



The influence of uncertainty in the development of a CO₂ infrastructure network



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HIGHLIGHTS

- We model CO₂ infrastructure development with and without uncertainty.
- A real option approach is used for modelling the CO₂ infrastructure with uncertainty.
- Investments in carbon capture and storage are postponed with uncertainty.
- Carbon capture and storage can best be stimulated by reducing CO₂ price volatility.
- Uncertainty will lead to up to 4.5 times higher average transport and storage costs.

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ABSTRACT

This study aimed to analyze whether, and how, uncertainty influences the layout and costs of a CO₂ transportation network. The case without uncertainty is modelled with a perfect foresight (PF) model and with uncertainty with the real option approach (ROA). In this study, uncertainties in the CO₂ price, tariff received per tonne of CO₂ transported, the willingness, probability and moment that sources join the CO₂ transportation network are incorporated in the analysis. The results show that uncertainty leads to higher required CO₂ prices before investments in carbon dioxide capture and storage (CCS) are made. With a volatility of 47% in the CO₂ price, the required CO₂ price almost triples in comparison with the net present value approach. Hence, under uncertainty less sources are retrofitted with CCS and less CO₂ is captured and stored over time. For instance, for the analyzed case study 31 Mt and 137 Mt CO₂ is projected to be captured in the base scenario of ROA and PF model, respectively, in the period 2015–2050. If the volatility of the CO₂ price is reduced with 50%, 96 Mt is projected to be captured in the ROA, which is still about one third less than in the PF model.

Furthermore, the results show that uncertainty leads to less development of trunklines. All this leads to an increase in the transport and storage costs. For instance, for our case study, the average CO₂ transport and storage costs in 2050 increase from 2.8 €/t to 13 €/t in the base scenario of the ROA compared to the PF model. If the volatility is reduced with 50%, the transport and storage costs decrease to 7.5 €/t in the ROA, which is still 2.5 times as much as in the PF model.

Our findings indicate that the implementation of CCS can best be stimulated by reducing the volatility of the CO₂ price, reducing capture costs and facilitating cooperation between nearby sources.

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1. Introduction

Carbon dioxide capture and storage (CCS) is a CO₂ mitigation measure that can contribute significantly to the reduction of greenhouse gas emissions to limit climate change [1–3]. However, one of the hurdles for implementing CCS at a large scale is the lack of a

suitable CO₂ transportation infrastructure [4,5]. Therefore, the International Energy Agency (IEA) identifies the stimulation of an efficient CO₂ transportation network by taking into account future demand and volumes, as one of the main actions in the short term [4].

To facilitate the development of CO₂ transportation networks, several studies have modelled possible layouts of CO₂ infrastructure. For instance, Dahowski et al. [6,7] constructed cost curves for CO₂ transport and storage costs for the United States and China.

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They assume that each source-sink connection has a dedicated pipeline, thereby providing a conservative cost estimation, because combining sources in a trunkline could lead to economies of scale [7]. Other models include trunklines but they assume that the network is built overnight [8–11], thereby ignoring the fact that CO₂ capture installations will develop over time. Timing effects are incorporated in the models of, for instance, van den Broek et al. [12,13]; Piessens et al. [14,15]; Morbee et al. [16]; Middleton et al. [17] and Oei et al. [18]. However, these models analyze the development of CO₂ infrastructure network by assuming perfect foresight, i.e., all (investment) decisions are made with the optimized outcome in mind, without incorporating any barriers or uncertainties. An exception in this sense is the model of Piessens et al. [14,15], who analyzed the influence of uncertainty in the storage capacity on the layout of a CO₂ infrastructure. However, they assume perfect foresight to make oversizing of pipelines possible. Also, Middleton et al. [19] investigate the influence of uncertainty in the storage capacity, but they do not include timing effects.

With perfect foresight, investments are conducted which may be not advantageous in the short term, but will lead to significant cost savings in the longer term [14,15]. For instance, Middleton et al. [17] has indicated that for transporting initially 1 Mt/y, a trunkline with a capacity of 12 Mt/y is constructed, because this large capacity is needed after 15 years. Similar results for oversizing pipeline can be seen in the study of van den Broek et al. [12] and Morbee et al. [16].

Although combining CO₂ flows from different sources in a trunkline can lead to large economies of scale [11,20], it remains a large financial risk if there are no contract agreements with other CO₂ emitters [21,22]. Middleton et al. [17] estimate that the pipeline length would almost double and the overall transportation costs will increase with about 50% in the Texas panhandle, if only point-to-point pipelines are constructed compared to a fully (optimized) integrated network.

One way of dealing with investment decisions in an uncertain environment is a real option analysis [23,24]. Real options incorporate the strategic and flexibility value of an investment opportunity. Especially investments that have an irreversible character, a timing decision attached to it, and uncertain future revenues are suitable for a real option approach (ROA) [23,24]. All these characteristics are applicable to CCS investments. Consequently, several CCS studies have used a ROA to analyze the effect of an uncertain CO₂ price, electricity price and/or investment costs on the implementation rate of CCS. It has, for instance, been used to assess optimal investment decisions for replacing coal power plants [25–27] or to analyze the optimal timing for a CCS retrofit [28,29]. However, none of these studies analyzed the impact of uncertainty on the development of a CO₂ transport infrastructure.

Besides analyzing the option to invest, ROA can also be used to value the flexibility of different engineering options [30–32]. For instance, de Neufville et al. [32] analyzed the value of constructing a parking garage with stronger columns such that there is the option to add additional floors if demand increases over time. Overall, the different engineering studies concluded that investing initially in a smaller design that can be expanded if needed, is more cost-effective than investing in a large factory at once. The reason for this is that the risk of disappointing demand is covered, while there is still the opportunity (after investing in additional modules) to benefit from strong demand growth. A pipeline network is different because the capacity is (almost) fixed after the pipeline is constructed. Hence, there are two extreme options, install an oversized pipeline to benefit from significant economies of scale, or install a point-to-point pipeline with no possibility to increase capacity. Another difference is that multiple companies are involved in the development of a network. If a company constructs an oversized pipeline, this can stimulate other sources to start with

CCS and join the network. However, a source can also ‘steal’ a CO₂ storage opportunity and increase the costs for other sources. Hence, the decisions of the different sources are interrelated and uncertainty plays a role at each decision moment of building up a network.

In the context of CO₂ infrastructure development, uncertainty is mainly present in the timing when sources will start with CCS, and if they start with CCS, whether they invest in a trunkline or point-to-point pipeline. The moment when sources start with CCS depends on, among other things, fuel and electricity prices, readiness of the (capture) technology, distance to a suitable sink, availability of a CO₂ infrastructure and CO₂ price. According to Zhu and Fan [27], the CO₂ price has the most significant impact on the investment decision in CCS, in comparison with uncertainties related to the investment and variable costs.

The decision to invest in a trunkline or point-to-point pipeline depends on the profitability of each option. The profitability of a trunkline, in comparison with point-to-point pipelines, decreases with increasing time difference between the moment of construction and the moment that other sources connects to the trunkline [11,33]. The profitability of a trunkline also depends on the tariff received per tonne of CO₂ transported. Hence, (possible) variability and uncertainty in the transportation tariff, time difference and probability that mass flows join the network seem to be crucial uncertainties for investing in a trunkline.

The aim of this study is to analyze the impact of uncertainty on the development and costs of a CO₂ transportation network, and more specifically the role of uncertainty in the decision to oversize the pipelines. To analyze this, the infrastructure development is modelled both with perfect foresight and with a ROA for a stylized case study and uncertainty is included in the CO₂ price, tariff per tonne of CO₂ transported, the time difference and the probability that sources join the transportation network. The developed method cannot only be used for CO₂ infrastructure development but can also be applied to other (infrastructure) problems, like a hydrogen infrastructure, glass fiber network, highways, etc.

2. Method

2.1. Real option approach

It is often assumed that an investment decision will be taken if a project has a positive net present value (NPV). However, in reality, the decision is often not a now or never, but can also be postponed [23,24]. Waiting for more information has a (economic) value because if the expected NPV of an (irreversible) investment opportunity increases, the investment can still be done, while if the NPV decreases, the company does not have to invest [23]. The option to invest will only be exercised if the NPV of the investment is higher than the waiting value. This is the main concept behind the real option theory. For additional information, see [23,24].

In this study, a ROA is used to examine the optimal timing for CCS investment. Subsequently, a decision has to be made to invest in either a point-to-point (PtP) pipeline, a trunkline or join an existing trunkline. The method is summarized in Fig. 1 and explained in more detail in the sections below.

2.1.1. To invest or not to invest in CCS

To decide if each individual source wants to invest in CCS now or wait, the first step is to calculate the NPV, see the [supplementary material](#) for the equations. The NPV is based on an infinite lifetime for the decision whether to invest in a CCS project. In reality, a CO₂ capture unit has a lifetime of thirty to forty years and the storage field may even have a shorter lifetime. However, an infinite lifetime is assumed for simplicity. This is justified by the fact that

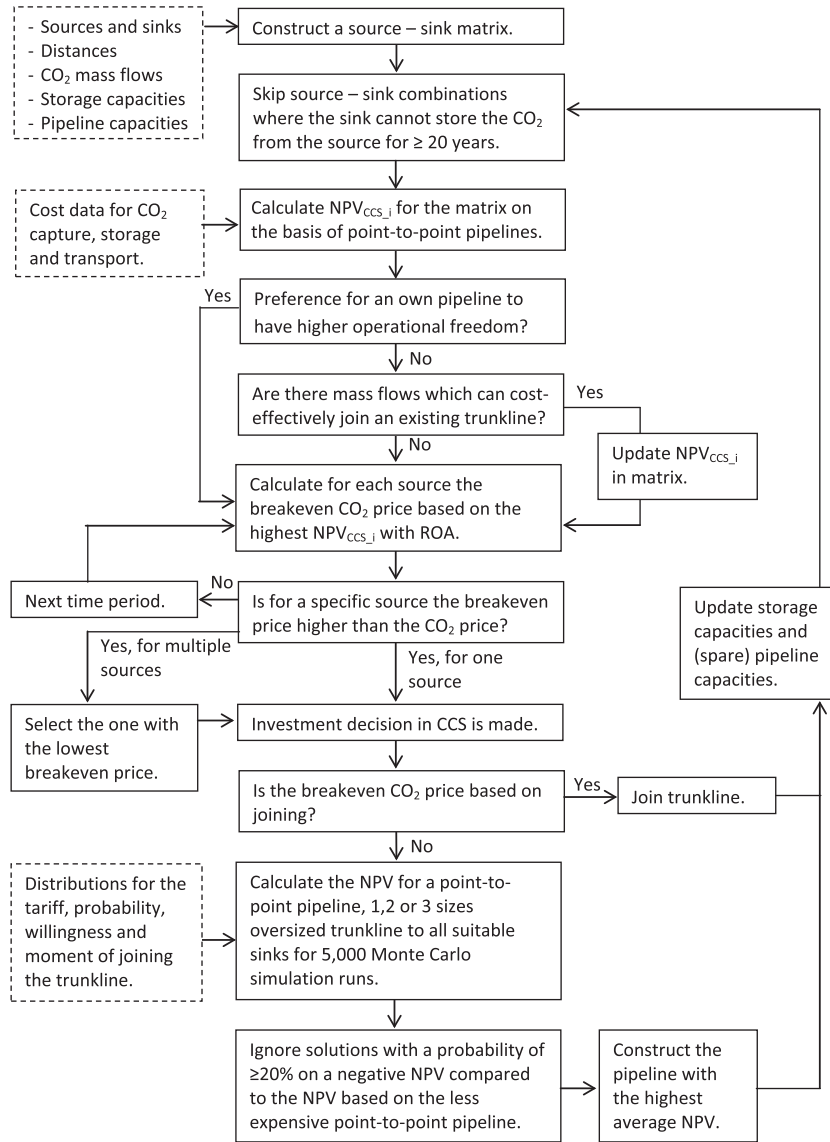


Fig. 1. Flow diagram for the decision to start with CCS and the decision to construct a point-to-point pipeline, a trunkline or join an existing pipeline under uncertainty.

future cash flows are worth less than current cash flows, due to the impact of discounting [34]. Additionally, it is observed that lifetimes of existing power and industrial plants are often extended, which will probably also be the case for CCS projects.

Second, for each source, the sink is selected which results in the lowest NPV. In this study, only sinks are considered which are capable of storing the CO₂ emissions of the source for at least 20 years. In principle, CO₂ from one source can be distributed and stored in multiple sinks, but this is not included in the ROA.

Third, the option values are calculated for the selected source-sink combinations. The option value is related to the uncertainty in the CO₂ price, which is assumed to follow a geometric Brownian motion, see Eq. (1) [27–29,35]. The option value is calculated with a binominal lattice model, like was done by [28,29,36,37]. Furthermore, the breakeven CO₂ price is calculated by setting the option value equal to NPV.

In the fourth step, the investment decision in CCS is taken if the breakeven CO₂ price is lower than the current CO₂ price. For a certain time period, it may be optimal to invest in CCS for multiple emitters. The project with the lowest breakeven CO₂ price is assumed to be constructed first. This may have consequences for

the other projects because it could, for instance, diminish the available storage capacity or a new trunkline can be constructed, which changes the transportation costs. Hence, the NPV of all source-sink combinations and breakeven CO₂ prices are recalculated after a project is constructed. If all projects with a breakeven price lower than the current CO₂ price are constructed, the next period is analyzed. Note that in this new period, the CO₂ price will change (see Section 3.1). The process is repeated until all sources implement CCS or the time horizon of 2050 is reached.

$$dP_c = \alpha P_c dt + \sigma P_c dW \quad (1)$$

where P_c is the CO₂ price (€/t); α is the constant risk-adjusted drift or growth rate of the CO₂ price (%); σ is the constant volatility or standard deviation of the CO₂ price (%); and dW is the increment to a standard Wiener process, which is normally distributed with a mean of zero and a variance of dt .

2.1.2. Point-to-point pipeline or trunkline

Once an investment decision in CCS is made, a decision has to be made on whether to invest in a trunkline, in a point-to-point pipeline or to join an existing trunkline. In this study, the trunkline

can be one, two or three nominal pipe sizes (NPS) larger than the point-to-point pipeline.¹

If there is an existing trunkline with enough spare capacity, it may be more cost-effective to join an existing trunkline instead of constructing a new pipeline. A source will only be able to join an existing trunkline, if there is enough spare capacity available to transport its entire CO₂ mass flow. The costs of joining consist of three components. Firstly, a tariff per tonne of CO₂ transported. Tariffs are regulated and should cover operational expenses, depreciation of the pipeline and additionally generate a reasonable rate of return [38], see Eq. (2).² Secondly, a distribution pipeline to the trunkline has to be constructed, which is assumed to connect to the trunkline at the start of the trunkline or at the point where the onshore–offshore connection is made (i.e., landfall point). Thirdly, a new well has to be drilled at expenses of the source joining the trunkline if not enough spare capacity is present in the existing well(s), otherwise the storage costs are zero. Although cost-effective to join an existing trunkline, a company may have a preference for constructing an own pipeline, see Fig. 1. Possible reasons for this are higher operational freedom or not willing to match the requirements set by the owner with respect to maximum inlet temperature, impurity levels, etc.

To estimate the profitability of investing in a point-to-point (PtP) pipeline, a one (Trunk1), two (Trunk2) or three (Trunk3) sizes larger trunkline, a Monte Carlo analysis is conducted in this study. Monte Carlo is a powerful tool to generate probability distributions based on uncertainty in the parameters. In this study, the tariff, the probability and moment that sources are joining the trunkline are uncertain. With Monte Carlo 5000 simulation runs are calculated. For each simulation run, the NPV of a point-to-point pipeline and trunklines to suitable sinks are calculated. The expected revenues (and costs) until 2060 are taken into account. We assume that companies prefer investments with a high average NPV and with a low risk of a negative NPV. According to Hacura et al. [39] a probability of 20% for making a loss is quite safe for investment decisions. Therefore, in this study, only trunkline solutions are considered acceptable which have a ≤20% probability that the NPV is lower than the point-to-point pipeline. Subsequently, the solution with the highest NPV is selected.

Finally, the projected pipelines are visualized with maps, to show the infrastructure development over time. Note that investments done in the previous period cannot be changed in the ROA.

$$TF = \frac{I_{trunk} \times OM_{trans} + I_{store} \times OM_{store} + RRR \times (I_{trunk} + I_{store})}{D_{cap}} \quad (2)$$

$$RRR = r_{equ} \times p_{equ} + (1 - p_{equ}) \times r_{debt} \quad (3)$$

where TF is the tariff per tonne of CO₂ transported (€/t CO₂ transported); I_{trunk} is the initial investment cost of the trunkline (€); OM are O&M costs as percentage of the investment costs (%); I_{store} are the initial investment costs of the storage facility (€); RRR is the reasonable rate of return (%); D_{cap} is the design capacity of the pipeline (t/y); r_{equ} is the rate of return on equity (%); p_{equ} is the share of equity (%); r_{debt} is the costs of debt (%).

¹ Pipeline diameters are available in standard sizes, so-called nominal pipe sizes. In this study, the following diameters are included: 0.11; 0.17; 0.22; 0.27; 0.32; 0.41; 0.51; 0.61; 0.76; 0.91; 1.07; 1.22; 1.32 and 1.42 m.

² Eq. (2) has two adaptations compared to the original tariff calculation. Firstly, the tariff is based on the design capacity of the pipeline rather than on the mass flow transported, which leads to an underestimation of the tariff. Secondly, the value of the asset is assumed to be constant over time (i.e., there is no depreciation), which leads to an overestimation of the tariff. These adaptations are made to come to a constant tariff over time, which is easier to model and probably closer to reality if agreements are made.

2.2. Perfect foresight

In the perfect foresight case, the objective is to maximize the NPV of the entire system by taking into account constraints relating to the maximum capacity of the sources, pipelines, wells and sinks and ensuring that all captured CO₂ is actually stored. In this study, a mixed integer linear programming (MILP) is used. A MILP model can ‘look ahead’ to the end of the model period to find the configuration leading to the highest NPV over the whole period [40]. In this study, the period 2015–2060 was analyzed and results up to 2050 are reported. The reason for also analyzing the period 2050–2060 is that otherwise none (or very few) investments will be done in the period 2045–2050 because there is (almost) no time to recover the initial investment costs.

The perfect foresight case is inspired on the scalable infrastructure model for CCS (SimCCS) developed by Middleton and Bielicki [8]. A few adaptations were made. Firstly, a CO₂ price was included instead of a target amount of CO₂ that has to be sequestered as was originally done in SIM^{PRICE} by Kuby et al. [41]. Secondly, the development of the CO₂ network was analyzed over time instead of building the network overnight, as was originally done in SIM^{TIME} by Middleton et al. [17]. In addition, the following adaptations were implemented to make the perfect foresight model comparable to the ROA:

- The CO₂ flow from a given source is completely captured or not at all, meaning that it is not possible to capture only a part of the CO₂ flow.
- Only source–sink connections are made, where the sink is capable of storing the CO₂ emissions of the source for a minimum of 20 years.
- A construction period of one year is included.
- A differentiation is made between capacities and costs for onshore and offshore pipeline.
- Fixed offshore pipeline costs are added of 35 M€, which are needed to mobilize the equipment for offshore pipeline laying and realize the onshore–offshore connection [33].
- Operation and maintenance costs are added as percentage of the investment costs.

The objective function and constraints including these adaptations are given in the appendix. The optimization model was written in AMPL [42] and solved with CPLEX 12.6.1 [43].

3. Case study

The influence of uncertainty in the development of a CO₂ infrastructure is demonstrated with a case study. To have a realistic set of sources and sinks, a stylized case study was developed based on a number of sources in and sinks around the Amsterdam–IJmuiden region in the Netherlands. This region was chosen because it is a main industrial areas with different types of CO₂ sources located near the shore. However, it has to be stressed that the goal of this study is to show the difference between developing an infrastructure with and without uncertainty and not to optimize the infrastructure in the Amsterdam–IJmuiden region.

3.1. Input variables and uncertainties

In this study, a volatility of 46.8% and a risk adjusted drift of 3.1% are used, see Table 1 [29]. With the risk adjusted drift the CO₂ price would increase less rapidly over time than projected by the IEA in the 450 ppmv scenario [44,45], see Fig. 2.³ The

³ The CO₂ prices of 2012, 2020, 2030 and 2035 are based on the World Energy Outlook 2013 [44] and for 2050 on the Energy Technology Perspectives 2012 [45]. Intermediate values are found by assuming constant growth rates. After 2050, the CO₂ price is assumed to increase at a similar rate as in the period 2035–2050.

Table 1
Economic parameters used in this study.

Parameter	Symbol	Unit	Value	Comment/reference
Construction period		y	1	^a
Risk free rate	r_f	%	5	^b
Discount rate	r	%	10	^c
O&M costs capture	OM_{cap}	% of I_{cap}	4	^d
O&M costs transport	OM_{trans}	% of I_{trans}	1.5	[33]
O&M costs storage	OM_{store}	% of I_{store}	5	[12]
CO ₂ price in 2015	P_{CO_2}	€/t CO ₂	10	Own assumption
Risk adjusted drift for the CO ₂ price ^e	α	%	3.08	[29]
CO ₂ price volatility ^e	σ	%	46.83	[29]
Mean costs of debt	μ_{r_debt}	%	7.0	^f
Standard deviation costs of debt	σ_{r_debt}	%	1.1	^f
Mean return of equity	μ_{r_equ}	%	14.9	^f
Standard deviation return of equity	σ_{r_equ}	%	6.6	^f
Mean share of equity	μ_{p_equ}	%	56	^f
Standard deviation of share of equity	σ_{p_equ}	%	11	^f

^a The construction time is relatively short. However, longer construction periods would complicate the modeling process. According to Chladná et al. [46], the results would not change qualitatively, if it is assumed that the lead times will not (drastically) differ between the different sources. Therefore, it is chosen to include a construction period of only 1 year as was also done by Abadie and Chamorra [29].

^b This risk free rate is within the range of 4–5% used for CCS projects in literature [27–29,36,47].

^c The continuously compounded discount rate is set on 10%, which equals the risk free rate plus a market risk premium of 5%, to incorporate that a higher return is required for investments, which are not risk free. This is comparable to the risk premium of 4.5–5.5% estimated by several models [48].

^d O&M costs for CO₂ capture are industry specific, technology dependent and fuel related. For instance, O&M costs for CO₂ capture are estimated at 2–3% for natural gas combined cycle (NGCC), 4% for pulverized coal (PC) and integrated gasification combined cycle (IGCC) [40], 5% for steel production, and 12% for cement production with steam import [49]. For simplicity reasons, 4% O&M costs for CO₂ capture is used throughout this study.

^e In literature, several drift rates and volatilities are mentioned. The volatility for CO₂ prices range from 2.0% to 46.8% and the drift from 2.0% to 5.9% [26,27,35–37,50–52]. In this study, the volatility and risk-adjusted drift are based on the CO₂ allowances traded in the context of the second phase (December-08 and December-2012) of the EU Emissions Trading Scheme [29]. A risk-adjusted drift means that a risk premium is subtracted from the drift to compensate for the risk that CO₂ prices may not rise as fast as expected.

^f These uncertainties are based on the financial data published by 32 pipeline companies in the period 2005–2009 [53]. One of the 32 pipeline companies realized a negative rate of return of –6.2%. This data point is ignored in estimating the mean and standard deviation. The return on equity is best approached with a lognormal distribution, while the cost of debt and the share of equity are approached with a normal distribution.

450 ppmv scenario aims to stabilize the long term CO₂ emissions in the atmosphere on 450 parts per million volume, which would limit, with a reasonable possibility, the average increase in global temperature to 2 °C. In this study, the year when sources start with CCS are based on the CO₂ price projections of the 450 ppmv scenario from the IEA.

Several assumptions were made for the decision to invest in a point-to-point pipeline, invest in a trunkline, or joining an existing trunkline:

- The earliest moment when sources may join a trunkline is assumed the starting year under perfect foresight, because uncertainty leads to postponement of decisions. The latest possible moment of joining is based on the projected year with the ROA when an investment in CCS is made without the trunkline under consideration. All years have the same chance of being selected (i.e., an uniform distribution), as no better distribution is known.
- The uncertainty in the tariff is mainly found in the reasonable rate of return (RRR), which can be distributed between three variables, namely the costs of debt, the return and share of equity, see Eq. (3) and Table 1. To avoid that the reasonable rate of return can be lower than the discount rate of 10%, the RRR is truncated at 10% in the Monte Carlo analysis. For further calculations, the tariff is based on the average RRR.
- The willingness of joining will probably be larger for small sources, because they benefit the most from joining a trunkline.⁴ Hence, in this study it is assumed that sources capturing

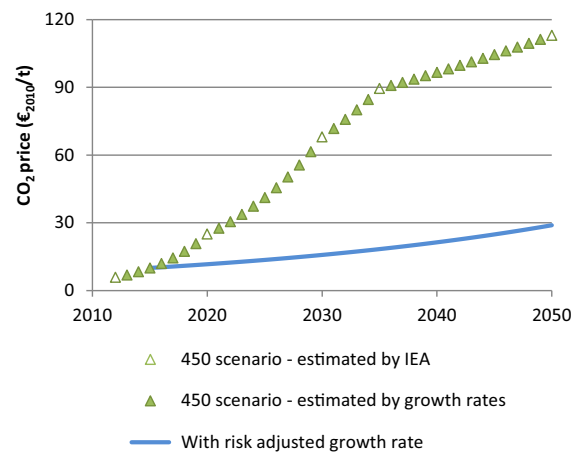


Fig. 2. CO₂ price estimated up to 2050 with the 450 ppmv scenario and with the risk adjusted growth rate.

less than 1 Mt/y are always willing to join. For larger sources, it is assumed that in 75% of the cases the source prefers the construction of an own pipeline. Additionally, scenarios are analyzed where the willingness of joining is set on 100% for all sources.

- The probability of joining is related to the cost-effectiveness of joining in comparison with the costs of constructing an own pipeline. The probability of joining is set on 75% for all sources, but a probability of 100% is assumed in a few scenarios.

Other economic parameters used throughout this study are stated in Table 1. All costs in this study are expressed in €₂₀₁₀. Costs

⁴ For instance, the levelized costs for an onshore point-to-point pipeline over 100 km are 3.9 €/t and 2.0 €/t for mass flows of 0.5 Mt/y and 2 Mt/y, respectively. These costs reduce to 1.4 €/t for both mass flows if an existing trunkline with a capacity of 5 Mt/y is joined.

Table 2CO₂ emissions, capacity factor, investment and variable costs for CO₂ capture (including compression to 11 MPa) for the power and industrial sector.

No.	Industry type	Capacity factor ^a (%)	CO ₂ captured (Mt/y)	Avoided CO ₂ allowances (Mt/y) ^b	Capital costs ^{c,d} (€ ₂₀₁₀ /t CO ₂ captured)	Variable costs ^c (€ ₂₀₁₀ /t CO ₂ captured)	Comment
1	Steel	90	1.8	1.8	80	26	e
2	CHP-CCGT	70	0.40	0.35	216	10	f
3	Ammonia	90	0.15	0.15	54	4.9	g
4	NGCC	50	1.4	1.2	347	29	h
5	Paper	65	0.10	0.10	158	9.4	i
6	Waste plant	90	1.1	1.1	318	20	j
7	NGCC	50	0.70	0.59	427	29	h
8	PC	80	2.5	2.0	145	11	k
9	Food processing	90	0.10	0.07	120	46	l

^a Capacity factors differ for different industry types. Waste incineration, ammonia, steel and food production are normally characterized with high capacity factors and are assumed to be 90% in this study. For the boilers in the paper industry, an average capacity factors is used [56]. For power generation, typical capacity factors are used. Note that these may change in the future due to the implementation of renewables, but this is not taken into account in this study.

^b The amount of CO₂ allowances avoided is the number of allowances that have to be bought less if CCS is applied. This is calculated from the amount of CO₂ captured minus the CO₂ emitted in the production of the required steam and electricity on-site.

^c If no scaling factor is mentioned, the investment costs are scaled with a scaling factor of 0.7 [57]. The variable costs are assumed to be independent of scale.

^d The total investment costs can be calculated by multiplying the investment costs per tonne of CO₂ captured with the amount of CO₂ captured divided by the capacity factor. In this way, the capture unit is scaled for the peak load.

^e The CO₂ is captured from a standard air blown blast furnace with MEA (without CO–CO₂ conversion). The variable costs are calculated with an average power equivalent factor of 0.23 for steam and an electricity price of 60 €/MWh [49].

^f The costs are based on a natural gas based CHP with a 0.5 heat-to-power ratio, a 90% capture ratio and a MEA process. The costs in the article of Kuramochi et al. [58] are converted by assuming a CO₂ emission factor of 56 kg CO₂/GJ_{LHV} and a natural gas price of 5 €/GJ_{LHV}. The required heat and electricity are generated by the CHP.

^g Typical capture costs (excluding compression) are estimated at 3.5 €₂₀₁₀/t CO₂ for capturing a pure CO₂ stream originating from ammonia production [59]. These costs are converted to investment costs, by assuming that they consist of investment and O&M costs and using the data in Table 1. The compression costs from atmospheric pressure (0.11 MPa) to 11 MPa are calculated with the method stated in the supplementary material. Electricity is assumed to come from the grid at the cost of 60 €/MWh.

^h The capture costs (including compression to 10–11 MPa) for a standard natural gas combined cycle (NGCC) are based on a single shaft F-class turbine and post-combustion capture with advanced amines [60]. The variable costs are based on a natural gas price of 5 €/GJ_{LHV} [60].

ⁱ In the paper industry, CO₂ could be captured from boilers with MEA. The investment costs of Hektor and Berntsson [61] included compression to 8 MPa and the investment and variable costs are corrected to reflect an outlet pressure of 11 MPa. The required heat is coming from better heat integration and burning biofuel in the boiler. The biofuel is assumed to be carbon neutral and costs 5.3 €/GJ. The electricity costs are estimated at 60 €/MWh.

^j No cost estimations in public literature was found for a waste incineration plant with CCS. The CO₂ concentration in the flue gas is about 10%, but would vary day by day due to a different composition of the feedstock [62]. This CO₂ concentration is in between the ones of PC (3–5%) and NGCC (12–15%) [60]. Therefore, the fixed and variable costs of a PC and NGCC plant are averaged as a first estimation for adding a CCS unit to a waste plant. This approach does not incorporate the potentially higher electricity cost and cleaning costs for the flue gas of the waste incineration plant compared to a PC and NGCC. However, no better approach is known, and therefore, the average costs are used as first approximation.

^k The capture costs (including compression to 10–11 MPa) are based on a typical ultra-supercritical pulverized coal (PC) power plant running on bituminous coal [60]. The CO₂ is captured with advanced amines and the variable capture costs are based on a coal price of 3.2 €/GJ_{LHV}.

^l The costs are based on a conventional boiler running on natural gas with CO₂ capture based on chemical absorption [63]. The costs of Switzer et al. [63] include compression to 22 MPa. The investment and variable costs are corrected to reflect an outlet pressure of 11 MPa. The required steam for regeneration is assumed to be generated by an on-site boiler with an efficiency of 90%, while the electricity is imported. Additional assumptions are electricity costs of 60 €/MWh, natural gas costs of 5 €/GJ_{LHV}, and a CO₂ emission factor of 56 kg/GJ_{LHV} for natural gas.

are converted by using the chemical engineering plant cost index [54] and an exchange rate of 0.75 €₂₀₁₀/\$₂₀₁₀ [55].

3.2. Capture locations and costs

The investment and variable costs of CO₂ capture for the different sources are based on state-of-the-art literature and are given in Table 2. The location of the sources is given in Fig. 3. Based on their location, the different sources are divided into two groups, or so-called clusters. Cluster 1 consists of sources 1–5 and cluster 2 consists of sources 6–9.

3.3. Storage location and costs

Five hydrocarbon fields and one aquifer are included as possible storage locations in this study. The specifications and costs of the included sinks are given in Table 3 and the locations (based on [64]) are pictured in Fig. 3.

3.4. Pipeline distances and transportation costs

The location of landfall points are regulated to ensure effective land use in the Netherlands. In this study, one landfall point is included, see Fig. 3. The distances between the landfall point, sources and sinks are given in Table 4. These distances are based on “straight line” distances. The distances for onshore pipelines

are multiplied with a terrain factor of 1.17, to correct for the fact that onshore pipelines will not be placed in straight lines [69].

The pipeline configurations and costs of CO₂ pipeline transport are based on previous work [33,70]. Several additional assumptions in the cost and optimization model are made to simplify the modelling process. This leads to the following assumptions:

- All pipelines are assumed to transport pure CO₂ in the dense phase, meaning that the pressure is above the critical pressure independent of temperature. Viscosity (83.9 μPa s) and density (867 kg/m³) of CO₂ are assumed to be constant in onshore and offshore pipelines.
- The onshore pipeline is designed with basic pipeline safety measures consisting of a design factor of 0.72, marker tape, burying depth of 1.0 m and block valves every 32 km [70].
- Onshore pipelines are made of carbon steel with steel grade X80, while offshore pipelines are made of X65. All pipelines are designed with a maximum allowable operation pressure of 15 MPa.
- Pumping stations are not allowed offshore and not included onshore to simplify the modelling process.
- One of the NPS is selected based on a design pressure drop of 30 Pa/m, which is in the middle of the range of 15–45 Pa/m indicated as the optimal specific pressure drop for pipelines transporting CO₂ in the dense phase [33]. Note that often a lower specific pressure drop will be realized due to the limited

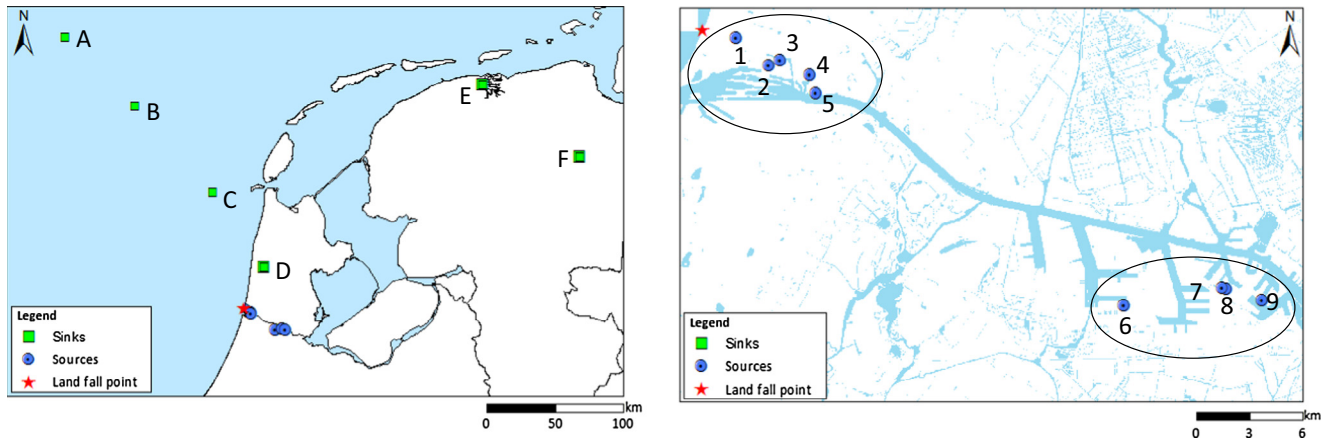


Fig. 3. Location of the landfall point, sources, and sinks included in this study. Numbers and letters refer to specific sources and sinks, see Tables 2 and 3.

Table 3

An overview of the characteristics and costs of the different sinks included in this study.

	Type of reservoir	Injectivity (Mt/y) ^a	No. wells needed ^{a,b}	Useful storage capacity (Mt) ^a	Depth (km) ^a	Costs per well (M€) ^c	Fixed costs (M€) ^c
A	Offshore gas field	1.1	1	21	3.2	14	20
B	Offshore gas field	1.7	1	34	3.6	15	20
C	Offshore aquifer ^d	5.5	2	110	2.0	8.6	94
D	Onshore gas field	1.6	1	33	2.1	6.8	5.1
E	Onshore gas field	1.6	1	33	3.7	12	5.1
F	Onshore gas field	6.6	3	131	2.9	9.4	5.1

^a For each hydrocarbon storage field, three scenarios with different injections rates were identified by Neele [65]. With low injection rates, the time that they can be sustained is longer and the total volume stored is higher. In this study, the injectivity, required number of wells, and the useful storage capacity of the low injectivity scenario of Neele [65] are used.

^b These numbers of wells are needed to reach the maximum injectivity. The injectivity is assumed to be the same for each well in the storage field. Furthermore, only the number of wells are constructed which are needed for the projected mass flow, so no over-dimensioning takes place.

^c Van den Broek et al. [12] give drilling costs for wells per meter depth as well as fixed investment costs for onshore and offshore hydrocarbon fields and aquifers. The fixed investment includes the costs for surface, site development and monitoring. These costs only have to be spent once for each reservoir.

^d The estimated storage capacity is 110–225 Mt, the injectivity is up to 10 Mt/y [66] and about 3–4 wells are needed for this [67]. For the model, it is assumed that 110 Mt can be injected in 20 years, leading to an annual injectivity of maximal 5.5 Mt/y (with 2 wells). The depth of the aquifer is estimated based on the fact that oil production takes place on a depth of 1.5 km [68], which is in the upper part of the aquifer. CO₂ will be injected in the lower part of the aquifer and this depth is, therefore, estimated at 2 km.

Table 4

Distances in kilometer between the source clusters and sinks.^a

	Source cluster		Sink						Landfall point
	1	2	A	B	C	D	E	F	
Source cluster 1	n.a.	35	n.a.	n.a.	n.a.	40	280	315	10
Source cluster 2	35	n.a.	n.a.	n.a.	n.a.	55	270	300	40
Within source cluster	5	5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sink A	n.a.	n.a.	x	75	155	n.a.	n.a.	n.a.	240
Sink B	n.a.	n.a.	75	x	85	n.a.	n.a.	n.a.	170
Sink C	n.a.	n.a.	155	85	x	n.a.	n.a.	n.a.	90
Sink D	40	55	n.a.	n.a.	n.a.	x	285	285	n.a.
Sink E	280	270	n.a.	n.a.	n.a.	285	x	105	n.a.
Sink F	315	300	n.a.	n.a.	n.a.	285	105	x	n.a.

^a In this table, 'n.a.' refers to not applicable. For instance, the connection from source cluster 1 to sink A cannot be made directly, but has to go via the landfall point. Hence, the distances from onshore sinks or source clusters to offshore sinks are not included in the table.

amount of diameters available. However, the costs for selecting a diameter too small are considerably higher than selecting a diameter too large.

The capture costs include compression till 11 MPa, but higher or lower inlet pressures may be needed depending on the length and diameter of the pipeline. Initial runs showed that the energy savings or additional energy costs are minor in comparison with the other costs. Hence, these are not taken into account to simplify the modeling process.

3.5. Scenarios

Different scenarios of the case study are analyzed to assess the sensitivity of various input parameters for the perfect foresight model and the ROA. In this study, a base scenario and six variants of the base scenario are included in this study:

- (A) *Base scenario*: CO₂ can be stored onshore and offshore; the volatility of the CO₂ price is 47%; the risk adjusted drift is 3.1%; CO₂ prices increase according to the 450 ppmv

Table 5

Breakeven CO₂ prices (P_c^*) in €/t for the different sources with a point-to-pipeline to the cheapest sink possibility with the NPV and ROA. Breakeven years are calculated with the projected CO₂ price in the 450 ppmv scenario.

Source	Onshore and offshore sinks available					Only offshore sinks available				
	Sink	ROA		NPV		Sink	ROA		NPV	
		P_c^*	Year	P_c^*	Year		P_c^*	Year	P_c^*	Year
1	F	100	2043	35	2024	C	119	>2050	42	2026
2	D	116	>2050	43	2026	B	196	>2050	74	2032
3	D	84	2034	32	2023	B	257	>2050	99	2042
4	D	191	>2050	68	2030	B	219	>2050	79	2033
5	D	151	>2050	57	2029	B	410	>2050	158	>2050
6	D	137	>2050	50	2027	B	169	>2050	62	2030
7	D	226	>2050	81	2034	B	280	>2050	103	2044
8	F	99	2042	36	2024	C	116	>2050	43	2026
9	D	320	>2050	114	>2050	B	697	>2050	262	2104

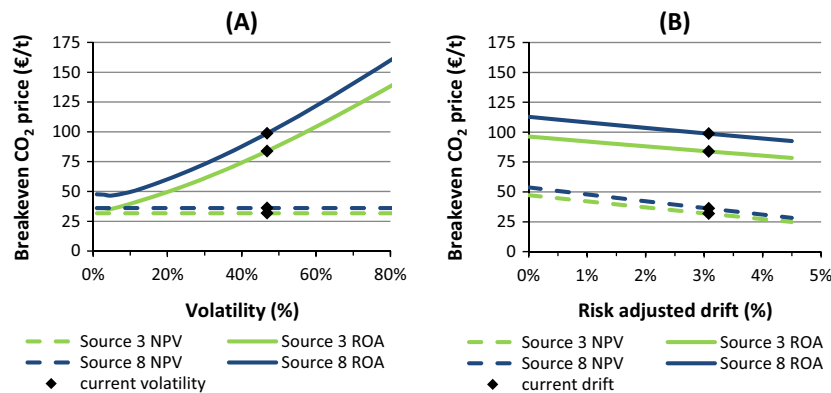


Fig. 4. The breakeven CO₂ prices for two different sources to an onshore sink in relation to (A) volatility and (B) risk adjusted drift.

scenario; the willingness of joining is 75% for large sources (>1 Mt/y) and 100% for small sources; and the probability of joining is 75% for all sources.

- (B) *Only offshore*: CO₂ can only be stored offshore.
- (C) *Lower capture costs*: the initial investment as well as the variable costs for CO₂ capture are 30% lower.
- (D) *Lower volatility*: the volatility of the CO₂ price is assumed to be 50% lower than in the base scenario.⁵
- (E) *Higher joining*: the probability and willingness of joining is set on 100% for all sources, meaning that if a source start with CCS, the source will join the network.
- (F) *Optimistic onshore*: the capture cost decrease with 30%, volatility is 50% lower and the probability and willingness of joining is 100% for all sources (combination of scenario A, C, D and E).
- (G) *Optimistic offshore*: same as optimistic onshore, but only the offshore sinks are available (combination of scenario B, C, D and E).

4. Results

4.1. To invest or not to invest in CCS

In Table 5, breakeven CO₂ prices and years (based on the 450 ppmv scenario) are given for the NPV and ROA based on a point-to-point pipeline to the cheapest sink possibility. All sources prefer an onshore sink, if possible. If CO₂ storage onshore is not allowed, the breakeven CO₂ prices increase with 15–210%. Especially, the breakeven CO₂ prices for the smaller sources increase

considerably. The main reasons for this are the larger share of transportation costs in the overall cost and the larger influence of the fixed offshore transportation costs of 35 M€₂₀₁₀ for smaller sources, combined with the fact that the nearest offshore sink is farther away than the nearest onshore sink.

Furthermore, the results in Table 5 indicate that the breakeven CO₂ prices for the ROA are almost three times as high compared to the NPV approach. In Fig. 4, the influence of a different volatility and risk adjusted drift on the breakeven CO₂ price is assessed for sources 3 and 8. From Fig. 4A, it can be seen that if the volatility decreases, for instance, with 50–23%, the breakeven price from source 8 decreases with 35% to 64 €/t. This would mean that the breakeven year to invest is sooner (2030 instead of 2042). Note that there is still a difference in the breakeven price between the NPV and the ROA if the volatility approaches zero.⁶ For instance, for source 8 the breakeven price is 47 €/t with a volatility of 5%, which is about 30% higher than the breakeven price of 36 €/t in the NPV approach. The reason for this is that even without uncertainty in the CO₂ price, it is still valuable to wait because the CO₂ prices are expected to increase with about 3% per year.

If the CO₂ price is expected to grow at a lower rate (or even not at all, i.e., $\alpha = 0$), the expected revenues for the CCS unit would be lower and the required breakeven price to stimulate CCS investment would be higher for the ROA and the NPV method (Fig. 4B). For instance, if the risk adjusted drift would increase with 50%, the breakeven price decreases for source 8 with 13% to 86 €/t and the breakeven year becomes 2035 instead of 2042. Hence,

⁵ The resulting volatility of 23.4% is comparable to the volatility of oil (21%) and, to lesser extent to, natural gas (33%), measured in October 2014 [71].

⁶ With a very low volatility, the risk free probability of a decrease becomes negative. To avoid this, the time step is decreased in such a way that the risk free probability is zero. The smaller time step leads to a slight increase in the breakeven CO₂ price, which is visible in Fig. 4.

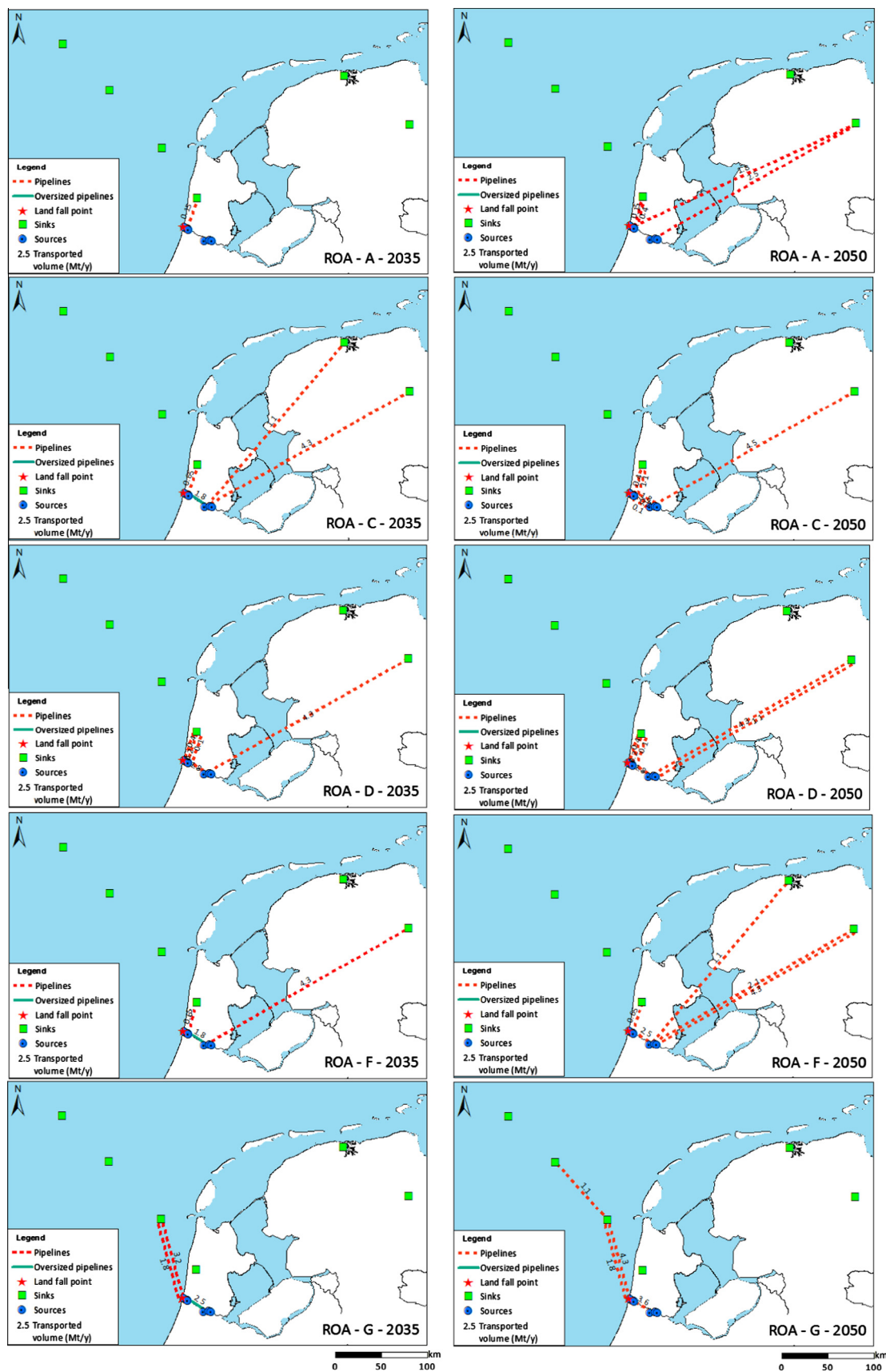


Fig. 5. Resulting layouts from the ROA and PF model in 2035 and 2050, (A) for the base scenario, (B) for the only offshore storage scenario, (C) for the lower capture costs scenario, (D) for the lower volatility, (F) for the optimistic onshore, and (G) for the optimistic offshore scenario. Oversized is defined as a pipeline with a smaller diameter can also handle the transported volume. Note that not for every ROA and PF scenario a layout is given because no infrastructure development take place or they are comparable to other scenarios.

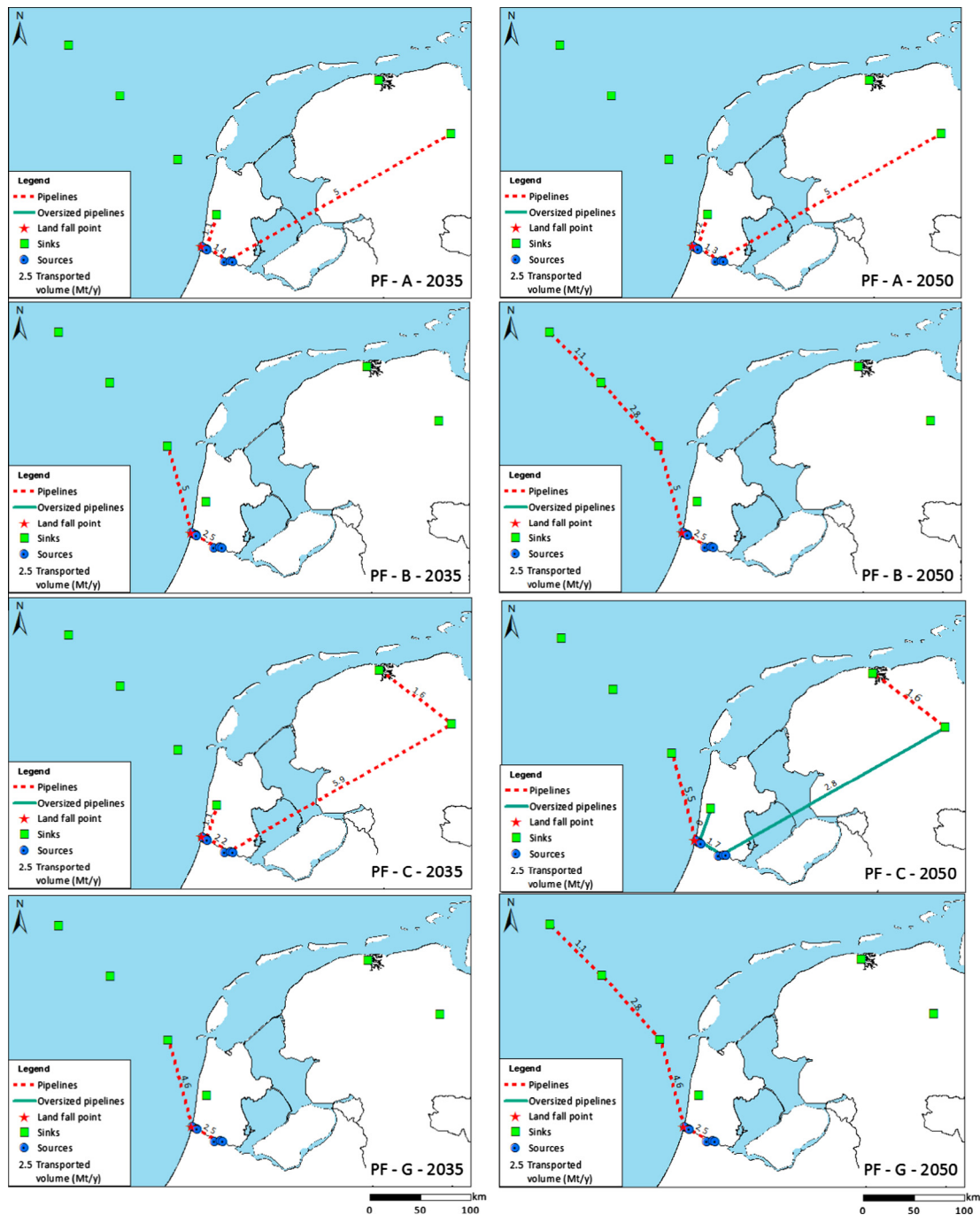


Fig. 5 (continued)

volatility has a stronger influence on the breakeven price and year than the risk adjusted drift.

4.2. Infrastructure development

In Fig. 5, the layouts of the infrastructure development over time for the ROA and the PF are given for the different scenarios. Five layouts are not pictured for various reasons. The layout of the only offshore ROA scenario is not shown here because in this scenario no pipelines are constructed until 2050. Furthermore, the layout of the higher joining ROA scenario is not given because it is very similar to the ROA base scenario. The only difference is that, in the higher joining scenario in 2050, one pipeline is constructed to sink D instead of two point-to-point pipelines. In

addition, a lower volatility or a higher joining probability has no effect on the layout or costs of the infrastructure in the PF model. Hence, these scenarios are not shown in this article as the lower volatility and higher joining PF scenarios are similar to the PF base scenario while the optimistic onshore PF scenario is similar to the lower capture cost PF scenario.

Three main observations can be made from comparing the projections of the PF and the ROA. Firstly, the development of a CO₂ infrastructure network is projected to start 5–10 years later in the ROA scenarios compared to the corresponding PF scenarios. In addition, more sources start with CCS and are connected to the CO₂ infrastructure network in the PF model, where consequently also more sinks are used. For example, all nine sources have CCS in the lower capture cost PF scenario in

Table 6Costs and amount of CO₂ stored for the different scenarios analyzed in this study with the PF model and ROA.^a

		Cumulative amount of CO ₂ stored (Mt)			Cum. investment and variable costs (M€)			Cum. transport & storage costs (M€)			Average transport & storage costs (€/t CO ₂)		
		2025	2035	2050	2025	2035	2050	2025	2035	2050	2025	2035	2050
A) Base scenario	PF	0.25	46	137	58	2283	4446	31	306	389	124 ^b	6.7	2.8
	ROA	0	0	31	0	28	1632	0	20	410	n.a.	n.a.	13
B) Only offshore	PF	0	35	109	0	1636	3561	0	299	678	n.a.	8.6	6.2
	ROA	0	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.
C) Lower capture costs	PF	14	79	202	957	2792	5657	319	455	848	22	5.8	4.2
	ROA	0	2.5	84	0	625	2355	0	237	382	n.a.	95 ^b	4.5
D) Lower volatility	ROA	0	18	96	0	1394	3730	0	428	726	n.a.	24	7.5
E) Higher joining	ROA	0	0	31	0	28	1522	0	20	300	n.a.	n.a.	9.7
F) Optimistic onshore	ROA	0	33	132	0	1617	4321	0	410	694	n.a.	12	5.3
G) Optimistic offshore	PF	0	46	114	0	1338	2716	226	299	674	n.a.	6.6	5.9
	ROA	0	22	112	0	1533	3779	0	464	814	n.a.	21	7.3

^a No results from the PF model are given for the lower volatility and higher joining scenario, because these are similar to the base scenario. Likewise, the optimistic and the lower capture cost PF scenario are comparable.

^b These very high average transport and storage costs are caused by significant investments conducted just before the indicated year, combined with the limited amount of CO₂ stored. This also explains the large drop in the average transport and storage costs of the next period.

2050, against six sources in the ROA. Four different sinks are used in the lower capture cost PF scenario, and almost 60% of the overall storage capacity is used in 2050 and almost 80% in 2060. In the optimistic offshore PF scenario, 70% and 100% of all available storage capacity is occupied in 2050 and 2060, respectively. Hence, the storage capacity available limits the timing and number of sources that can join the network in the optimistic offshore PF scenario.

Secondly, most pipelines that are constructed with the ROA are point-to-point pipelines with a limited capacity. In most cases, the financial risk of not earning back the additional investment costs for trunklines is too large in the ROA and point-to-point pipelines are constructed instead. Trunklines are present in the lower capture costs (C), lower volatility (D), higher joining (E), optimistic onshore (F) and optimistic offshore (G) ROA scenarios. Only a few of these trunklines are oversized in the ROA, see Fig. 5. In this study, oversized is defined as a pipeline transporting a volume that can also be handled by a pipeline with a diameter one size smaller. It is observed that after an oversized pipeline is constructed, it is almost immediately joined by other sources, especially smaller ones. An exception is the oversized pipeline between the two source clusters in the optimistic onshore ROA scenario in 2035 (see Fig. 5). This pipeline is constructed in 2028 with the expectation that sources 2 and 5 would join the trunkline within two years. However, for these sources it is more cost-effective to join the other trunkline. Consequently, only 18 years after construction, the pipeline capacity is fully utilized. This example illustrates that some pipelines were not correctly sized, which is a consequence of designing a pipeline network under uncertainty.

In contrast to the ROA, in the PF model none of the pipelines transports CO₂ originated from only one source. Although it is not visible on the maps, pipelines are more frequently oversized in the PF model than in the ROA.

Finally, parallel pipelines are projected in multiple ROA scenarios, but not in the PF scenarios.⁷ For instance, two parallel pipelines are projected to be constructed from the landfall point to sink C in the optimistic offshore scenario of the ROA. Although enough spare capacity is left in the trunkline, it was more cost-effective for source 1 to construct an own pipeline than joining the trunkline. To make joining cost-effective, the tariff has to decrease with 40%, which is

comparable with a RRR of 8.6% instead of 16%. Another reason for constructing parallel pipelines is that not enough spare capacity is left in the existing pipeline. This was, for instance, the case with the second pipeline constructed to sink D in 2050 in the ROA base scenario. The first source constructs a point-to-point pipeline to sink D because the probability that a trunkline had a lower NPV than the point-to-point pipeline was too high (>54%). Overall, parallel pipelines are constructed in the ROA due to a) the relatively conservatively oversizing strategy and b) too high tariffs for especially large scale sources.

In Table 6, the costs of the different layouts and the amount of CO₂ stored in each scenario are given. Considerably less CO₂ is stored in the ROA compared to the PF scenarios. For instance, in the base scenario in 2050, almost 140 Mt CO₂ is projected to be (cumulative) captured in the PF compared to only 31 Mt in the ROA. The difference becomes smaller in the scenarios C (lower capture costs), D (lower volatility) and F (optimistic onshore). However, the difference between the two approaches is still 30–60%. Only in the optimistic offshore scenario, a similar amount of CO₂ is stored. This is caused by the lack of available storage capacity in the offshore PF scenario.

With respect to the average transport and storage costs, these are over 350% higher in the base scenario of the ROA than in the PF model in 2050 (see Table 6). The difference in average transportation and storage costs between the two approaches is smaller, with 160% in the lower volatility; 30% in the optimistic onshore and 7% in the lower capture costs scenario. The difference is considerably smaller in the lower capture costs and optimistic onshore scenario because an expensive offshore storage location needs to be made available to store the CO₂ in the PF model. In general, the transport and storage costs in the ROA are considerably higher than in the PF approach, due to the less integrated network and lower economies of scale.

5. Discussion and conclusion

In this study, the CO₂ infrastructure development was modelled with two different approaches, namely a perfect foresight (PF) and a real option approach (ROA). The PF model can be considered as the optimal future, realizing the lowest cost solution for the entire system. In contrast, the ROA incorporates explicitly uncertainty in the CO₂ price, probability that sources start with CCS and join the network, etc. Hence, the ROA reflects more the current situation, while the perfect foresight model can be a situation to strive for.

⁷ Pipelines starting from the same source cluster to the same sink (or other source cluster) are assumed to be parallel. In Fig. 5, they are drawn exaggerated separately from each other for clarity reasons. In reality, it is very likely that these pipelines will be placed very close to each other to make use of the same right-of-way.

5.1. Considerations regarding the real option approach and perfect foresight model

Similar assumptions were made for the perfect foresight model and the ROA. However, still some differences are present. Firstly, the decision to start with CCS was based on infinite lifetime in the ROA, while in the PF model the time frame till 2060 was incorporated. A shorter lifetime in the ROA would imply that sources start even later with CCS. Secondly, in the perfect foresight model it was possible to split up a mass flow between different trunklines, while in the ROA this was not possible. Thirdly, there were more starting locations for trunklines in the perfect foresight than in the ROA scenarios. The reason for this simplification in the ROA was that the underlying data of probability and willingness of joining for different kind of trunklines is completely unknown. Hence, all trunklines are assumed to start at the source and other starting locations were not incorporated for lack of data issues and simplicity reasons. Nevertheless, valuable insights are learnt from comparing the infrastructure development with and without uncertainty.

To incorporate explicitly the uncertainties in the ROA, more input data is required than for the perfect foresight model. More specifically, data is required on the volatility of the CO₂ price, the tariff paid per tonne of CO₂ transported, possible CCS starting dates for nearby sources, and for each of these sources the probability and willingness of joining. In particular, these last parameters are difficult to quantify and relatively simplistic assumptions were made. Nonetheless, certain trends, such as more uncertainty leading to postponement of CCS investments and less and smaller trunklines, can clearly be seen.

Considering the additional data requirements and involved effort of conducting a ROA, a balance has to be found between applying the ROA instead of the more simple NPV calculation and perfect foresight model. In this study, ROA is used for two decisions. First, the moment of investment is analyzed. According to Dixit and Pindyck [23], ROA has the most added value for large initial investments, which concern an inflexible asset with large uncertainties in future revenues and costs. Second, a decision has to be made for an appropriated sized pipeline. In our opinion, additional requirements to give ROA an added value for these kinds of decisions are large economies of scale and a long time planning. Examples which would benefit from ROA include infrastructural projects (dikes, highways, bridges, etc.) and large scale technological innovations (GSM network, electric fuel stations, fiber optics, etc.). Even if there is chosen not to conduct a ROA, it has to be considered that results from the net present value calculation and perfect foresight model may be too optimistic with respect to timing, implementation rate and costs.

5.2. Summary and discussion of main results

CO₂ sources tend to postpone the decision to invest in CCS because of uncertainty. In this study, the required CO₂ price to stimulate CCS development almost triples in the ROA compared to the NPV approach. This required price is highly influenced by the volatility of the CO₂ price. For instance, with a volatility of 47% a pulverized coal power plant will start with CCS at a CO₂ price of 99 €/t, while with a volatility of 5%, this is reduced to 47 €/t. Nonetheless, this is still 30% higher than the breakeven price of 36 €/t in the NPV approach.

Consequently, as sources start later with CCS under uncertainty, less CO₂ is captured over time. Results of our case study show that 137 Mt CO₂ is projected to be captured until 2050 in the PF base scenario, in comparison with 31 Mt CO₂ in the ROA base scenario. If the volatility of the CO₂ price is reduced with 50%, 96 Mt is projected to be captured up to 2050 in the ROA. This is still about one third lower than in the PF model. With respect to the CO₂ transport

and storage infrastructure, there were clear differences between the PF model and the ROA. In the PF scenarios, trunklines are projected between the source clusters and the different sinks. None of the pipelines transport CO₂ from only one source in the PF scenarios. In the ROA, the infrastructure is mostly based on point-to-point pipelines. If trunklines are constructed, they are often only oversized with one nominal pipe size (i.e., limited oversizing). Consequently, several parallel pipelines are projected as well. In one case, a trunkline was constructed, but the spare capacity was not used. Parallel pipelines and unused spare capacity clearly indicate that pipelines can be incorrectly sized when an infrastructure is designed under large uncertainty.

There is a clear difference between the overall average transport and storage costs of the two approaches. For instance, the average CO₂ transport and storage in 2050 are over 4.5 times as high in the base scenario of the ROA (13 €/t) compared to the PF model (2.8 €/t). If the volatility is reduced with 50%, the transport and storage costs decrease to 7.5 €/t in the ROA. However, this is still 2.5 times as much as in the PF model.

Overall, uncertainty leads to a less integrated CO₂ infrastructure network with many point-to-point pipelines and limited oversized trunklines. Scenarios based on a perfect foresight model are most likely to overestimate the role of economies of scale of constructing a CO₂ infrastructure network and thereby underestimate the transport and storage costs. Furthermore, PF scenarios might overestimate the implementation rate of CCS as they do not incorporate the fact that sources postpone the decision to invest in CCS and the fact that a lack of trunklines increase the cost of CCS, especially for small CO₂ emitters.

5.3. Policy implications and recommendations

The results of this study lead to the following policy implications:

- Significant higher amounts of CO₂ are projected to be captured and stored over the investigated period with the PF model than with the ROA. Many future energy projections, like the ones of the IEA, do not take into account uncertainty. Hence, the amount of CO₂ stored (and avoided) with CCS projected with these energy projections is probably too optimistic. This implies that to reach the projected amount of CO₂ captured other measures, besides a CO₂ price, will be necessary to stimulate or force companies to start with CCS. This study shows that a 30% reduction in the capture costs has a positive effect on the implementation rate of CCS. Hence, research and development to this topic should also be stimulated.
- The required CO₂ price when companies start with CCS is highly dependent on the volatility of the CO₂ price. Even if the volatility is reduced to lower levels, the CO₂ price required to stimulate investment in CCS is higher than with the standard NPV approach. Hence, policy makers should not only focus on the level of the CO₂ price, but also on the uncertainty in the CO₂ price.
- Trunklines realize economies of scale in the transportation network and stimulate CCS development, especially of smaller sources. More trunklines are developed when there is reduced uncertainty in the probability and time frame that other sources join the CO₂ network. Hence, policy makers should stimulate cooperation between the different sources to facilitate trunkline development and, in this way, decrease the average transport and storage costs.
- If onshore CO₂ storage is not allowed, the required CO₂ prices to stimulate CCS development increase considerably, especially for smaller sources. Hence, policy makers should reconsider the prohibition of onshore CO₂ storage, which is currently regulated

in the Netherlands and Denmark. Local public opposition to CCS projects may be (partly) overcome by offering compensation to individuals or to the host community [72]. Another possibility is to compensate companies in the additional transport and storage costs to offshore instead of to onshore CO₂ storage fields.

5.4. Research recommendations

This study was a first attempt to analyze the effect of uncertainty on the development of a CO₂ infrastructure network. It can be improved by incorporating the following:

- Relatively large storage reservoirs were included in this study. Furthermore, a constrain was added that the reservoir should be capable to store the CO₂ of the source for minimal 20 years. It would be interesting to assess the influence (of a cluster) of small storage reservoirs without minimal storage requirements on the infrastructure layout.
- In this study, uncertainty was not included in every variable to limit the scope of the research. For instance, CO₂ mass flows and possible capture locations may not be constant over time because existing facilities could be closed, shrink or extend their production activities. In addition, costs were assumed to be certain and fixed over time, while in reality costs are uncertain and may decrease over time due to learning. Although learning is positive for the overall capture costs, it would also lead to more postponement because it gives companies an additional incentive to wait.
- More research is needed to come up with concrete and cost-effective policy measures, which can stimulate CCS development under uncertain conditions.
- The pipeline design in this study was based on the total amount of CO₂ transported in a year. In reality, the CO₂ flow would vary every day (or even every hour) and the pipeline design should be based on peak flows. Consequently, the pipeline would be larger and the transportation costs will be slightly higher. Furthermore, flow variations could lead to a multi-phase flow and the consequences of this for a CO₂ network are not fully understood yet. Hence, dynamic modelling of CO₂ flows deserves more attention.

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Appendix A

In this appendix, the objective function as well as the constraints are given for the perfect foresight model.

A.1. Objective function and constraints for modelling perfect foresight

The objective is maximizing the NPV of the entire system, see Eq. (11). The NPV consists of the value of the CO₂ emission allowances spared, minus the fixed and variable capture, transport and storage costs (4–10).

The maximization function is subject to various constraints. Constraints 12 and 13 are set to ensure that a reservoir can only be opened once and a capture unit can only be retrofitted once.

To ensure that maximum capacity of a given pipeline is not crossed for onshore as well as offshore pipelines, constrain 14 and 15 are added. Furthermore, three balancing constraints are set. First, all CO₂ captured at or flowing into a source node must be transported out of the node (16). Second, all CO₂ transported to a landfall point should also be transported from the landfall point (17). Third, all CO₂ flowing into a sink node must be stored or transported out of the node (18).

In addition, four constraints are set to ensure that the reservoir properties are respected. First, the amount of CO₂ stored cannot be higher than the sink capacity (19). Second, the sink has to be capable of storing the annual CO₂ amount for at least 20 years (20). Third, the injectivity per well is limited (21). Fourth, there is a maximum numbers of wells that a storage reservoir can accommodate (22).

Finally, constraints (23)–(30) are binary, integral and non-negativity constraints. The explanation of the abbreviations, decision variables, input parameters and sets is given in Table 7.

$$FC_{cap} = \sum_{i \in S} \sum_{t \in T} (F_i^s \times S_{it} \times e^{-rt}) \quad (4)$$

$$VC_{cap} = \sum_{i \in S} \sum_{t \in T} \sum_{\tau=0}^{t-1} (S_{it\tau} \times e^{-rt} \times (F_i^s \times OM_{cap} + V_i^s \times m_i)) \quad (5)$$

$$FC_{trans} = \sum_{k \in K} \sum_{d \in D} \sum_{t \in T} [(F_d^{pl} \times v_k \times L_k + F_d^{pz} \times z_k \times L_k + F^{go} \times z_k) \times y_{kdt} \times e^{-rt}] \quad (6)$$

$$VC_{trans} = \sum_{k \in K} \sum_{d \in D} \sum_{t \in T} \sum_{\tau=0}^{t-1} (y_{kdt\tau} \times OM_{trans} \times e^{-rt} \times (F_d^{pl} \times v_k \times L_k + F_d^{pz} \times z_k \times L_k + F^{go} \times z_k)) \quad (7)$$

$$FC_{store} = \sum_{j \in J} \sum_{t \in T} (F_j^{sr} \times u_{jt} + F_j^w \times w_{jt}) \times e^{-rt} \quad (8)$$

$$VC_{store} = \sum_{j \in J} \sum_{t \in T} \sum_{\tau=0}^{t-1} (F_j^{sr} \times u_{jt\tau} + F_j^w \times w_{jt\tau}) \times OM_{store} \times e^{-rt} \quad (9)$$

$$NPV_{CO_2-price} = \sum_{i \in S} \sum_{t \in T} \sum_{\tau=0}^{t-1} (a_i \times S_{it\tau} \times P_t \times e^{-rt}) \quad (10)$$

$$\text{Maximize : } NPV_{CO_2-price} - (FC_{cap} + VC_{cap} + FC_{trans} + FC_{trans} + VC_{trans} + FC_{store} + VC_{store}) \quad (11)$$

Subject to:

$$\sum_{\tau=0}^{t-1} u_{jt\tau} \leq 1 \quad \forall j \in J; \forall t \in T \quad (12)$$

$$\sum_{\tau=0}^{t-1} S_{it\tau} \leq \quad \forall i \in S; \forall t \in T \quad (13)$$

$$x_{ijt} \times v_k \leq \sum_{d \in D} \sum_{\tau=0}^{t-1} y_{kdt\tau} \times Q_d^{vp} \quad \forall t \in T; \forall k \in K \quad (14)$$

$$x_{ijt} \times z_k \leq \sum_{d \in D} \sum_{\tau=0}^{t-1} y_{kdt\tau} \times Q_d^{zp} \quad \forall t \in T; \forall k \in K \quad (15)$$

$$\sum_{j \in N_i} x_{jit} - \sum_{j \in N_i} x_{jit} = \sum_{\tau=0}^{t-1} S_{it\tau} \times m_i \quad \forall i \in S; \forall t \in T \quad (16)$$

Table 7

Decision variables, input parameters and sets for the perfect foresight case.

		Unit
Decision variables		
y_{kdt}	1, if a pipeline is built using arc k with diameter d in period t 0, otherwise	
s_{it}	1, if a capture unit is added to source i in period t 0, otherwise	
u_{jt}	1, if reservoir j is opened in period t 0, otherwise	
v_k	1, if a pipeline using arc k is onshore 0, otherwise	
z_k	1, if a pipeline using arc k is offshore 0, otherwise	
w_{jt}	Number of wells constructed at reservoir j in period t	
x_{ijt}	Annual amount of CO ₂ transported from i to j during period t	kt CO ₂ /y
b_{jt}	Amount of CO ₂ stored in reservoir j during period t	kt CO ₂ /y
Inputs		
$F^s, F^{pl}, F^{pz}, F^{so}, F^{sr}, F^w$	Fixed costs for constructing a CO ₂ capture installation at the source (^s), constructing a pipeline onshore (^{pl}), constructing a pipeline offshore (^{pz}), making an onshore–offshore connection (^{so}), opening a storage reservoir (^{sr}), and constructing a well (^w)	k€
$VC_{cap}, VC_{trans}, VC_{store}$	Variable costs for CO ₂ capture (_{cap}), transport (_{trans}) and storage (_{store})	k€
$FC_{cap}, FC_{trans}, FC_{store}$	Fixed costs for CO ₂ capture (_{cap}), transport (_{trans}) and storage (_{store})	k€
$NPV_{CO_2-price}$	Net present value of the CO ₂ emission allowances spared	k€
L_k	Pipeline length of a given arc	km
V_i^s	Variable costs for capturing CO ₂ from source i	€/t
$OM_{cap}, OM_{trans}, OM_{store}$	O&M costs for capturing (_{cap}), transporting (_{trans}) and storing (_{store}) CO ₂ as percentage of the investment costs	%
Q^{vp}, Q^{zp}, Q^w	Maximum capacity of a given onshore (^{vp}) or offshore pipeline (^{zp}), and maximum capacity of a well (^w)	kt CO ₂ /y
Q^r	Maximum capacity of a reservoir (^r)	Mt CO ₂
p^w	Maximum number of wells at each reservoir site	
m_i	Amount of CO ₂ captured at source i	kt CO ₂ /y
a_i	Amount of allowances that do not have to be bought if CCS is applied at source i	kt CO ₂ /y
r	Discount rate (=10%)	%
τ	τ is used for summing over time periods	y
P_t	CO ₂ price in time t	€/t CO ₂
Lifetime	Minimum lifetime of the CCS project (=20 years)	y
Sets		
I, K, S, J, L, T	Set of all nodes, candidate arcs (links between the nodes), sources, reservoirs, landfall points and time periods	
D	Set of maximum pipeline capacities of all discrete diameters	
N_i	Set of nodes adjacent to node i	

$$\sum_{j \in N_i} x_{ijt} - \sum_{j \in N_i} x_{jlt} = 0 \quad \forall i \in I; \forall t \in T \quad (17) \quad s_{it} \in 0, 1 \quad \forall i \in S; \forall t \in T \quad (24)$$

$$\sum_{j \in N_j} x_{ijt} - \sum_{j \in N_j} x_{jit} = \sum_{j \in J} b_{jt} \quad \forall j \in J; \forall t \in T \quad (18) \quad u_{jt} \in 0, 1 \quad \forall j \in J; \forall t \in T \quad (25)$$

$$\sum_{t \in T} b_{jt} / 10^3 \leq \sum_{\tau=0}^{t-1} u_{j\tau} \times Q^r \quad \forall j \in J \quad (19) \quad w_{jt} \in 0, 1, \dots, P_j^w \quad \forall j \in J; \forall t \in T \quad (26)$$

$$b_{jt} / 10^3 \times lifetime \leq \sum_{\tau=0}^{t-1} u_{j\tau} \times Q^r \quad \forall j \in J; \forall t \in T \quad (20) \quad v_k \in 0, 1 \quad \forall k \in K \quad (27)$$

$$b_{jt} \leq \sum_{\tau=0}^{t-1} w_{j\tau} \times Q^w \quad \forall j \in J; \forall t \in T \quad (21) \quad z_k \in 0, 1 \quad \forall k \in K \quad (28)$$

$$\sum_{\tau=0}^{t-1} w_{j\tau} \leq P_j^w \quad \forall j \in J; \forall t \in T \quad (22) \quad x_{ijt} \geq 0 \quad \forall i \in I; \forall j \in N_i; \forall t \in T \quad (29)$$

$$y_{kdt} \in 0, 1 \quad \forall k \in K; \forall d \in D; \forall t \in T \quad (23) \quad b_{jt} \geq 0 \quad \forall j \in J; \forall t \in T \quad (30)$$

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apenergy.2015.08.024>.

References

- [1] Moomaw W, Yamba F, Kamimoto M, Maurice L, Nyboer J, Urama K, et al. Renewable energy and climate change. In: Edenhofer O, Madruga RP, Sokona Y, editors. IPCC special report on renewable energy sources and climate change mitigation. Cambridge, United Kingdom and New York, USA: Cambridge University Press; 2011. p. 1–68.
- [2] IEA. World energy outlook 2010. Paris, France: Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA); 2010.
- [3] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A roadmap for moving to a competitive low carbon economy in 2050. COM (2011) 112 final; 2011. p. 1–16.
- [4] IEA. Technology Roadmap. Carbon capture and storage. Paris, France: IEA publications; 2010.
- [5] Benson SM, Bennaceur K, Cook P, Davison J, de Coninck H, Farhat K, et al. Carbon capture and storage. In: Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L, editors. Global Energy Assessment (GEA). Towards a sustainable future. Cambridge UK and New York, NY, USA: Cambridge University Press; 2012. International Institute for Applied Systems Analysis, Laxenburg, Austria, Chapter 13. p. 993–1068.
- [6] Dahowski RT, Dooley JJ, Davidson CL, Bachu S, Gupta N. A CO₂ storage supply curve for North America; 2004. PNWD-3471. p. 1–92.
- [7] Dahowski RT, Li X, Davidson CL, Wei N, Dooley JJ. Regional opportunities for carbon dioxide capture and storage in China. A comprehensive CO₂ storage cost curve and analysis of the potential for large scale carbon dioxide capture and storage in the people's Republic of China. Prepared for the U.S. Department of Energy; 2009. PNNL-19091. p. 1–85.
- [8] Middleton RS, Bielicki JM. A scalable infrastructure model for carbon capture and storage: SimCCS. *Energy Policy* 2009;37:1052–60.
- [9] Weihs GA, Fimbres, Wiley DE. Steady-state design of CO₂ pipeline networks for minimal cost per tonne of CO₂ avoided. *Int J Greenhouse Gas Control* 2012;8:150–68.
- [10] Sun L, Chen W. The improved ChinaCCS decision support system: a case study for Beijing–Tianjin–Hebei Region of China. *Appl Energy* 2013;112:793–9.
- [11] ElementEnergy. CO₂ pipeline infrastructure: an analysis of global challenges and opportunities. IEA GHG; 2010. p. 1–134.
- [12] Van den Broek M, Brederode E, Ramírez A, Kramers L, van der Kuip M, Wildenberg T, et al. Designing a cost-effective CO₂ storage infrastructure using a GIS based linear optimization energy model. *Environ Modell Softw* 2010;25:1754–68.
- [13] Van den Broek M, Ramírez A, Groenenberg H, Neele F, Viebahn P, Turkenburg W, et al. Feasibility of storing CO₂ in the Utsira formation as part of a long term Dutch CCS strategy: an evaluation based on a GIS/MARKAL toolbox. *Int J Greenhouse Gas Control* 2010;4:351–66.
- [14] Piessens K, Welkenhuysen K, Laenen B, Ferket H, Nijs W, Duerinck J, et al. Policy support system for carbon capture and storage and collaboration between Belgium – The Netherlands – “PSS-CCS”. Final report ed. Brussels: Belgian Science Policy; 2012.
- [15] Piessens K, Laenen B, Nijs W, Mathieu P, Bael JM, Hendriks C, et al. Policy support system for carbon capture and storage; 2008. SD/CP/04A. p. 1–269.
- [16] Morbee J, Serpa J, Tzimas E. Optimised deployment of a European CO₂ transport network. *Int J Greenhouse Gas Control* 2012;7:48–61.
- [17] Middleton RS, Kuby MJ, Wei R, Keating GN, Pawar RJ. A dynamic model for optimally phasing in CO₂ capture and storage infrastructure. *Environ Modell Softw* 2012;37:193–205.
- [18] Oei P, Herold J, Mendelevitch R. Modeling a carbon capture, transport, and storage infrastructure for Europe. *Environ Model Assess* 2014;19: 515–31.
- [19] Middleton RS, Keating GN, Viswanathan HS, Stauffer PH, Pawar RJ. Effects of geologic reservoir uncertainty on CO₂ transport and storage infrastructure. *Int J Greenhouse Gas Control* 2012;8:132–42.
- [20] Chandel MK, Pratson LF, Williams E. Potential economies of scale in CO₂ transport through use of a trunk pipeline. *Energy Convers Manage* 2010;51:2825–34.
- [21] Mikunda T, Van Deurzen J, Seebregts A, Kerssemakers K, Tetteroo M, Buit L. Towards a CO₂ infrastructure in North-Western Europe: legalities, costs and organizational aspects. *Energy Proc* 2011;4:2409–16.
- [22] Mikunda T, van Deurzen J, Seebregts A, Tetteroo M, Kersemakers K, Apeland S. Towards a transport infrastructure for large-scale CCS in Europe. Legal, financial and organizational aspects of CO₂ pipeline infrastructures. CO₂ Europe; 2011. D3.3.1:1–48.
- [23] Dixit AK, Pindyck RS. Investment under uncertainty. New Jersey, U.S.A.: Princeton University Press; 1994.
- [24] Hull JC. Options, futures, and other derivative securities. 2nd ed. New Jersey, U.S.A.: Princeton University Press; 1993.
- [25] Reinelt PS, Keith DW. Carbon capture retrofits and the cost of regulatory uncertainty. *Energy J* 2007;28:101–27.
- [26] Szolgayova J, Fuss S, Obersteiner M. Assessing the effects of CO₂ price caps on electricity investments – a real options analysis. *Energy Policy* 2008;36:3974–81.
- [27] Zhu L, Fan Y. A real options-based CCS investment evaluation model: case study of China's power generation sector. *Appl Energy* 2011;88:4320–33.
- [28] Zhang X, Wang X, Chen J, Xie X, Wang K, Wei Y. A novel modeling based real option approach for CCS investment evaluation under multiple uncertainties. *Appl Energy* 2014;113:1059–67.
- [29] Abadie LM, Chamorro JM. European CO₂ prices and carbon capture investments. *Energy Econ* 2008;30:2992–3015.
- [30] Cardin M, Ranjbar-Bourani M, De Neufville R. Improving the lifecycle performance of engineering projects with flexible strategies: example of on-shore LNG production design. *Syst Eng* 2015;18:253–68.
- [31] de Neufville R. Flexibility in engineering design. Using flexibility to creating value. In: CRAG-IRGC symposium; 2013.
- [32] de Neufville R, Scholtes S, Wang T. Real options by spreadsheet: parking garage case example. *J Infrastruct Syst* 2006;12:107–11.
- [33] Knoop MMJ, Guijt W, Ramírez A, Faaij APC. Improved cost models for optimizing CO₂ pipeline configurations for point-to-point pipelines and simple networks. *Int J Greenhouse Gas Control* 2014;22:25–46.
- [34] Heydari S, Ovenden N, Siddiqui A. Real options analysis of investment in carbon capture and sequestration technology. *Comput Manage Sci* 2012;9:109–38.
- [35] Fuss S, Szolgayova J, Obersteiner M, Gusti M. Investment under market and climate policy uncertainty. *Appl Energy* 2008;85:708–21.
- [36] Sarkis J, Tamarkin M. Real options analysis for “Green Trading”: the case of greenhouse gases. *Eng Econ: J Devoted Problems Capital Invest* 2005;50:273–94.
- [37] Kato M, Zhou Y. A basic study of optimal investment of power sources considering environmental measures: economic evaluation of CCS through a real option approach. *Electr Eng Jpn* 2011;174:9–16.
- [38] Energy Information Administration. Energy policy act transportation study: interim report on natural gas flows and rates; 1995. DOE/EIA-0602(95):1–139.
- [39] Hacura A, Jadamas-Hacura M, Kocot A. Risk analysis in investment appraisal based on the Monte Carlo simulation technique. *Eur Phys J B* 2001;20:551–3.
- [40] Van den Broek M, Faaij A, Turkenburg W. Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. *Int J Greenhouse Gas Control* 2008;2:105–29.
- [41] Kuby MJ, Bielicki JM, Middleton RS. Optimal spatial deployment of CO₂ capture and storage given a price on carbon. *Int Regional Sci Rev* 2011;34:285–305.
- [42] AMPL. AMPL. Streamlined modelling for real optimization; 2014.
- [43] IBM ILOG. IBM ILOG CPLEX Optimization Studio V12.6.1 Documentation; 2015.
- [44] IEA. World energy outlook 2013. Paris, France: Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA); 2013.
- [45] IEA. Energy Technology Perspective 2012. Paris, France: Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA); 2012.
- [46] Chladná Z, Chladný M, Möllersten K, Obersteiner M. Investment under multiple uncertainties: the case of future pulp and paper mills. Interim report of the International Institute for applied systems analysis; 2004. IR-04-077:1–53.
- [47] Ho SP, Liu LY. An option pricing-based model for evaluating the financial viability of privatized infrastructure projects. *Constr Manage Econ* 2002;20:143–56.
- [48] Koller T, Goedhart M, Wessels D. Valuation. Measuring and managing the value of companies. John Wiley & Sons, inc.: New Jersey, USA; 2010.
- [49] Kuramochi T, Ramírez A, Turkenburg W, Faaij A. Comparative assessment of CO₂ capture technologies for carbon-intensive industrial processes. *Prog Energy Combust* 2012;38:87–112.
- [50] Zhou W, Zhu B, Fuss S, Szolgayová J, Obersteiner M, Fei W. Uncertainty modeling of CCS investment strategy in China's power sector. *Appl Energy* 2010;87:2392–400.
- [51] Abadie LM, Galarra I, Rübbecke D. Evaluation of two alternative carbon capture and storage technologies: a stochastic model. *Environ Modell Softw* 2014;54:182–95.
- [52] Oda J, Akimoto K. An analysis of CCS investment under uncertainty. *Energy Proc* 2011;4:1997–2004.
- [53] Natural Gas Supply Association. Pipeline cost recovery report. 32 Major pipelines; 2005–2009. p. 1–142.
- [54] Chemical Engineering. Chemical plant cost index (CEPCI); 2013.
- [55] OANDA. Historical exchange rates. OANDA; 2014.
- [56] Energy and Environment Analysis. Characterization of the U.S. industrial/commercial boiler population. Prepared for Oak Ridge National Laboratory; 2005. p. 1–65.
- [57] Kuramochi T, Ramírez A, Faaij A, Turkenburg W. Prospects for cost-effective post-combustion CO₂ capture from industrial CHPs. *Int J Greenhouse Gas Control* 2010;4:511–24.
- [58] Kuramochi T, Ramírez A, Turkenburg W, Faaij A. Techno-economic prospects for CO₂ capture from distributed energy systems. *Renew Sust Energy Rev* 2013;19:328–47.
- [59] Hendriks C, Graus W, Van Bergen F. Global carbon dioxide storage potential and costs. Prepared by Ecofys and TNO by order of the Rijksinstituut voor Volksgezondheid en Milieu; 2004. EEP-02001:1–59.
- [60] ZEP. The costs of CO₂ Capture. Post-demonstration CCS in the EU; 2011. p. 1–81.
- [61] Hektor E, Berntsson T. Future CO₂ removal from pulp mills – process integration consequences. *Energy Convers Manage* 2007;48:3025–33.
- [62] Johnke B. Emissions from waste incinerations. In: Intergovernmental Panel on Climate Change, editor. Background papers. IPCC experts meetings on good practice guidance and uncertainty management in national greenhouse gas inventories. Japan: Institute for Global Environmental Strategies (IGES); 2002. p. 455–468.
- [63] Switzer L, Rosen L, Thompson D, Sirman J, Howard H, Bool L. Cost and feasibility study on the Praxair advanced boiler for the CO₂ capture project's

- refinery scenario. In: Thomas DC, editor. Carbon dioxide capture for storage in deep geological formations – results from the CO₂ capture project. Capture and sequestration of carbon dioxide from combustion sources. The Netherlands: Elsevier Ltd.; 2005. p. 561–79.
- [64] Christensen NP, Holloway S. Geological storage of CO₂ from combustion of fossil fuel. 2nd ed., The GESTCO project. Summary report. European Union Fifth Framework Programme for Research and Development; 2004. p. 1–32.
- [65] Neele F. CATO2 sink database; 2013.
- [66] Neele F, ten Veen J, Wilschut F, Hofstee C. Independent assessment of high-capacity offshore CO₂ storage options. TNO report 2012. TNO-060-UT-2012-00414/B. p. 1–93.
- [67] Neele F. Personal communication about CO₂ storage in aquifers and hydrocarbon fields in the Netherlands; 2014.
- [68] Verweij JM, Simmelink HJ, Van Balen RT, David P. History of petroleum systems in the southern part of the Broad Fourteens Basin. *Neth J Geosci* 2003;82:71–90.
- [69] Brown DR, Humphreys KK, Vail LW. Carbon dioxide control costs for gasification combined-cycle plants in the United States. Prepared for the U.S. Department of Energy; 1993. PNL-SA-22634:1–94.
- [70] Knoop MMJ, Raben I, Spruijt M, Ramírez A, Faaij APC. The influence of risk mitigation measures on the risk contours, costs and routing of CO₂ pipelines. *Int J Greenhouse Gas Control* 2014;29:104–24.
- [71] Energy Information Administration. Short-term energy outlook market prices and uncertainty report. Independent Statistics & Analysis; 2014 October 1–11.
- [72] ter Mors E, Terwel BW, Daamen DDL. The potential of host community compensation in facility siting. *Int J Greenhouse Gas Control* 2012;11 (Supplement):S130–8.