 4.9 €/t_{CO2}, with the additional transport and storage costs from the European hub coming on top of that.
It is worth noting that the costs of train-based export are more uncertain than in the pipeline case, due to the limited public availability of cost data related to this CO_2 transport system.
Finally, while the results clearly show that pipeline transport is the most efficient option for both transport destinations considered, the potential of train-based CO_2 transport, if any, shall be further evaluated in

[12] Even if the number of wagons increases.

function of distance and capacity, as previously done for the pipeline and shipping options (Roussanaly et al., 2014; Roussanaly et al., 2013b).

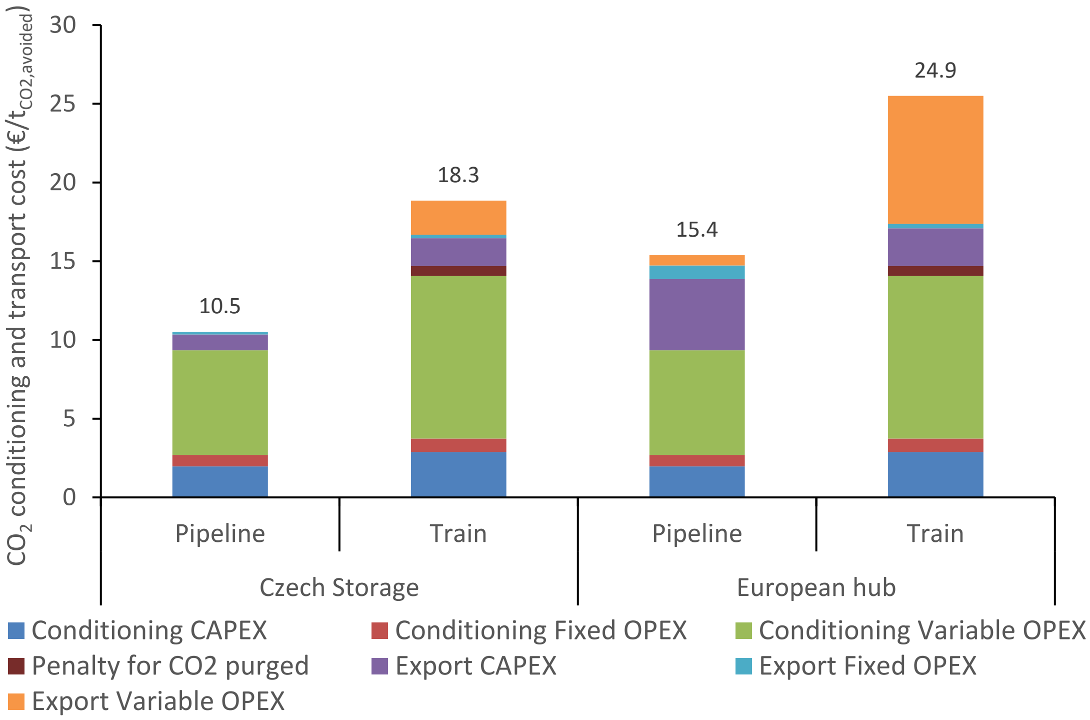

Figure 12: Overall cost of transport and conditioning for the four considered scenarios

In order to identify the impact of uncertainties on CO_2 conditioning and transport costs of both transport options and transport delivery location scenarios, sensitivity analyses for both scenarios are presented in Figure 13 and Figure 14. In all four cases, the analyses show that the CO_2 conditioning variable operating cost (i.e. electricity consumption cost) is one of the most important parameters. However, for the European hub case, in which the transport distance is larger, the pipeline investment cost and the train variable operating cost also have a powerful impact on the total cost of CO_2 conditioning and transport. The transport distance, the project duration and the discount rate also have a significant impact on the total cost, especially for the long-distance case. Finally, it is worth noting that, in each of the sensitivity analyses, pipeline-based transport remains cheaper than train-based transport.

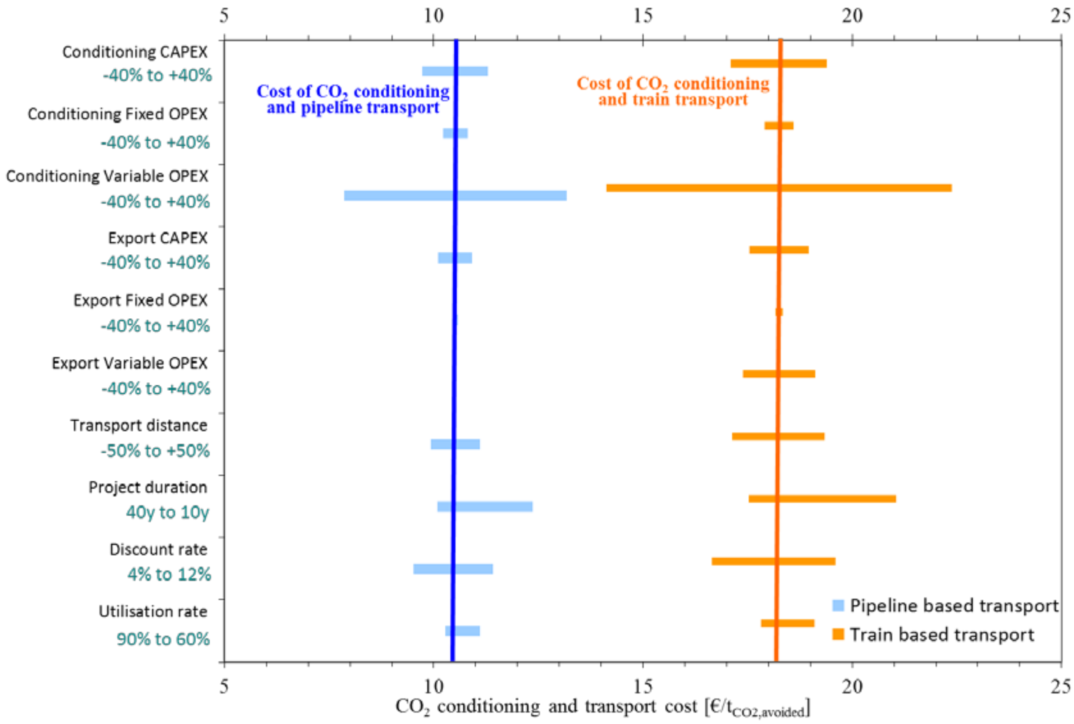

Figure 13: Sensitivity analyses of conditioning and transport costs for the Czech storage scenario

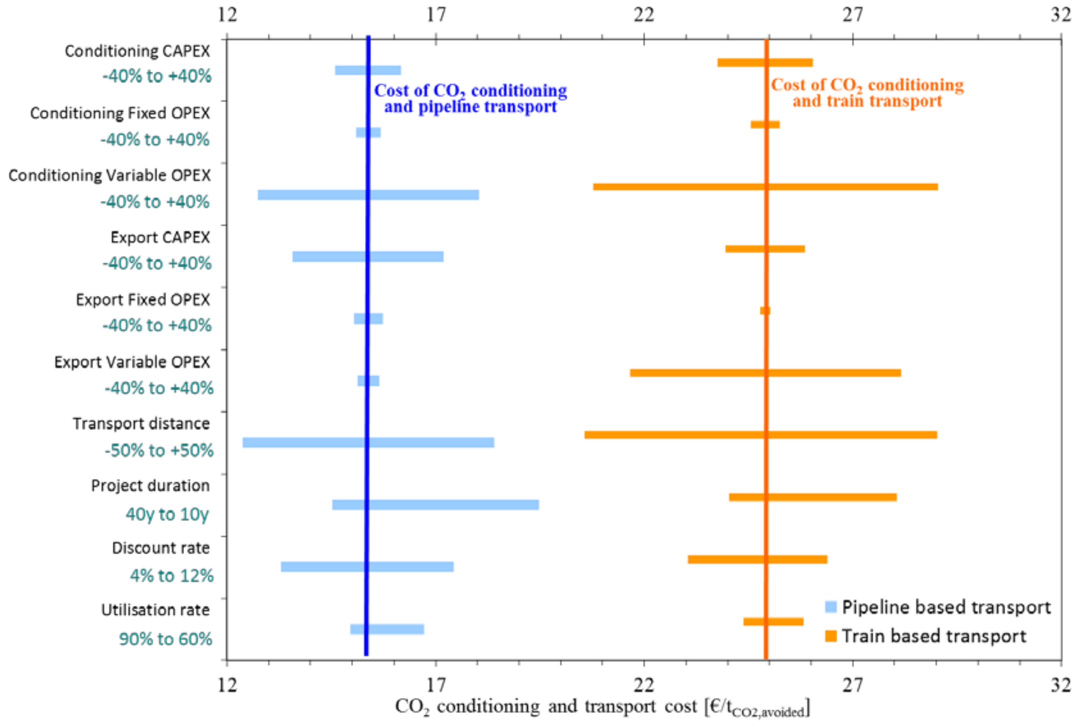

Figure 14: Sensitivity analyses of conditioning and transport costs for the European hub scenario

4 Discussions

4.1 Impact of impurities

The impact of impurities on CO_2 conditioning, transport and storage has been a sharper focus of research in the course of the past few years (Aursand et al., 2016a; Brunsvold et al., 2016; Porter et al., 2016; Rütters et al., 2016; Skaugen et al., 2016; Talemi et al., 2016). However, many evaluations (Brunsvold et al., 2016; Porter et al., 2016; Rütters et al., 2016; Skaugen et al., 2016) have demonstrated that the impact of impurities is very case-specific and dependent on the type and concentration of the impurities involved. The impact of the impurities present in the CO_2 streams considered is therefore investigated by comparing the energy and cost performances of the CO_2 conditioning and transport for streams both with and without

impurities. The impact of impurities on the energetic and cost performances of the CO_2 conditioning and transport is presented in Figure 15 and Figure 16 for the four cases considered. It is worth nothing that here the mass flow of CO_2 is assumed to remain the same in both the cases with and without impurities.
The results show that, for pipeline-based transport, the impurities appear to have a very limited impact on the specific power requirement (2.2%) for the Czech storage case. Indeed, in this case, the impurities have a limited impact on the CO_2 conditioning which is the main cost contributor due to the short transport distance involved. However, this impact increases to 5% for the European hub case due to the longer transport distance. This difference between the Czech storage and European hub cases highlights the importance of the transport distance on the impact of impurities for pipeline-based transport. In terms of cost, both the Czech storage and the European hub scenarios result in CO_2 conditioning and transport costs 1.6-2% higher (0.2-0.3 €/t_{CO2}) when impurities are involved. It is worth noting that although the presence of impurities has a stronger impact on the energy performances in the European hub case, the relative cost increase linked to the impurities presence remains limited, only 1.6%, due to the higher pipeline investment costs.
For the train-based transport cases, the evaluations show that the presence of impurities results in a specific power requirement around 8.5% higher than for pure CO_2. This major difference is due to three reasons. First, the power consumptions increase due to the higher inlet flow and change in properties when impurities are present. Secondly, for pure CO_2 streams, the liquefaction can take place at lower pressure (20.3 bar instead of 30 bar), thus requiring less compression power for both the CO_2 compression train and the recycle stream compression[13]. Finally, in the presence of impurities, purging after partial liquefaction is required to prevent impurities from accumulating in the process, and this produces losses of around 1.8% of the CO_2 entering the conditioning process prior to train transport. However, this purge is not required for pure CO_2 streams, which means that the overall power requirement is normalised to a higher amount of CO_2 transported. It is worth noting that the impurities in the CO_2 stream have a very limited impact on the transport section, as the CO_2 transported by train is almost pure (99.5%). In terms of cost performance, the evaluation shows that the impurities result in increases of 11.4 and 7.8 % (1.9 1 €/t_{CO2}) in CO_2 conditioning and transport costs respectively. In both cases, the difference is directly due to the increase in conditioning investment and electricity consumption due to the increase in power requirements, as well as the cost penalty due to the purging of CO_2. Therefore, for train-based transport, the impact of impurities decreases with the transport distance, as the contribution of conditioning costs to the overall cost diminishes with the transport distance.
Overall, the impurities present in the CO_2 streams lead to increases in CO_2 conditioning and transport costs ranging from 1.6 and 11.4% (0.2 to 1.9 €/t_{CO2}). However, in addition to depending on the type of impurities as previously presented (Brunsvold et al., 2016; Skaugen et al., 2016), the energetic and cost impacts associated with the impurities is highly dependent on the transport technology and the transport delivery location scenario.

[13] Although slightly higher power consumption is associated with the ammonia cooling cycle.

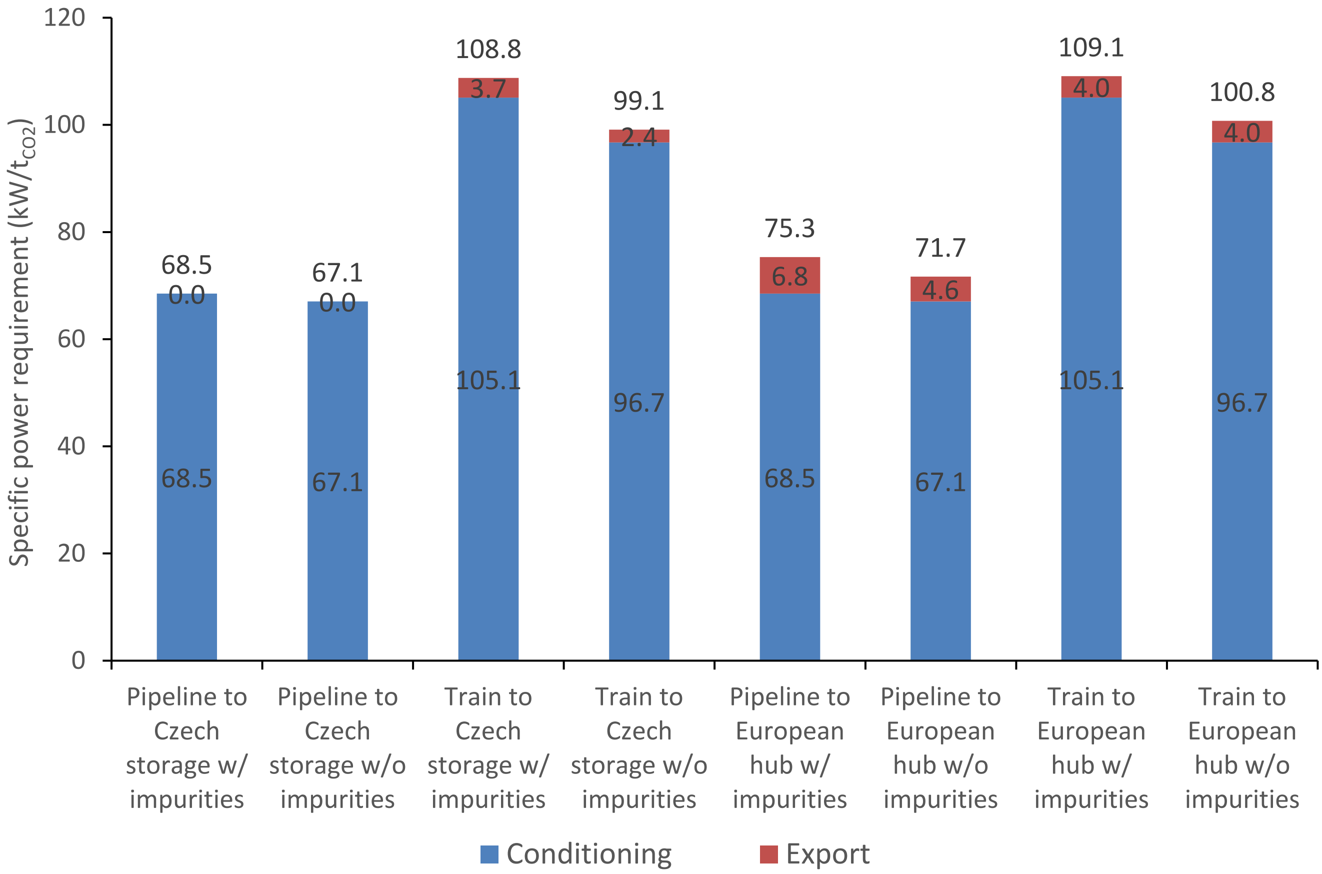

Figure 15: Impact of impurities on specific power requirement for the four cases considered

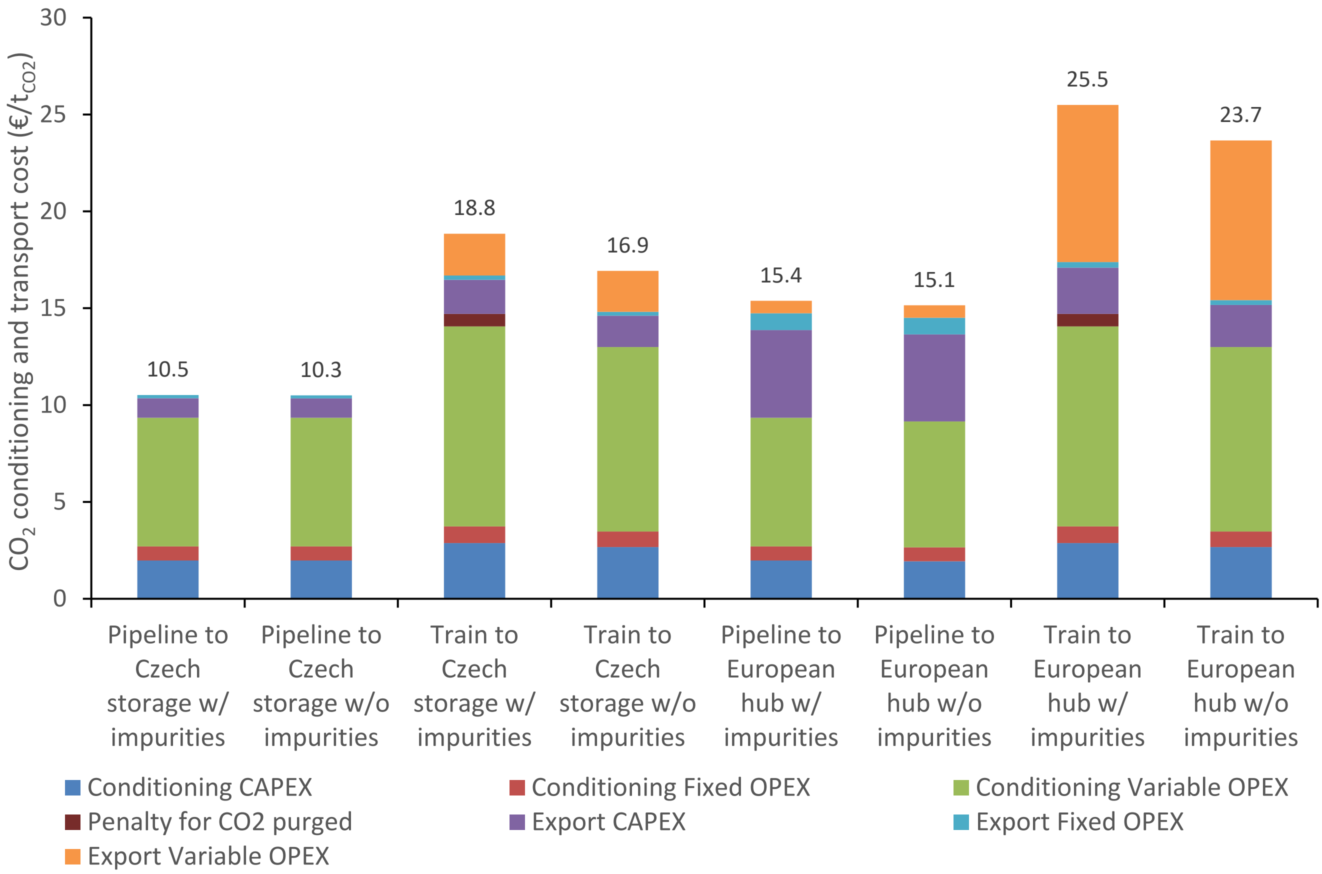

Figure 16: Impact of impurities on CO_2 conditioning and transport costs for the four cases considered

4.2 Alternative designs of CO_2 conditioning for train transport

To design a cost- or energy-optimal liquefaction process for CO_2 with impurities, two important process parameters need to be considered: the liquefaction process pressure and the partial condensation end temperature[14]. Both the selected pressure and temperature at the end of the condenser affect the vapour quality, the amount of vapour and liquid exiting the separator, the overall energy penalty, and thus the total cost of conditioning.

Figure 17 can be used to visualise some of these trade-offs in an easier way. On this contour map, the green solid lines show the CO_2 recovery iso-lines, which correspond to the ratios between CO_2 exported and CO_2 captured, from 99% to 95%. The blue dotted lines represent iso-lines for the liquefaction duty that is required from the refrigeration system. Finally, the red dashed lines show the corresponding compression power consumption for the two ammonia compressors, the recycle-gas compressor and the last compression stage of the conditioning process. While the conditioning process described above is designed for the partial liquefaction to take place at -24°C and 30 bar, two additional cases are evaluated to quantify the impact of reducing the CO_2 losses through the purged gas, on the process energy and cost performances. Indeed, reducing CO_2 losses through the purge could have a cost benefit when considering the entire CCS chain, as the purged CO_2 has been captured at a cost of 36[15] €/t_{CO2} (Roussanaly et al., 2017). The first alternative set of partial liquefaction conditions is -35 °C at 26 bar, which will lead to slight increases in the compression power and refrigeration capacity but increase the CO_2 recovery to 99% instead of 98.2%. In the second alternative design, the partial liquefaction takes place at -32 °C at 30 bar, which also results in increases in both compression power and refrigeration capacity but also reach a 99% CO_2 recovery rate.

The energy and cost performances of the CO_2 conditioning process before train export for the three sets of partial condensation conditions are displayed in Figure 18. The energy evaluation shows that the two alternative set of conditions lead to increases of respectively 6.3 and 6.9%, while the CO_2 conditioning costs, including the capture cost impact associated with the CO_2 losses, increase by 1.8 and 3.8%. In absolute terms, this corresponds to increases in conditioning costs of 0.3 and 0.6 €/t_{CO2} for a reduction in CO_2 losses of less than 1%. This indicates that, here, increasing the CO_2 recovery compared to the base case does not appear to be good strategy even when the capture cost impact associated with these losses is taken into account. This may mean that selecting the partial liquefaction conditions to slightly decrease the CO_2 recovery ratio may be a more cost-efficient strategy. However, the first and second liquefaction processes would become more competitive than the base case process if the purged CO_2 was captured at cost of at least 70 or 110 €/t_{CO2} respectively.

[14] The condensation will be at constant pressure but with a gliding temperature due to the presence of impurities.
[15] This cost excludes the cost and energy associated with the CO_2 conditioning.

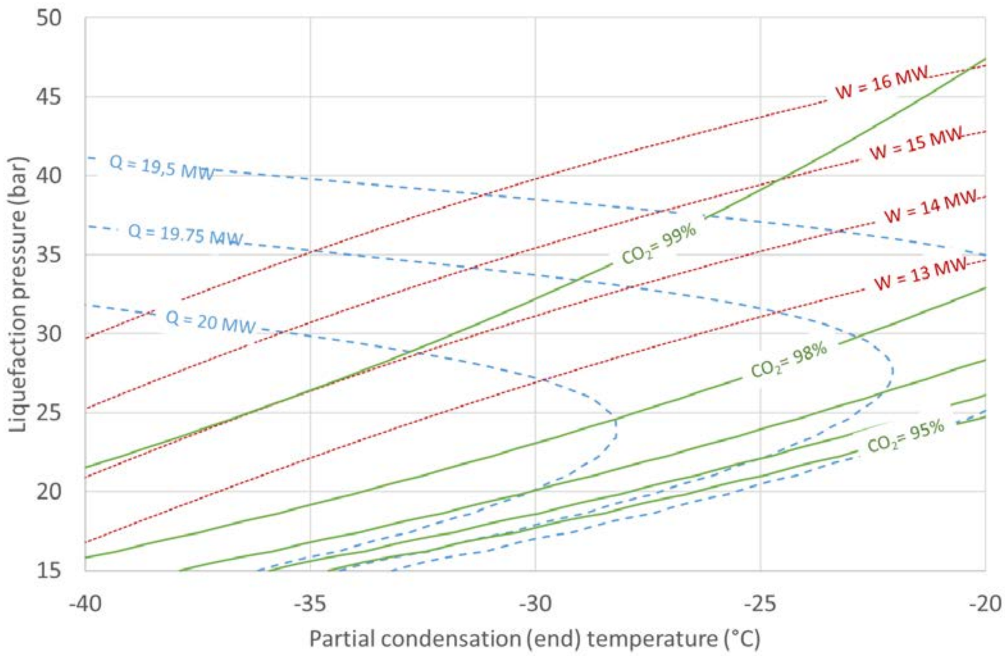

Figure 17: Process effects of choice of liquefaction pressure and condensing temperature. "W" indicates total compression power, "Q" is the required refrigeration capacity and the "CO_2" indicates the ratio between CO_2 exported and captured

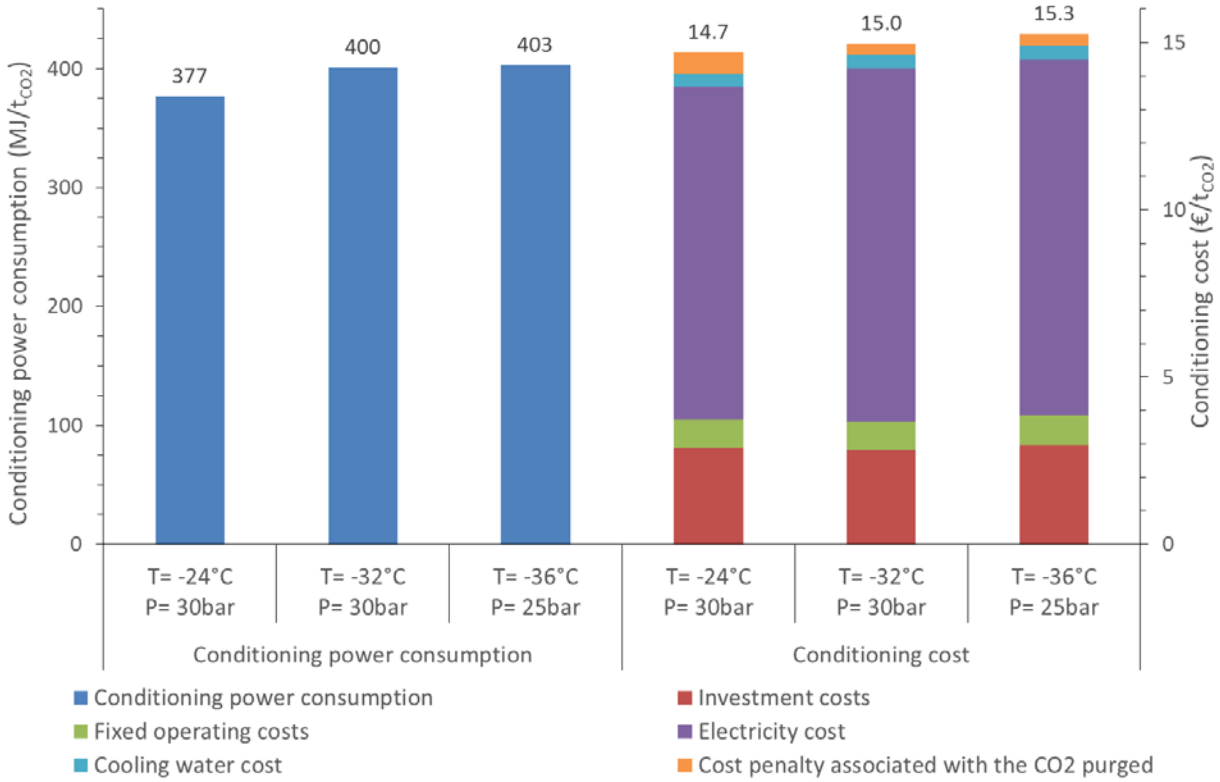

Figure 18: Energetic and cost performances of CO_2 conditioning for train export under different partial condensation conditions

4.3 The potential of train-based CO_2 transport

For both transport delivery location scenarios discussed above, pipeline-based CO_2 conditioning and transport is cheaper than the train-based system. However, to assess the potential of train-based transport, it is important to identify in a more generic manner whether train-based transport could compete with pipeline system. The CO_2 conditioning and transport costs of both train-based and pipeline-based systems are therefore evaluated as a function of the transport distance. As discussed above, train-based export is partly penalised by the significantly higher cost of conditioning when the CO_2 is captured by a Rectisol-based process. However, certain capture technologies, like low-temperature CO_2 capture, have been shown to involve a very limited additional cost to deliver CO_2 at conditions required for train-based export compared to the pipeline export conditions (Anantharaman et al., 2017). Therefore, the CO_2 conditioning and transport costs of both train-based system and pipeline-based systems are also assessed to represent a case associated with low-temperature capture by considering an additional cost of 1 €/t_{CO2} for the train-based conditioning compared to the pipeline-based conditioning[16] (Anantharaman et al., 2017). The results of these assessments are presented in Figure 19 for a 25 years project economic valuation and in Figure 20 for a 10 years valuation. It is worth nothing that in both assessments the transport distances are considered to be identical for both in the train and pipeline transports. In practice, the geographical context and existing infrastructures may advantage one of the two technologies as in the base cases considered in this paper (Czech storage and European hub).

As illustrated in the literature for the case of pipeline versus shipping transport (Geske et al., 2015; Metz et al., 2005; Roussanaly et al., 2014; Roussanaly et al., 2013b), the results show that there is a distance beyond which train-based transport (tanked transport) becomes cheaper than pipeline based transport. However, for the transport volume discussed here and the 25 years project economic valuation, this switching distance appears at distances significantly greater than presented previously for the pipeline versus ship comparison. Indeed, the switching distances are here 900km and 350 km for the Rectisol and low-temperature cases respectively. A possible explanation for this difference is that CO_2 shipping benefits from significant cost reductions with distance, due to both the use of larger and more efficient ships and a higher utilisation rate[17] of the fleet when longer distances are involved. This is not the case for train export as the train investment and operating costs increase fairly linearly with the transport distance after a certain point. However, while Figure 19 indicates that train-based transport has a limited potential in the Rectisol-based capture case, it has greater potential in the case when integrated with CO_2 capture technologies such as low-temperature capture, which results in low additional costs to deliver CO_2 at conditions required for train-based export, compared to the pipeline export conditions.

Finally, if a shorter period is considered for the economic valuation of the conditioning and transport to represent risk-averse investment decisions, train-based transport becomes a serious alternative to pipeline transport, as shown in Figure 20. The switching distances can be as short as 425 km for the Rectisol base case and 175 km for the low-temperature capture case, due to the higher contribution of investment in the pipeline-based transport system. However, it is important to note that considering a shorter period for the economic valuation results, by definition, in higher CO_2 conditioning and transport costs compared to a longer valuation period.

In conclusion, train-based transport could potentially be a cost-optimal alternative to pipeline-based transport for medium to long distances especially in cases in which additional conditioning cost for the train-based transport compared to pipeline remains limited or in the case of risk-averse decision-making. However, the assessments of train-based CO_2 transport performed here are one of the firsts and shall be refined in future works to increase data quality and reduce uncertainties. Moreover, the impacts of capacity, transport distance differences between the two transport systems, constrains on the use of existing railroad infrastructures, and required construction of additional railroad infrastructure need to be further evaluated.

[16] It is worth noting that for low-temperature capture, the CO_2 is delivered directly at the required train transport conditions and therefore the cost of CO_2 conditioning in this case is considered to be 0€/t_{CO2}.

[17] i.e. a reduced contribution of arrival/loading/departure activities

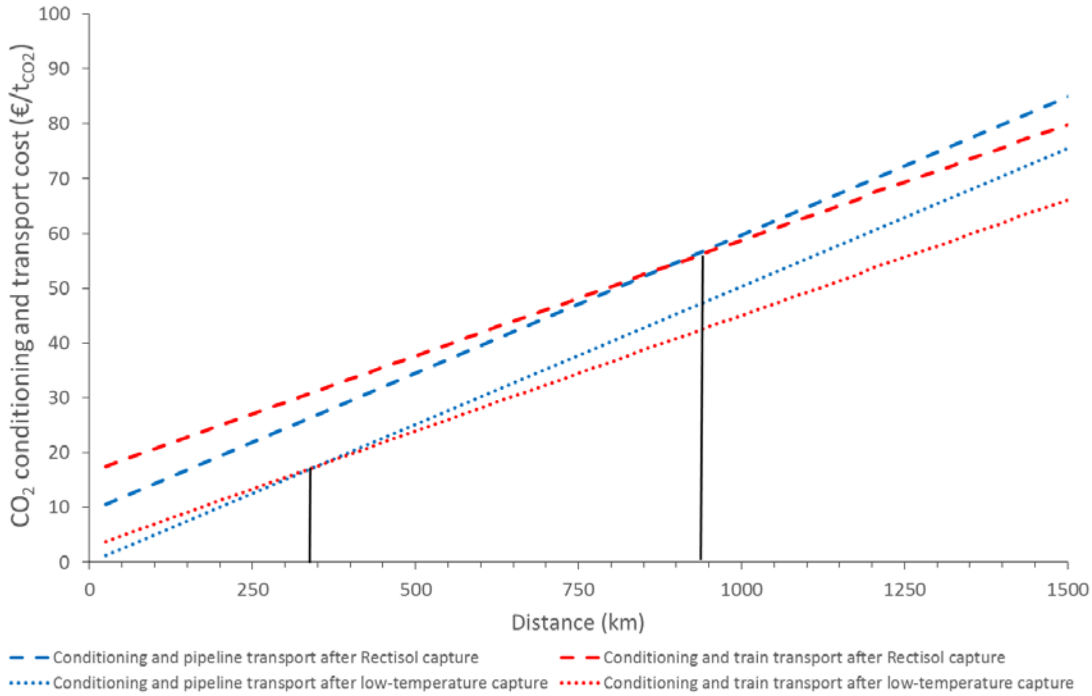

Figure 19: CO_2 conditioning and transport costs of pipeline- and train-based transport and two capture technologies depending on the transport distance for a 25 years project economic valuation period

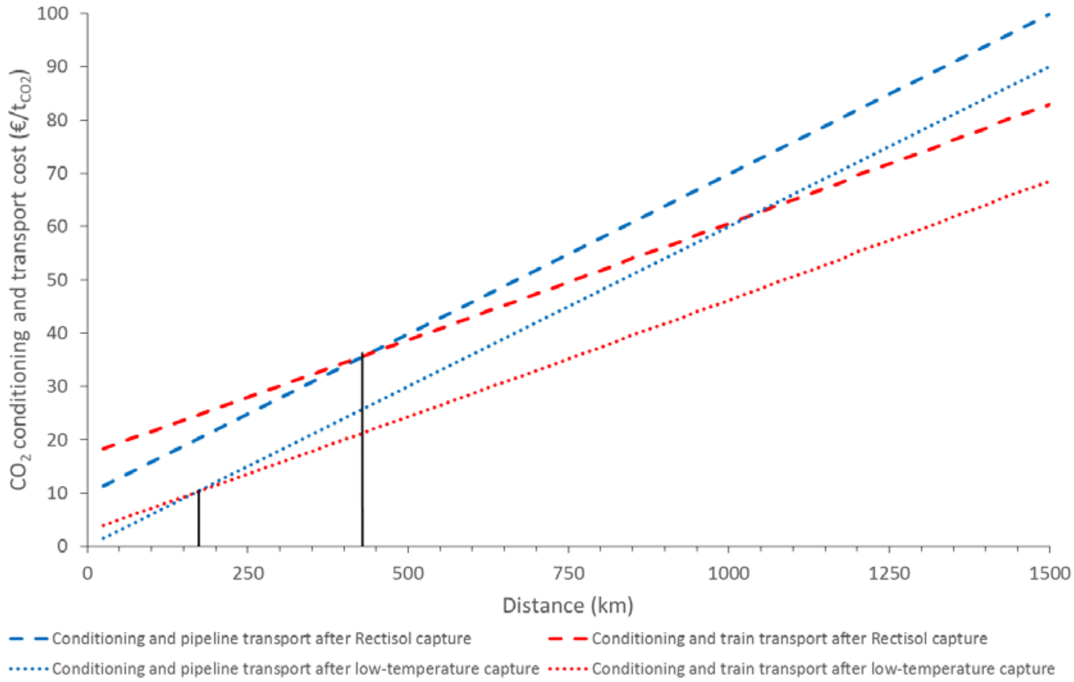

Figure 20: CO_2 conditioning and transport costs of pipeline- and train-based transport and two capture technologies depending on the transport distance for a 10 years project economic valuation period

5 Conclusions

This paper investigates strategies for conditioning and transport of CO_2 captured from a lignite-fired integrated gasification combined cycle (IGCC) power plant in Czech Republic. The analyses consider the design, evaluation and comparison of four cases that combine two transport delivery sites and two transport technology options are designed and discussed, taking also into account the impact of impurities present in the CO_2 captured streams. While the two technology options considered are pipeline-based and train-based transport, the two transport scenarios involve delivery to two different locations: a nearby Czech storage site and a more distant hypothetical European transport hub location. Due to the use of

existing railroad infrastructures, the CO_2 is transported over longer distances when train transport is considered for both the Czech storage case (50 vs. 23 km) and the European hub case (200 vs. 120 km).
The technical evaluation of the conditioning processes for both types of export shows that conditioning prior to train is 50% more energy-intensive than for pipeline transport, and that 1.8% of the inlet CO_2 is purged to avoid the accumulation of impurities in the liquefaction process prior train transport. As energy consumption is the major contributor to the cost of CO_2 conditioning, this difference leads to conditioning costs of 9.3 and 14.7 €/t_{CO2} for pipeline- and train-based exports respectively. Regarding the export systems, while the number of trains and wagons in the train supply chain is optimised to minimize the transport cost, the pipeline optimisation is based on the selection of the cost-optimal pipeline diameter. The cost evaluation of the export systems shows that, partly due to the difference in transport distance between the two technologies, the train-based export is also more costly than the pipeline export (4.1 versus 1.2 €/t_{CO2} in the Czech storage case and 10.8 versus 6 €/t_{CO2} in the European transport hub case).
For the Czech storage case, the cost evaluation of CO_2 conditioning and transport results in costs of 10.5 and 18.3 €/t_{CO2} for the pipeline and train options respectively. In the European hub scenario, these CO_2 conditioning and transport costs are estimated at 15.4 and 24.9 €/t_{CO2}.
These results clearly indicate that pipeline transport is the cost-optimal option for CO_2 conditioning and transport in both delivery scenarios, due to the higher transport distance and conditioning costs of train-based transport. Moreover, the comparison of the transport scenarios also shows that if CO_2 storage is not possible at the Czech storage and that the CO_2 shall pass by the European hub, this would result in an increase of at least 4.9 €/t_{CO2} plus the additional transport and storage costs after the European hub. Meanwhile, sensitivity analyses show that the most important parameters for the conditioning and transport cost are the electricity consumption associated with the CO_2 conditioning, the pipeline investment costs, the train operating costs, the transport distance and the project valuation parameters (discount rate and project duration).
In addition, the impact of the presence of impurities in the CO_2 streams from the capture plant on the CO_2 conditioning and transport cost are evaluated for the four combinations of transport scenarios and technology options. The results show that the impurities present in the CO_2 streams lead to increases in CO_2 conditioning and transport costs ranging between 1.6 and 11.4% (0.2-1.9 €/t_{CO2}). However, the energy and cost impacts associated with the impurities are highly dependent on the transport technology and transport delivery location scenario considered. Indeed, for the pipeline-based transport, the impact varies between 2% and 1.6% for the Czech storage and European hub cases respectively. Meanwhile stronger impact (7.8 to 11.4%) are observed for train-based transport due to the effects of the impurities on the power requirement and design of the conditioning process, as well as the cost penalty due to purging of CO_2. However, in this case, the cost impact of impurities decreases with the transport distance.
Furthermore, the process energy and cost performance of two alternative CO_2 liquefaction processes, designed to decrease the CO_2 losses through the purged gas, are also evaluated. Indeed, decreasing CO_2 losses could provide a cost benefit when the whole CCS chain perspective is taken into consideration, as this CO_2 has been captured at a relatively high cost. Once the capture cost impact associated with these CO_2 losses is included, the conditioning cost of the two alternative designs lead to an increase of 0.3-0.6 €/t_{CO2} compared to the base case design. This suggests that increasing the CO_2 recovery rate compared to the base case does not appear to be a good strategy, unless high costs (70-110 €/t_{CO2}) were spent to capture the CO_2 that is purged. While, it may mean that selecting the partial liquefaction conditions to slightly decrease the CO_2 recovery ratio may be a more cost-efficient strategy, this needs to be investigated further by optimising the CO_2 conditioning process prior to train export taking into account the cost that was spent in capturing the CO_2 purged.
Finally, the potential of train-based transport is evaluated by comparing CO_2 conditioning and transport cost for both pipeline and train transports as a function of the distance for different train conditioning cost scenarios and project economic valuation periods. The results show although pipeline is always the cost-optimal alternative for short distances, train-based export could outperform it for medium to long transport distances. Furthermore, the train-based transport benefits especially from cases in which additional conditioning costs for the train-based transport compared to pipeline are limited or in cases of financial risk-averse decision-making. However, the impact of capacity and transport distance differences between the two transport systems should be further investigated.

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6 Appendix A: Impact of inlet/design pipeline pressure on the conditioning and transport cost of the Czech storage scenario

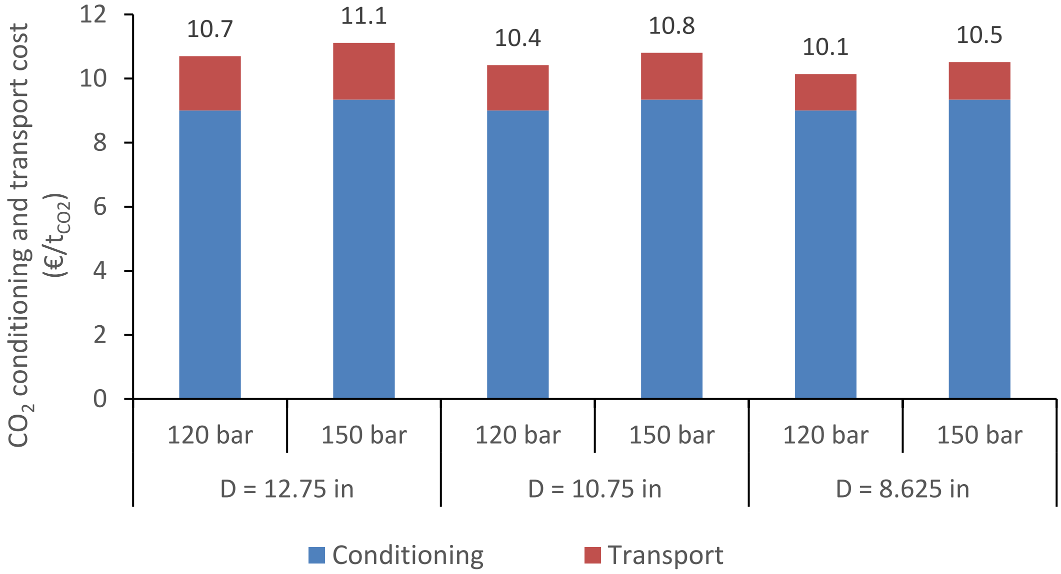

Figure 21: CO_2 conditioning and transport of pipeline transport for the Czech storage scenario depending on the pipeline inlet/design pressure and the diameter considered[18]

[18] The diameter of 6.625 inch is excluded as repumping would be required in this case.