

# Unravelling uncertainty and variability in early stage techno-economic assessments of carbon capture technologies



Mijndert van der Spek<sup>a,\*</sup>, Eva Sanchez Fernandez<sup>b</sup>, Nils Henrik Eldrup<sup>c</sup>,  
Ragnhild Skagestad<sup>c</sup>, Andrea Ramirez<sup>a</sup>, André Faaij<sup>d</sup>

<sup>a</sup> Copernicus Institute of Sustainable Development, Section Energy & Resources, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

<sup>b</sup> Institute of Mechanical, Process, and Energy Engineering, Heriot Watt University, EH14 4AS Edinburgh, UK

<sup>c</sup> Tel-Tek, Kjølnes Ring 30, 3918 Porsgrunn, Norway

<sup>d</sup> Energy and Sustainability Research Institute, University of Groningen, Blauwborgje 6, 9747 AC Groningen, The Netherlands

## ARTICLE INFO

### Article history:

Received 2 May 2016

Received in revised form 4 November 2016

Accepted 16 November 2016

Available online 8 December 2016

### Keywords:

Early stage techno-economic assessment

Carbon capture and storage

AMP/PZ

Pedigree analysis

Uncertainty analysis

Feasibility study

Advanced amines

## ABSTRACT

This paper addresses the uncertainty and variability in techno-economic studies of carbon capture technologies, based on a detailed comparison of the results of different studies on postcombustion CO<sub>2</sub> capture with advanced amines, and on an in-depth uncertainty analysis using a combination of sensitivity and pedigree analyses. The results show that despite efforts to harmonize capital cost estimates, the capital cost results of the same PCC carbon capture systems can still show large (65%) differences. This uncertainty may simply be inherent to early stage cost estimates. Amongst the most important causes for the variability shown in this work are differences in equipment sizing methods and purchased equipment cost estimates. This capital cost variability only mildly propagates into the Levelised Cost of Electricity and Cost of CO<sub>2</sub> Avoided, more so in case of low power plant utilisation scenarios. To enhance insight into these uncertainties and enable their communication, the paper argues to use in-depth uncertainty evaluation for early stage techno-economic studies. It suggests to complement current practice of sensitivity analysis with pedigree analysis and to combine the results of both analyses in diagnostic diagrams. This may lead to more informed interpretation of the results of techno-economic studies, and helps focus techno-economic research efforts towards the parameters that most influence final performance indicators.

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## 1. Introduction

CO<sub>2</sub> Capture and Storage (CCS) is considered an effective and necessary option to mitigate anthropogenic CO<sub>2</sub> emissions from power generation and industrial sources (Metz et al., 2005; IPCC, 2014). CCS significantly reduces the CO<sub>2</sub> emissions of a power plant but comes at the expense of lower power plant efficiency and thus higher electricity prices (Rubin et al., 2015). To minimize these drawbacks, in the past two decades there has been an ongoing search for new and more efficient CO<sub>2</sub> capture technologies (e.g., Figueroa et al., 2008; Rubin et al., 2012). Amongst the most frequently studied carbon capture technologies are postcombustion CO<sub>2</sub> capture (PCC) solvents, of which Monoethanolamine is a common benchmark (Cullinane and Rochelle, 2005; Hilliard, 2008; Cesar, 2011; Versteeg and Rubin, 2011; Zhao et al., 2013).

Techno-economic studies are a means to assess and compare the feasibility of these new carbon capture technologies. These studies are used by a large audience including governmental organisations, industry, and NGO's (Rubin et al., 2013). Given the importance of these uses, techno-economic studies should have a sufficient level of reliability and comparability.

To facilitate the production of reliable and comparable (CCS) cost estimates, many textbooks on cost engineering are available (e.g. Gerrard, 2000; Towler and Sinnott, 2013), as well as specific studies/guidelines on the topic of CCS technology costing (NETL, 2010; Rubin et al., 2013; IEAGHG, 2014). Given the large body of knowledge on techno-economic studies, and the efforts that have been made to streamline the way we assess the costs of CCS technologies (Rubin, 2012; Rubin et al., 2013), it is expected that results of studies on the same technologies would be comparable. However, as we will show in this paper, even when following prescribed costing methods, results can vary significantly, raising questions on their reliability. This observation implies that there is still residual, and possibly inherent, uncertainty in early stage costing studies of CCS

\* Corresponding author.

E-mail address: [m.w.vanderspek@uu.nl](mailto:m.w.vanderspek@uu.nl) (M. van der Spek).

technologies, which makes their interpretation and use all the more challenging.

Acknowledging the presence of large uncertainties in early stage cost estimates, this work aims to present an approach to tackle these uncertainties; not by reducing them, but by providing an enhanced understanding of the uncertainty and quality of the cost study. This should help users to better interpret the results of techno-economic studies, and to form an opinion on their reliability and comparability.

To this end, this paper will (1) quantify and assess differences and causes of uncertainty and variability using two case studies; and (2) show how a combination of sensitivity analysis (quantitative uncertainty analysis) and pedigree analysis (qualitative uncertainty analysis) can improve our understanding of the inherent uncertainties of a cost estimate.

## 2. Methods

To identify and assess the (causes of) uncertainties in early stage cost estimates of carbon capture technologies, we used the following approach: first, we selected two different studies that investigate the techno-economic performance of postcombustion carbon capture (PCC) with the same advanced amine (an AMP/piperazine blend). The selected studies were retrieved from the European Benchmarking Taskforce (EBTF) (Sanchez Fernandez et al., 2014; Manzolini et al., 2015) and from the EDDiCUT consortium (Singh et al., 2016; Van der Spek et al., 2016a). They are based on exactly the same flue gas flow rate and composition. From here onwards, the EBTF PCC study is called *study 1* and the EDDiCUT study is called *study 2*. Detailed comparisons were done of the differences in technical performance, equipment list, equipment costing, and capital costing. Second, the technical and cost models of the study 1 and study 2 capture and compression models were combined with a harmonized model of the technical and cost performance of a reference coal power plant, and with harmonized costs for CO<sub>2</sub> Transport and Storage (T&S). In this way, the full CCS value chain is included in the techno-economic assessment, but only the capture and compression models are different. This allows to assess the impacts of the CO<sub>2</sub> capture and compression performance on the economics of the total chain. Third, the economic performance (LCOE and CCA) of study 1 and study 2 was assessed when combined with the harmonized reference power plant, using harmonized financial performance parameters (Fig. 1). Fourth, the results were compared with other techno-economic studies on PCC with (advanced) amines that were retrieved from open literature. Last, the uncertainty of study 1 and study 2 was assessed using a combination of sensitivity and pedigree analysis. Note that in each of the above steps, the drivers of the (techno-) economic uncertainty/variability were made explicit to increase their understanding.

As a point of reference, also the techno-economic results of a previous study on coal power with MEA carbon capture are presented throughout the study. The technical performance of this MEA plant was reported in Van der Spek et al. (2016b).

### 2.1. Technical design

#### 2.1.1. Power plant

The harmonised power plant is an 830 MW (gross) advanced super critical pulverised coal (ASC PC) plant (Fig. 2). The power plant design is based on the European Benchmarking Task Force (EBTF) (Cesar, 2011). The plant design includes selective catalytic reduction (SCR) for NO<sub>x</sub> control, an electrostatic solids precipitator (ESP) for fly ash removal, and a wet flue gas desulphurization (FGD)

unit for sulphur polishing. For further information on power plant design specifications, see Van der Spek et al. (2016a).

#### 2.1.2. CO<sub>2</sub> capture and compression plant

The AMP/PZ CO<sub>2</sub> capture plant uses a standard absorber-stripper configuration, including a direct contact cooler for flue gas cooling and polishing, and water washes on both absorber and stripper for gas polishing (Fig. 2). The stripper reboiler uses steam from the steam cycle's IP/LP crossover. The compression section includes a five-stage intercooled compressor and a liquid CO<sub>2</sub> pump, increasing the pressure to a final value of 110 bar, which is the pressure at which the CO<sub>2</sub> is delivered for transport. Part of the heat that is rejected in the compression train is used to heat up the low pressure feed water in the power plant steam cycle.

#### 2.1.3. CO<sub>2</sub> transport and storage

For CO<sub>2</sub> transport and storage, we assumed offshore storage in a depleted oil or gas field without reuse of legacy wells at a storage location approximately 180 km from the capture site. The choice for offshore storage was made because there is currently much public opposition in NW-Europe towards onshore storage.

### 2.2. Technical performance assessment

#### 2.2.1. Power plant model

The power plant was modelled in Aspen Plus V8.4. The model includes a detailed representation of coal combustion, the ASC steam cycle, the SCR, and the ESP. The FGD was modelled as a black box, and was assigned a parasitic power use of 5340 kJ<sub>el</sub>/kg SO<sub>2</sub> removed following the EBTF (Cesar, 2011).

#### 2.2.2. CO<sub>2</sub> capture plant models

The CO<sub>2</sub> capture and compression plant of study 1 was modelled with Aspen Plus. The model calculated the CO<sub>2</sub> absorption in the solvent based on chemical equilibrium (Sanchez Fernandez et al., 2014). For CCS solvent models this is often done; kinetically controlled models lead to similar results if absorption and desorption towers are chosen tall enough. Aspen plus features e-NRTL activity coefficient models to predict liquid thermodynamics for the AMP-H<sub>2</sub>O-CO<sub>2</sub> and the PZ-H<sub>2</sub>O-CO<sub>2</sub> system. Technical performance indicators of the ASC power plant with study 1's capture model were reported in Sanchez Fernandez et al. (2014).

Study 2's CO<sub>2</sub> capture and compression plant was modelled using Procede Process Software (PPS) (Van der Spek et al., 2016a). PPS features the rigorous assessment of CO<sub>2</sub> capture solvents using kinetically controlled column calculations and the Margules activity coefficient model to predict liquid thermodynamics of the AMP-PZ-H<sub>2</sub>O-CO<sub>2</sub> system. Technical performance indicators of the ASC power plant with this AMP/PZ capture model were reported in Van der Spek et al. (2016a).

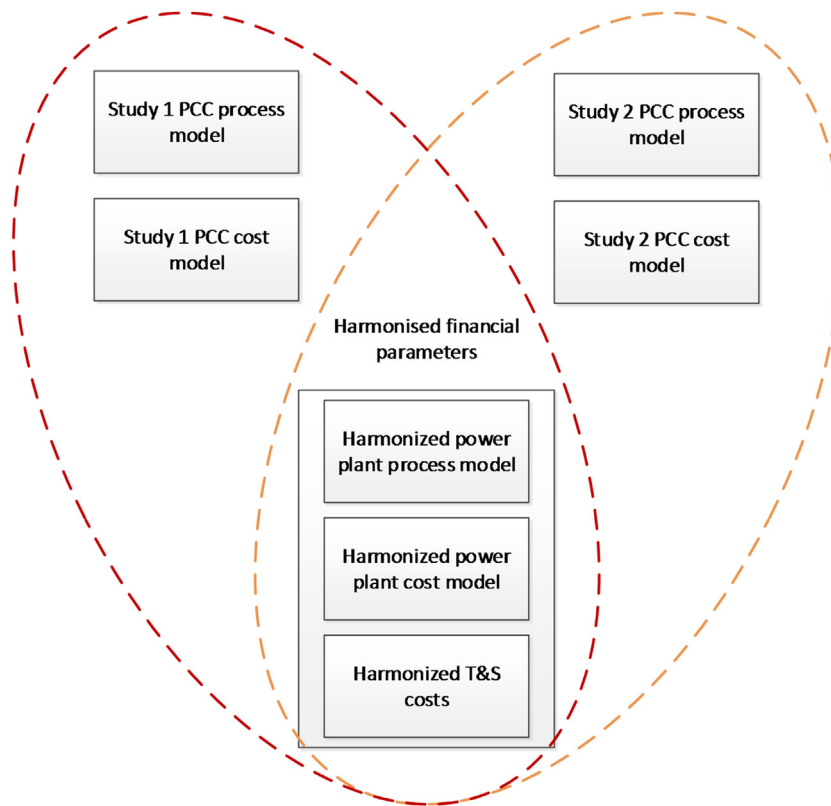
### 2.3. Economic analysis

#### 2.3.1. Economic performance indicators

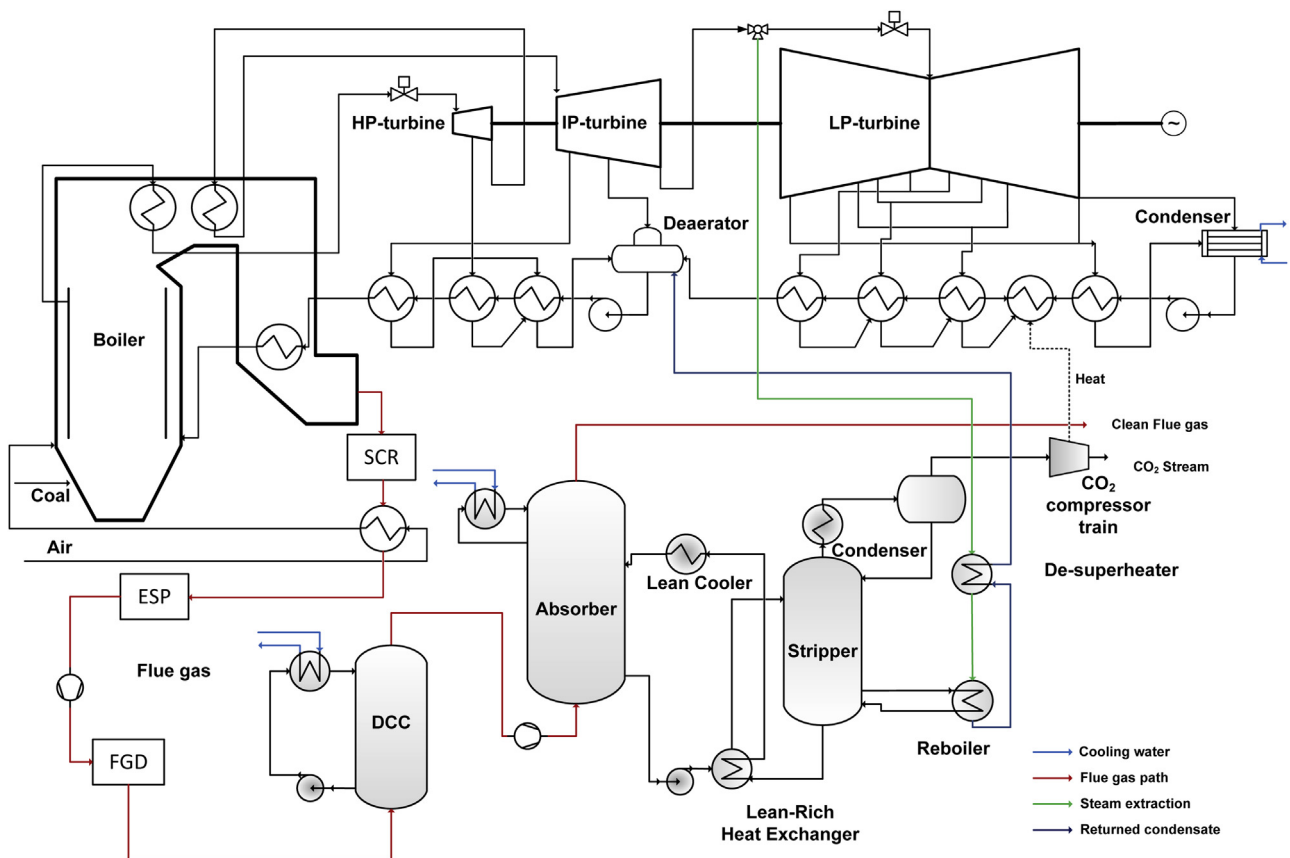
This work focused first on comparison of the capital cost estimates of study 1 and study 2. Secondly, the capital costs, as well as operational and fuel costs, were used to calculate the levelised cost of electricity (LCOE) and cost of CO<sub>2</sub> avoided (CCA) following equations Eqs. (1) and (2) (Rubin et al., 2013).

$$LCOE (\text{€}/\text{MWh}) = \frac{\sum_{i=1}^n \frac{I_i + O\&M_i}{(1+r)^i}}{\sum_{i=1}^n \frac{E_i}{(1+r)^i}} \quad (1)$$

Where  $I_i$  is the investment cost in year  $i$ ,  $O\&M_i$  are the operations and maintenance costs in year  $i$  (including fuel costs),  $r$  is the dis-



**Fig. 1.** Graphic representation of economic analysis of study 1 and study 2. The graphic shows that study 1 and 2 use their own technical and cost model for the PCC units, while using a common harmonised process and cost model for the power plant, harmonised costs for transport and storage, and harmonised financial parameters.



**Fig. 2.** Process flow scheme of the integrated power plant, capture unit, and compression unit (the latter highlighted in grey).

**Table 1**  
General economic assumptions used in study 1 and study 2.

Financial parameters	Unit	Value
Project base year		2013
Project life time	yr	40
Construction duration	yr	4
Levelised plant utilisation high	hr/a	7446 (85% CF)
Levelised plant utilisation low	hr/a	3942 (45% CF)
Discount rate	%	7.5

count rate (%), and  $E_i$  is the electricity production (MWh) in year  $i$ . The LCOE was calculated on a constant (real) 2013 Euro basis.

$$CCA \left( \text{€}/t \text{ CO}_2 \right) = \frac{LCOE_{cc} - LCOE_{ref}}{C_{ref} - C_{cc}} \quad (2)$$

Where  $LCOE_{cc}$  is the Levelised Cost of Electricity in the plant with CCS,  $LCOE_{ref}$  is the Levelised Cost of Electricity in the plant without CCS,  $C_{ref}$  is the  $\text{CO}_2$  intensity ( $t \text{ CO}_2/\text{MWh}$ ) in the plant without CCS, and  $C_{cc}$  is the  $\text{CO}_2$  intensity ( $t \text{ CO}_2/\text{MWh}$ ) in the plant with CCS.

### 2.3.2. Financial parameters

Table 1 shows the financial parameters used in this work. They were selected in consultation with industrial partners from the energy and utility sector and were validated against representative CCS costing studies (ZEP, 2011; IEAGHG, 2014; NETL, 2015). The discount rate is in constant (real) Euro. The project economics were calculated for a sea-based location in North-Western Europe. The site is assumed to be new, and has to be developed but is located in an existing industrial cluster, hence energy and utility infrastructures to the gate exist and are not taken into account.

Note that besides a high (levelised) utilisation scenario also a low (levelised) utilisation scenario was estimated.<sup>1</sup> Although coal power plants are capable of running around 85–90% of the year, they are utilised much less because of fluctuating demand patterns. In The Netherlands, Austria, Germany, and Italy, the 2014 plant utilisation of hard coal power plants was 60, 29, 47, and 46 percent respectively (based on ECN, 2014; ENTSOE, 2015). In the coming decades it is likely that intermittent renewable energy will increase whilst back-up fossil capacity is still required, suggesting sustained low utilisation of fossil power plants (Brouwer et al., 2015; Kang et al., 2015; Mac Dowell and Staffell, 2015). Therefore, when calculating the costs of fossil power plants with CCS, it is necessary to also include low utilisation scenarios, providing a balanced picture of CCS power costs.

### 2.3.3. Capital cost estimates

Different methods were used to calculate the (harmonised) capital costs of the power plant and the capital costs of the capture and compression plants. All cost estimates represent  $N^{\text{th}}$ -of-a-kind plants.<sup>2</sup>

**2.3.3.1. Power plant capital costs.** Several organisations have provided detailed cost estimates of coal power plants (e.g. NETL, 2010; IEAGHG, 2014), hence the power plant capital costs could be estimated using the exponent method. We adopted this approach for reasons of simplicity and time-efficiency. As basis for the power plant capex calculations the cost estimates by the US National

<sup>1</sup> The low utilisation scenario assumes that the power plant is “on”, running at 100% design capacity, or “off”, running idle. Electrical efficiency losses due to flexible operation are excluded in this work.

<sup>2</sup> Process contingencies were excluded in this work; currently, consensus is lacking whether or not to include them to calculate the costs of an  $N^{\text{th}}$ -of-a-kind plant. NETL includes small process contingencies in their studies (~13% of EPC), but IEAGHG studies explicitly do not. Further publications exploring this issue are under preparation.

Energy Technology Laboratory were used (NETL, 2010: case 11), because the NETL studies provide highly detailed cost estimates that allow for scaling the costs of separate power plant components (coal handling, boiler, turbines, etcetera) individually. The NETL study provides cost estimates for a Super Critical power plant, rather than an Advanced Super Critical power plant. This may lead to slightly optimistic estimates for the ASC plant capital estimate, because steam cycle and turbine costs in an ASC plant may be somewhat higher than in an SC plant due to more severe operating conditions. It was assumed that this difference in power plant capital cost would fall well within the  $\pm 30\%$  accuracy range, which was verified by comparison of this study's power plant capex result with results from a study on advanced super critical coal plants (Cesar, 2011).

The total capital requirement (TCR) of the NETL power plant is given in 2007 US\$. The TCR of the power plant in 2013 Euro was calculated following steps 1 through 5.

1. Calculate the power plant equipment cost in US\$<sub>2007</sub> using Eq. (3). An average scaling exponent of 0.65 was used as reported in cost estimating literature (Gerrard, 2000). This value is in line with guidelines by DOE/NETL (2013).

$$C = C_{ref} \left( \frac{Q}{Q_{ref}} \right)^n \quad (3)$$

Where  $C$  and  $C_{ref}$  are the capital costs of the equipment/plant in the new study respectively the reference study,  $Q$  is the equipment capacity in the new study,  $Q_{ref}$  is the equipment capacity in the reference study, and  $n$  is the scaling exponent.

2. Calculate the total plant cost (TPC) in US\$<sub>2007</sub> based on the factors/cost elements provided in NETL (2010) case 11.

3. Convert the TPC from US\$<sub>2007</sub> to €<sub>2007</sub> using the 2007 US\$/€ exchange rate of 1,3705 (IRS, 2015) and by using the 2007 location factor of 1.19 to represent the difference in cost between building a plant in The Netherlands versus building a plant in the US Midwest (Cost Data On Line Inc., 2008).

4. Calculate the total capital requirement (TCR) in €<sub>2007</sub> by adding the owner's cost and interest during construction (IDC) of the NETL study to the TPC. Owner's costs and IDC were first converted from US\$<sub>2007</sub> to €<sub>2007</sub> using the 2007 US\$/€ exchange rate of 1,3705 (IRS, 2015).

5. Convert the TCR from €<sub>2007</sub> to €<sub>2013</sub> with the EU Eurozone harmonised index of consumer prices (HICP) between 2007 and 2013 of 12,4% (Eurostat, 2015).

### 2.3.3.2. CO<sub>2</sub> capture and compression capital costs.

**2.3.3.2.1. Study 1.** The capital costs of study 1 were prepared using a detailed factor estimate. This factoring method was based on the method by Abu-Zahra et al. (2007a) (Supplementary materials). The basis for the factor method used in study 1 are the purchased equipment costs in the steel type in which the equipment is installed. It estimates the Total Plant Cost based on the estimate of the purchased equipment costs. The method includes full EPC costs, project contingencies, and some owner's costs, but excludes other owner's costs like land purchase and permitting. In this work it was complemented with an additional factor to account for the omitted owner's costs and interest during construction (IDC). Table 2 and the Supplementary materials show the cost items that were included in the original EBTF costing study, before adding a factor to include all owner's costs and IDC. Note that modifications to the power plant were excluded from this cost estimate.

Steps 1 through 5 below provide the calculation sequence of the TCR used for study 1's CO<sub>2</sub> capture and compression unit:

1. Derive equipment list from the process model (Supplementary materials). The equipment sizes of pumps and heat exchangers



**Table 2**

Composition of cost elements following the recommended nomenclature by Rubin et al. (2013). The table shows the cost elements that were included in the original capital cost estimates of study 1 and study 2, before addition of full owner's costs and IDC.

Capital cost element to be quantified	Sum of all preceding items is called:	Study 1	Study 2
Process equipment		✓	✓
Supporting facilities		✓	✓
Labour (direct and indirect)		✓	✓
<hr/>			
Engineering services	Bare Erected Cost (BEC)		
Contingencies:	Engineering, Procurement & Construction (EPC) Cost	✓	✓
Process			
Project		✓	✓
<hr/>			
	Total Plant Cost (TPC)		
<hr/>			
Owner's costs:			
Feasibility studies			
Surveys			
Land			
Insurance			
Permitting			
Finance transaction costs			
Pre-paid royalties			
Initial catalyst and chemicals		✓	
Inventory capital		✓	
Pre-production (start-up)		✓	
Other site specific items unique to the project			
<hr/>			
	Total Overnight Cost (TOC)		
<hr/>			
Interest during construction (IDC)			
Cost escalations during construction			
<hr/>			
	Total Capital Requirement (TCR)		

were derived from the EBTF Aspen Plus model. The size of the columns was calculated manually using the column design model presented in Abu-Zahra et al. (2007b) and informed by experimental trials in the Esbjerg power plant with an absorption column height of 17 metre (Knudsen et al., 2011).

2. Calculate the sum of the purchased equipment costs (EC) in €<sub>2008</sub>. To this end the costs of pumps and small equipment were calculated using the price booklet of the Dutch Association of Cost Engineers (DACE, 2008). The column costs were calculated using empirical relations from literature (Mulet et al., 1981; Vatavuk and Neveril, 1982). The purchase costs of all heat exchangers and of the compressor were estimated based on (confidential) vendor quotes using the exponent method.

3. Calculate the TPC using detailed cost factors (Supplementary materials) and Eq. (4):

$$TPC = \left( \sum_{i=1}^n [EC_i] \right) \times [F_a + F_b + \dots + F_z] \quad (4)$$

Where  $EC_i$  are the equipment costs of item  $i$  and  $F_a$ ,  $F_b$ , and  $F_z$  are factors for different cost items (erection, piping, engineering, etcetera).

3. Convert the TPC from €<sub>2008</sub> to €<sub>2013</sub> using the HICP, to make the EBTF cost estimate comparable to the EDDiCUT cost estimate.

4. Multiply the TPC with a factor (1,2) to arrive at a TCR estimate following Kang et al. (2015). This factor represents the omitted owner's costs and IDC from the original estimate. It was derived from IEAGHG (2014) for Rotterdam, The Netherlands.

2.3.3.2.2. Study 2. Study 2 used a different capital cost estimating method for the CO<sub>2</sub> capture and compression plant than study 1. Instead of using a detailed factor method, it used the detailed individual factor method, (Eldrup, 2009; Melien and Brown-Roijen, 2009).

Where the normal detailed factoring method uses general escalation factors that are equal for all equipment, the detailed individual method uses different factors for each equipment indi-

vidually. Thereby, the detailed individual factoring method may provide a more reliable total plant cost estimate. It uses the equipment costs in carbon steel as a basis and calculates the total plant cost of each piece of equipment following Eq. (5):

$$TPC = \sum_{i=1}^n [EC_i \times F_i] \quad (5)$$

Where  $EC_i$  are the equipment costs of equipment  $i$  and  $F_i$  is the individual escalation factor for equipment  $i$ .

The values of the individual factors are based on (confidential) empirical relations, using inputs such as equipment type, size and steel type, and site characterisation (Supplementary materials). These empirical equations are derived from a couple hundred of built industrial projects and/or material take-off cost estimates in the period from 1985 to 2000, which are summarized in an in-house database. The factors were checked several times against newly available (but confidential) costs of built plants, and against vendor cost estimates in the CCP project (Melien and Brown-Roijen, 2009), and were found to predict the costs of these projects well within the ±30% accuracy range. The method provides a TPC estimate, including full EPC costs and 20% project contingencies, but excluding all owner's costs and IDC (Supplementary materials). Like study 1, it was complemented with an additional factor to account for the omitted owner's costs and interest during construction. For reference, Table 2 shows which cost elements of the harmonised nomenclature by Rubin et al. (2013), were included in study 2, before addition of a factor to owner's costs and IDC.

Steps 1 through 6 provide the calculation sequence of the TCR for study 2's CO<sub>2</sub> capture and compression unit:

1. Derive equipment list from the process model (Supplementary materials).
2. Calculate individual equipment costs (EC) with the Aspen capital cost estimator (Q1 2010 database).
3. Convert EC to €<sub>2013</sub> using the Eurostat Consumer Price Index.

4. Calculate the detailed factor for every individual piece of equipment.
5. Calculate Total Plant Cost using Eq. (5).
6. Multiply the TPC with a factor (1,3) to arrive at an TCR estimate following Kang et al. (2015). This factor represents owner's costs and IDC for Rotterdam, The Netherlands (IEAGHG, 2014). Note that a higher factor was used than for study 1 because study 1's TPC estimate already included some owner's costs.

#### 2.3.4. Fuel and O&M cost estimates

**2.3.4.1. Power plant.** The operational expenses (labour, maintenance, chemicals) of the power plant are based on the NETL study (NETL, 2010) and are presented in Table 3. In case the operational costs are presented as unit costs (€/tonne), the yearly material flow was derived from the power plant model where possible (Section 2.2.1) or from existing technical studies (NETL, 2010; IEAGHG, 2014) where necessary, and multiplied with the unit costs to estimate the yearly operational costs. The unit cost of coal was taken from the Dutch Bureau of Statistics (CBS, 2015) instead of from NETL, representing the locational situation in NW-Europe.

**2.3.4.2. CO<sub>2</sub> capture and compression plants.** The operational units cost of the CO<sub>2</sub> capture and compression units include maintenance costs, cooling and process water costs, solvent replenishment and chemicals costs, reclaimer waste disposal, and labour (operators and plant technologist) (Table 3).

Solvent replenishment costs and other chemicals costs were based on the mass balance of the respective study 1 and study 2 process models and solvent degradation studies (Knudsen et al., 2009; Lepaumier et al., 2009; Freeman et al., 2010; Guedard et al., 2012; Sanchez Fernandez et al., 2012; Wang and Jens, 2014) and multiplied with a unit cost (Table 3).

**2.3.4.3. Transport & storage.** To calculate the costs of CO<sub>2</sub> transport and storage, unit costs were used from the ZEP reports (Zep, 2011a,b). The ZEP studies show that the costs for T&S can vary considerably, stemming from transport distance and storage location (onshore, offshore), type of storage site (saline aquifer, depleted oil and gas field), and possibility to reuse existing wells. The ZEP unit costs for CO<sub>2</sub> transport range from 1,5 €/tonne for a 180 km onshore pipeline to 16,3 €/tonne for a 1500 km offshore pipeline in case of 2,5 Mtpa transported. The costs for CO<sub>2</sub> storage range from 3 €/tonne for an onshore depleted oil and gas field (DOGF) where existing wells can be reused, to 14 €/tonne for an offshore saline aquifer that requires drilling of new wells.

Given that the T&S design in this study includes 180 km transport to an offshore DOGF, we assumed a total T&S cost of 16 €/tonne CO<sub>2</sub> (Table 3).

#### 2.3.5. MEA reference case costing

The MEA reference case was costed in exactly the same way as study 2's AMP/PZ case. Both capex and opex were estimated as described in Sections 2.3.3 (study 2)–2.3.4 and using the financial parameters presented in Section 2.3.2.

### 2.4. Uncertainty analysis

We argued in the introduction that it is important to provide good insight into the uncertainties of early stage techno-economic studies, with the aim to supply decision makers with the needed context to make informed decisions. To enable this, this work introduces the use of two complementary approaches for uncertainty analysis (sensitivity analysis and pedigree analysis) and applied them to both case studies.

#### 2.4.1. Sensitivity analysis

The first part of the uncertainty analysis includes testing the sensitivity of the LCOE to changes in PCC techno-economic parameters. Parameters in the sensitivity analysis included the main technical performance indicator (efficiency penalty: power plant net efficiency reduction due to CCS), as well as economic parameters that are particularly relevant for PCC cost estimates (PCC purchased equipment costs, applied costing factors, owner's costs and IDC costs, transport and storage costs, and solvent costs). Note that the power plant costs, fuel costs, and financial parameters were excluded from the sensitivity analysis, to maintain focus on the uncertainties in costing of the carbon capture technology. All inputs were varied with  $\pm 50\%$ , while keeping all other parameters equal. This is a crude method for sensitivity analysis, but allows to explain the combination with pedigree analysis in an understandable way. More sophisticated methods could include the simultaneous change of input parameters or Monte Carlo simulation (Saltelli et al., 2008).

#### 2.4.2. Pedigree analysis

Pedigree analysis is a structured approach to qualitatively assess the strength of data or models (Van der Spek et al., 2016b). It amongst others assesses the strength of the knowledge base underlying a parameter (how good is the knowledge on which the parameter value is based?). This is complementary to sensitivity analysis, which assesses the value range of a parameter, but not its quality or strength. Independent assessment of the strength of a model is an important feature of pedigree analysis. Therefore, to assess the studies, four researchers were selected that have a track record as well as advanced degrees in techno-economic assessment of carbon capture technologies. The experts were independent, i.e. they were not involved in the cost estimation process of the study they reviewed. Two of the four experts also co-authored this paper.

To facilitate the assessment, details on the techno-economic models were shared with the experts in an information pack. The pedigree analysis was done in a workshop session to enable the reviewers to discuss their scores and to ask clarifying questions to the modellers. The reviewers were asked to reach consensus on every score before providing the final value. The pedigree analysis was done using the pedigree matrix in Table 4.

#### 2.4.3. Diagnostic diagram

The results of the sensitivity and pedigree analyses were combined in a so-called diagnostic diagram. "The diagnostic diagram is based on the notion that neither spread alone nor strength alone is a sufficient measure" to show the uncertainty of a model (van der Sluijs et al., 2005: 483). It helps identify the parameters that are least robust, i.e., the parameters to which the model output is most sensitive but also have the lowest strength. In this way, it can provide detailed insight into the quality of cost model results.

### 3. Case study results

#### 3.1. Technical performance indicators

Table 5 presents the technical performance of the coal power plant with AMP/PZ capture and compares this to the coal power plant without capture and with MEA capture. The table exemplifies variability in early stage technical performance models: study 1 predicts a slightly lower energy penalty of the AMP/PZ system than study 2. The different models predict specific reboiler duties (SRD's) of 2,7 and 2,9 GJ/t CO<sub>2</sub> respectively, leading to net power plant efficiencies of 37,8 and 37,2%<sub>LHV</sub>. Note that both SRD values are close to the value of 3,0 GJ/t CO<sub>2</sub> that was measured in the large scale Esbjerg pilot plant (Knudsen et al., 2009, 2011).

**Table 3**

Operations cost assumptions used in study 1 and study 2.

Cost item	Unit	Study 1	Study 2
<b>Power plant</b>			
Coal	€ <sub>2013</sub> /tonne	80 <sup>a</sup>	
Fixed operating costs	k€ <sub>2013</sub> /a	40.429 <sup>b</sup>	
MU & WT chemicals	k€ <sub>2013</sub> /a	1.251 <sup>b</sup>	
SCR catalyst	k€ <sub>2013</sub> /a	560 <sup>b</sup>	
H <sub>2</sub> SO <sub>4</sub>	€ <sub>2013</sub> /tonne	640 <sup>c</sup>	
Ammonia	€ <sub>2013</sub> /tonne	630 <sup>c</sup>	
Limestone	€ <sub>2013</sub> /tonne	20.09 <sup>c</sup>	
Ash disposal	€ <sub>2013</sub> /tonne	15.08 <sup>c</sup>	
Gypsum sales/disposal	€ <sub>2013</sub> /tonne	0	
<b>Capture &amp; compression plant</b>			
Maintenance	% TPC/a	2,5 <sup>d</sup>	4 <sup>f</sup>
AMP	k€ <sub>2013</sub> /tonne	8 <sup>d</sup>	7,56 <sup>g</sup>
PZ	k€ <sub>2013</sub> /tonne	6 <sup>d</sup>	7,56 <sup>g</sup>
MEA	k€ <sub>2013</sub> /tonne	n.a. <sup>d</sup>	2,1 <sup>h</sup>
Active Carbon	k€ <sub>2013</sub> /tonne	2,7 <sup>e</sup>	2,7 <sup>i</sup>
Reclaimer waste disposal	k€ <sub>2013</sub> /tonne	0	0,375 <sup>j</sup>
Process water	€ <sub>2013</sub> /m <sup>3</sup>	6 <sup>d</sup>	1 <sup>k</sup>
Operators & supervision	k€ <sub>2013</sub> /a	1.126 <sup>d</sup>	421,5 <sup>l</sup>
Plant technologist	k€ <sub>2013</sub> /a	0	100 <sup>m</sup>
<b>Transport &amp; Storage</b>			
Transport (180 km offshore)	€/tonne	6 <sup>n</sup>	
Storage (offshore DOGF)	€/tonne	10 <sup>o</sup>	

<sup>a</sup> 2010–2014 average price of steam coal imported to the Netherlands from non-EU countries (CBS, 2015). Validated against IEA coal information 2013 (IEA, 2013) (coal import prices to western Europe).

<sup>b</sup> Costs are presented in the NETL study as US\$<sub>2007</sub>/a for a 582 MW gross power plant. To convert to required values they were adjusted to the size of the power plant in this study, converted to €<sub>2007</sub> using the 2007 exchange rate of 1,3705 and converted to €<sub>2013</sub> using the HCPI index (+12,4%).

<sup>c</sup> Costs are presented in the NETL study as US\$<sub>2007</sub>/tonne (short ton). First they were adjusted to US\$<sub>2007</sub>/metric tonne, using the ratio of 0.907. Then they were converted to €<sub>2007</sub> using the 2007 exchange rate of 1,3705 and converted to €<sub>2013</sub> using the HCPI index (+12,4%).

<sup>d</sup> Manzolini et al. (2015).

<sup>e</sup> Not applicable to this study, the EBTF did calculate a case for MEA, but this was not used in this work.

<sup>f</sup> Melien and Brown-Roijen (2009).

<sup>g</sup> MHI: AMP/PZ solvent cost are 3,6 times MEA solvent costs (Iijima, 2004).

<sup>h</sup> NETL (2010).

<sup>i</sup> Rao and Rubin (2002).

<sup>j</sup> Bellona (Shao and Stangeland, 2009).

<sup>k</sup> Sinnott (2004).

<sup>l</sup> Wage information retrieved from the Norwegian Confederation of Trade Unions (LO, 2014). 1 additional operator assumed in 6 shift rotation.

<sup>m</sup> Wage information retrieved from the Confederation of Norwegian Enterprises (NHO, 2014). One additional plant technologist assumed.

<sup>n</sup> Zep (2011a).

<sup>o</sup> Zep (2011b).

**Table 4**

Pedigree matrix for the assessment of economic parameters and model strength.

Strength	Criterion			
	Proxy	Reliability of source	Completeness	Validation process
0	Not correlated and not clearly related	non-qualified estimate or unknown origin	Incomplete data from a small number of samples for an unrepresentative period	No validation performed
1	Weak correlation but commonalities in measure	Non-reviewed data derived from open literature	Almost complete data but from a small number of samples and unrepresentative periods	Weak and very indirect validation
2	Correlated but does not measure the same thing	Reviewed data derived from independent open literature	Almost complete data but from a small number of samples or for unrepresentative periods or incomplete data from adequate number of samples and periods	Validation measurements are not independent, include proxy variables or have limited domain
3	Good fit to measure	Qualified estimate by industrial expert supported by industry data	Complete data from a large number of samples but for unrepresentative periods or from representative periods but for a small number of samples	Compared with independent data of similar systems that have not been built
4	A direct measure of the desired quantity	Measured/official industrial, vendor, and/or supplier data	Complete data from a large number of samples over a representative period	Compared with independent data from similar systems that have been built

Source: adapted from Weidema (1998) and van der Sluijs et al. (2005).

**Table 5**

Performance indicators of Advanced Super Critical Pulverized Coal power plant without carbon capture, with AMP/PZ carbon capture, and with MEA carbon capture.

Performance indicator	ASCPC w/o CCS	ASCPC MEA	ASCPC AMP/PZ	
			Study 1	Study 2
Gross Power Output (MW <sub>e</sub> )	833	727	755	738
Parasitic Load (MW <sub>e</sub> )	57	118	120	112
Net Power Output (MW <sub>e</sub> )	776	609	635	626
Gross Efficiency LHV (%)	49,5	43,2	44,8	43,9
<b>Net Efficiency LHV (%)</b>	<b>46,1</b>	<b>36,2</b>	<b>37,8</b>	<b>37,2</b>
CO <sub>2</sub> Intensity (kg/MWh)	734	94	91	91
Spec. Reboiler Duty (GJ/t CO <sub>2</sub> )	–	3,6	2,7	2,9
SPECCA <sup>a</sup> (GJ/t CO <sub>2</sub> )	–	3,4	2,6	2,9
Specific Cooling Water Use (kg/MW <sub>e</sub> )	34,0	55,4	55,5	54,0

<sup>a</sup> Specific Primary Energy Consumption per tonne of CO<sub>2</sub> Avoided.

### 3.2. Capital cost estimates

#### 3.2.1. Equipment lists and sizing

Comparison of the equipment lists (Supplementary data) shows that the included process equipment items are similar for both study 1 and 2. Study 2 includes some more equipment (filters, storage vessels and their pumps) than study 1, but this accounts for less than 1% of total purchased equipment costs. Also the selected steel types are comparable. Both studies use stainless steel (SS304 or SS316) for most process equipment.

Comparison of the equipment sizes (Supplementary materials) shows a mixed picture however. The sizes of pumps and compressors in the two studies are very comparable, which is logical because typical sizing quantities (power use and fluid flow rate) can be extracted directly from the simulation models, and should not differ too much in case of comparable simulation results. This can be different for column and heat exchanger sizes, because for sizing these equipment additional design assumptions need to be made.

To exemplify this, Fig. 3 shows the variability in design of four heat exchangers in the AMP/PZ capture process. The calculated HX surface areas, which largely determine the HX costs, differ much between study 1 and study 2 and do not seem to be correlated to HX duty. This can be explained by assumptions on the temperature approach, heat transfer coefficient, and HX type. For instance, the difference in reboiler surface area could be explained by the selection of HX type. In study 1, a plate and frame heat exchanger is assumed, while in study 2 shell and tube heat exchangers were assumed. Plate and frame exchangers typically have twice the heat transfer coefficient as shell and tube exchangers. As second example, the difference in condenser surface area can be explained by different assumptions on temperature approach and HX U-value. It is out of the scope of this work to go into further detail, but this example highlights the significance of equipment design assumptions and the sizes of resulting equipment.

#### 3.2.2. Equipment cost estimates

Analysis of the equipment cost estimates in Fig. 4 highlights a third source of uncertainty/variability: the estimation of purchased equipment cost resulting from the equipment list. The figure shows big differences in equipment cost estimates, especially for the columns and heat exchangers. These cost differences cannot (solely) be attributed to different equipment sizes, because for instance the absorber and stripper column sizes are almost identical in both studies (see Supplementary materials). Nevertheless, in study 2, these costs are more than twice as high as in study 1. This difference in equipment costs is caused by using different estimation methods. In study 1, the column and packing costs were estimated using relations from 30year old literature sources (see Section 2.3.3.2) which, even when updated with appropriate cost

**Table 6**

Comparison of intermediate and final cost estimates and equivalent escalation factors of the CCS equipment.

	Study 1	Study 2
<b>Equipment Cost (M€<sub>2013</sub>)</b>	70	116
<b>% Difference study 1–study 2</b>		66%
<b>EPC cost (M€<sub>2013</sub>)</b>	160	234
<b>% Difference study 1–study 2</b>		46%
<b>Factor EC-EPC</b>	2,3	2,0
<b>TPC (M€<sub>2013</sub>)</b>	184	281
<b>% Difference study 1–study 2</b>		53%
<b>Factor EC-TPC</b>	2,6	2,4
<b>TCR (M€<sub>2013</sub>)</b>	221	365
<b>% Difference study 1–study 2</b>		65%
<b>Factor EC-TCR</b>	3,2	3,2

indices, may inhabit a significant bias towards older types of technology. In study 2, they were calculated using the Aspen capital cost estimation software. Similarly, the cost estimate of the cross heat exchanger is higher in study 2, while the required surface area in that study is lower, which is counterintuitive (both studies assume a plate & frame cross heat exchanger). This is also explained by the different equipment cost estimating methods used.

Summing up the costs of individual equipment leads to an equipment cost of 70 M€ in study 1 and of 116 M€ in study 2, a significant 66% difference (Table 6).

#### 3.2.3. Total plant cost and total capital requirement

Besides the equipment cost estimates, Table 6 also presents the factoring of equipment cost to EPC cost, TPC, and TCR. The table shows that the difference in purchased equipment costs translates into a similar difference in total capital requirement. However, due to alternative factoring methods used, the intermediate cost figures vary a little less. This confirms that the factoring method may also be a significant source of variation, but it may also smoothen variation in equipment cost estimates.

### 3.3. Economic performance indicators

#### 3.3.1. High utilisation indicators

Although Section 3.2.2 showed that the capture and compression TCR of study 1 and study 2 differs by 65%, this propagates only mildly into the values of LCOE and CCA. For instance, Table 7 shows that the high utilisation LCOE of the coal power plant with AMP/PZ PCC is only 3 percent higher in study 2 than in study 1. For reference, also the performance indicators of the power plant without capture, and with MEA capture are presented.



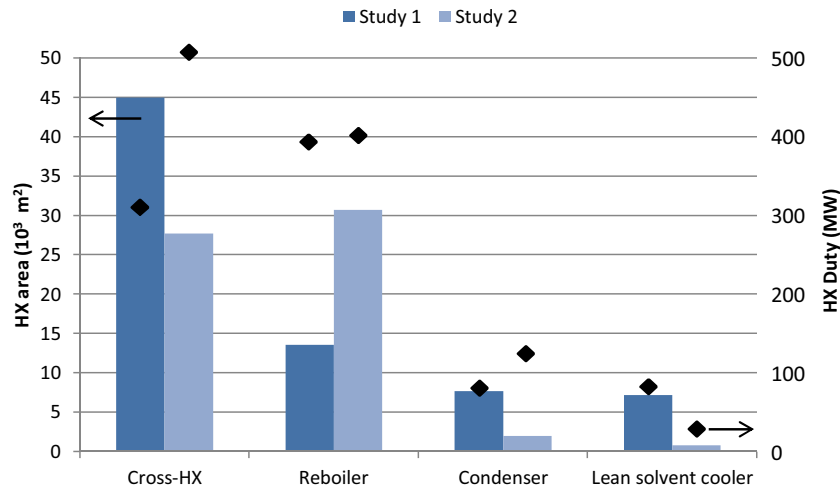


Fig. 3. Comparison of design of four heat exchangers. The figure shows the HX duty (diamonds, right axis) and the calculated HX area (bars, left axis).

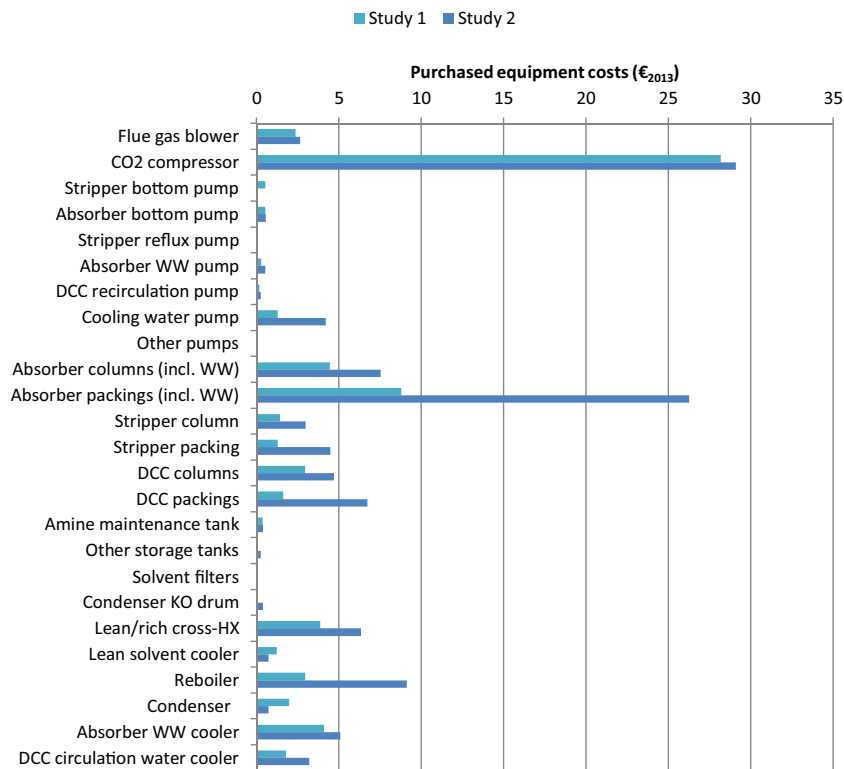


Fig. 4. Comparison of purchased Equipment Costs (EC) in €<sub>2013</sub>, study 1 and study 2.

### 3.3.2. Low utilisation indicators

Table 8 shows that the low utilisation LCOE and CCA are much higher than their high utilisation equivalents. For example, the LCOE for the AMP/PZ configuration is between 133 and 140 €<sub>2013</sub>/MWh at 45% capacity factor, vs 92–96 €<sub>2013</sub>/MWh at 85% CF. Although the influence of plant loading on power plant economics has been long known (see e.g. Rubin and Rao, 2003), economic figures for partial utilization are not often explicitly presented in existing literature. This example shows that presenting the low utilisation economics may be a useful addition to current reporting practice, especially because the capacity of a fossil power plant is rarely fully utilized, as argued in Section 2.3.2.

### 3.3.3. LCOE breakdown

Fig. 5 shows the LCOE breakdown at high and low utilisation. The figure shows that the power plant capital cost (excluding capture and compression), and particularly the fuel costs, contribute most to the LCOE. Part of the fuel costs are related to the energy required by the carbon capture plant, which is determined by the outputs of the AMP/PZ simulation model. So, uncertainties in the simulation model are also translated to uncertainties in the fuel costs.

Secondly, note the – expected – result that the contribution of capital costs to LCOE increases in the low utilisation scenarios from approximately 30% to just under 50%. Inherently, the contribution of fuel costs and other operational expenses decreases. This shows

**Table 7**  
Economic performance indicators of the high utilisation scenario. Capex, Opex, LCOE and CCA of the Advanced Super Critical coal power plant with AMP/PZ capture (study 1 and study 2), with MEA capture, and without capture. All cost are calculated as constant (real) and presented in €<sub>2013</sub>.

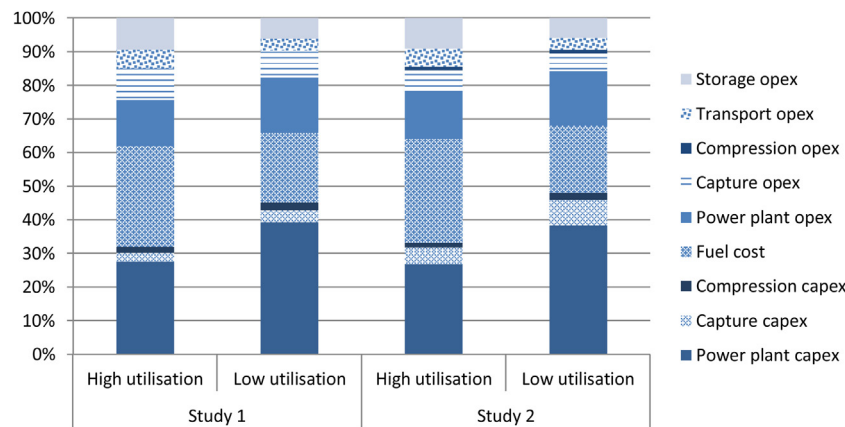
Case	W/o capture		MEA		AMP/PZ			
					Study 1		Study 2	
	TCR (M€)	OPEX (M€/yr)	TCR (M€)	OPEX (M€/yr)	TCR (M€)	OPEX (M€/yr)	TCR (M€)	OPEX (M€/yr)
Power Plant	1.468	187	1.468	187	1.468	187	1.468	187
CO <sub>2</sub> Capture			354	29	132	38	296	27
CO <sub>2</sub> Compression			82	6	89	n.s. <sup>a</sup>	75	5
CO <sub>2</sub> transport				23		23		23
CO <sub>2</sub> storage				38		38		38
<b>Total</b>	<b>1.468</b>	<b>187</b>	<b>1.904</b>	<b>283</b>	<b>1.689</b>	<b>286</b>	<b>1.839</b>	<b>279</b>
<b>% Increase w.r.t. w/o capture case</b>			<b>30%</b>	<b>52%</b>	<b>15%</b>	<b>53%</b>	<b>25%</b>	<b>49%</b>
<b>LCOE (€<sub>2013</sub>/MWh)</b>		<b>55,2</b>		<b>100,4</b>		<b>92,3</b>		<b>95,3</b>
<b>CCA (€<sub>2013</sub>/t CO<sub>2</sub>)</b>				<b>70,5</b>		<b>57,6</b>		<b>62,4</b>

<sup>a</sup> Not specified separately. Included in the opex of the capture plant.

**Table 8**  
Economic performance indicators of the low utilisation scenario. Capex, Opex, LCOE and CCA of the Advanced Super Critical coal power plant with AMP/PZ capture (study 1 and study 2), with MEA capture, and without capture. All cost are calculated as constant (real) and presented in €<sub>2013</sub>.

Case	W/o capture		MEA		AMP/PZ			
					Study 1		Study 2	
	TCR (M€)	OPEX (M€/yr)	TCR (M€)	OPEX (M€/yr)	TCR (M€)	OPEX (M€/yr)	TCR (M€)	OPEX (M€/yr)
Power Plant	1.468	125	1.468	125	1.468	125	1.468	125
CO <sub>2</sub> Capture			354	21	132	27	296	19
CO <sub>2</sub> Compression			82	4	89	n.s. <sup>a</sup>	75	4
CO <sub>2</sub> transport				12		12		12
CO <sub>2</sub> storage				20		20		20
<b>Total</b>	<b>1.468</b>	<b>125</b>	<b>1.904</b>	<b>182</b>	<b>1.689</b>	<b>184</b>	<b>1.839</b>	<b>179</b>
<b>% Increase w.r.t. w/o capture case</b>			<b>30%</b>	<b>46%</b>	<b>15%</b>	<b>47%</b>	<b>25%</b>	<b>44%</b>
<b>LCOE (€<sub>2013</sub>/MWh)</b>		<b>84,2</b>		<b>147,7</b>		<b>133,8</b>		<b>139,9</b>
<b>CCA (€<sub>2013</sub>/t CO<sub>2</sub>)</b>				<b>99,2</b>		<b>77,2</b>		<b>86,6</b>

<sup>a</sup> Not specified separately. Included in the opex of the capture plant.



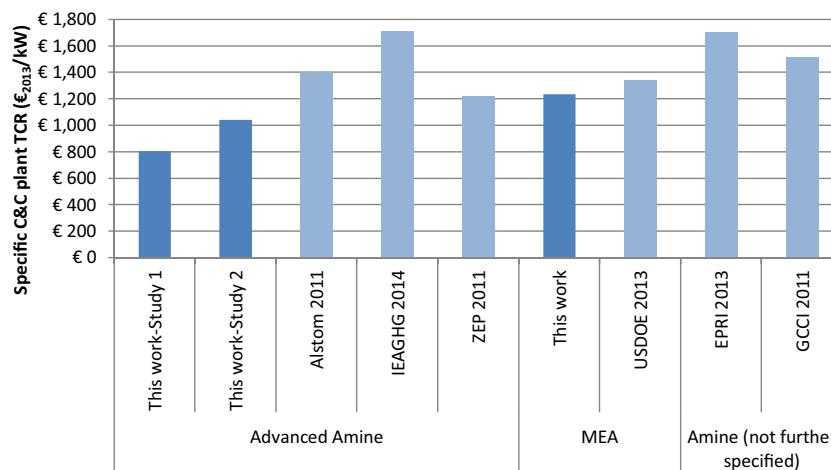
**Fig. 5.** Breakdown of study 1 and study 2 LCOE for the high and low utilisation scenario, presented as constant (real) €<sub>2013</sub>. Values included in Supplementary materials.

the increasing relevance of capital cost estimates for low utilisation and flexible operation economics compared to high utilisation economics.

### 3.4. Comparison with other cost studies

The previous section showed large differences in the capital costs of the AMP/PZ system between the EDDiCCUT and EBTf studies. To put these values into perspective, Fig. 6 compares the incremental specific capital costs of capture and compression cal-

culated in this work with five studies performed by energy and/or CCS NGO's and with one study by a technology vendor. Note that the incremental specific capital costs presented by the NGO's are also commonly based on cost estimates by technology vendors (see e.g. NETL, 2013; IEAGHG, 2014). Also note that the reported PCC technologies in the other studies are not AMP/PZ. However, they all use (advanced) amines and present very similar (if not the same) process flow diagrams as study 1 and study 2, thus justifying comparison.



**Fig. 6.** Incremental specific capital costs (TCR, €<sub>2013</sub>/kW) of capture and compression units of coal power plants. Dark blue columns represent values from this work, light blue bars represent values retrieved from other cost studies (NGO' and technology vendors, values retrieved from Rubin et al. (2015)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6 confirms that there is much variability between the capital cost estimates, but it also shows that the figures presented in this work are clearly lower than the figures from the energy research institutes. The difference between the advanced amine study with the lowest (this work, study 1) and the highest (IEAGHG) specific capital cost is as large as 110%. Further investigation finds that the TCR differences between study 1 and 2 and the NGO/vendor studies is explained specifically by a difference in purchased equipment cost estimates, whilst the factors used are fairly similar.

As background, all these feasibility studies state a  $\pm 30\%$  accuracy, which is in contradiction with the findings of Fig. 6. This may imply that the  $\pm 30\%$  accuracy claim is sometimes used unjustly. On this matter, the AACE states the accuracy range of feasibility studies (class 4 estimates) to be  $-15\%$  to  $-30\%$  on the low end, to  $+20\%$  to  $+50\%$  on the high end (Christensen and Dysert, 2011), which adds another 20%-point to the accuracy range on the high end. Based on our findings, for early stage CCS costing studies, it may be advisable to communicate the  $-30\%$  to  $+50\%$  accuracy range proposed by the AACE, rather than the commonly used  $\pm 30\%$  accuracy range.

This wider accuracy range however does not explain the total difference in capital costs between our capital cost estimates and the NGO/Vendor studies (NETL, IEAGHG, ZEP, Alstom, GCCSI, EPRI) (Fig. 6). In our experience, other justifications include the following.

In general, the above mentioned NGO/vendor cost estimates are prepared by engineering contractors with the help of technology vendors.<sup>3</sup> It is likely that engineering firms and vendors are more versed in designing and engineering of chemical plants than academic researchers are. This could mean that they have a better understanding of the scope of a process (e.g. including auxiliary systems), and are more experienced (thus more realistic) when it comes to design and sparing philosophies. In addition, they may have access to better and/or more recent cost databases.

On the other hand, vendors often present the equipment cost estimate of the carbon capture and compression plant as a lump sum (as in NETL, 2010, 2015; IEAGHG, 2014). This lacking transparency makes it difficult to uncover which costs are included in vendor quotes. It could be that these costs include more R&D, overhead costs, and/or profit margins than for instance the Aspen capital

cost estimator does. It could also be that the capture plant is not really costed as an N<sup>th</sup> of a kind plant, but rather as an early mover plant (Greig et al., 2014).

In addition, Table 9 compares the EDDiCCUT and EBTF economic performance indicators with those of the work by Alstom and IEAGHG on postcombustion capture with advanced amines (Léandri et al., 2012; IEAGHG, 2014). The table shows that the LCOE and CCA ranges are quite wide, but that values presented in this work lie within this range, contrary to the capital cost values.

### 3.5. Uncertainty analysis

We have shown by comparison that capital cost estimates (and to a lesser extent LCOE and CCA) of postcombustion CO<sub>2</sub> capture with (advanced) amines can vary significantly. However, in many early stage cost estimates comparison may prove difficult, e.g. because the estimate is the first for a specific technology. This stresses the importance of applying an all-inclusive uncertainty analysis to early stage cost estimates. In this section it is shown how the combination of sensitivity analysis and pedigree analysis is able to provide an uncertainty analysis that includes quantitative as well as qualitative uncertainties.

#### 3.5.1. Sensitivity analysis

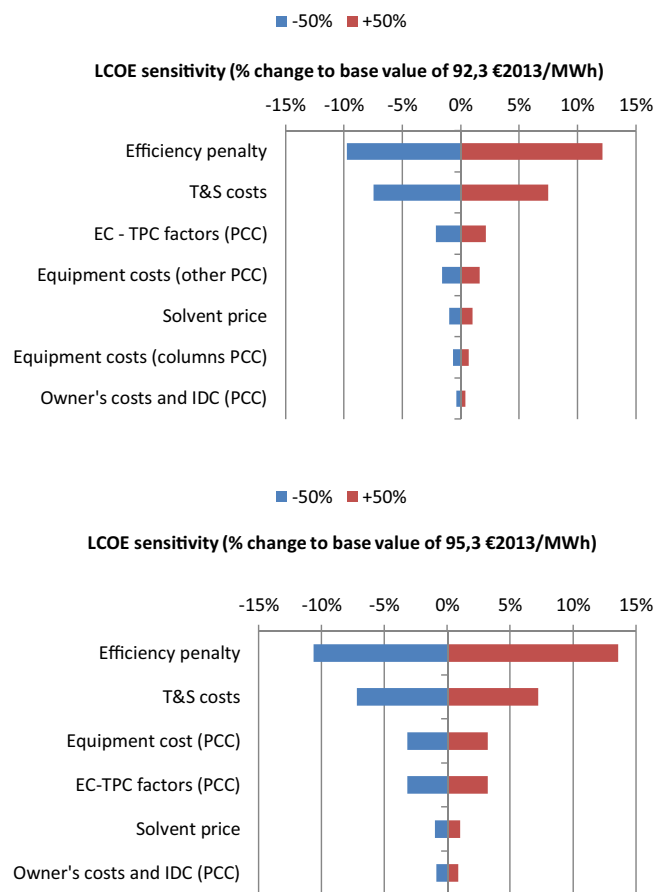
Fig. 7 shows the sensitivities of LCOE to input parameters for study 1 and 2. Note that the equipment costs for study 1 are split into columns and other equipment. This was relevant for the pedigree analysis and diagnostic diagram (next sections), because the costing methods used were very different.

A first observation is that the shape of both figures is similar, and that also the order of highest impact parameters is the similar for both studies, i.e. both are most sensitive to changes in *efficiency penalty*, and least sensitive to changes in *owner's costs and IDC*. The high sensitivity to *efficiency penalty* compared to capital cost items has been reported earlier in cost optimization studies (Sipöcz and Tobiesen, 2012; Kvamsdal et al., 2016). This implies that in terms of LCOE (and hence CCA) it may pay off to add efficiency improvement measures to a PCC plant design at the expense of higher capital costs. Also, note that LCOE is very sensitive to changes in T&S costs. Although this finding is not new, it confirms the relevance of clearly defining storage type and transport distance and cost this appropriately. Because of the split of equipment costs in study 1, the equipment cost items move slightly down the order for this case.

<sup>3</sup> IEAGHG cost estimates are prepared by Foster Wheeler, and include a vendor (Cansolv) estimate for the purchased equipment cost of the carbon capture technology. DOE NETL cost estimates are prepared by WorleyParsons and also include vendor (Fluor and recently Cansolv) quotes for the purchased equipment costs of the capture and compression technology.

**Table 9**  
Techno-economic performance parameters from this work and from two other advanced amine-based postcombustion capture studies (IEAGHG, 2014; Rubin et al., 2015). Values presented as constant (real) €<sub>2013</sub>.

	This work-Study 1	This work-Study 2	Alstom 2011	IEAGHG 2014
Power plant type	ASC PC	ASC PC	ASC PC	SC PC
Solvent technology	AMP/PZ	AMP/PZ	Adv. Amine	Adv. Amine
Net efficiency reference power plant (% LHV)	46,1	46,1	46,2	44,1
Net efficiency with CCS (% LHV)	37,8	37,2	37,9	35,2
Reference plant LCOE (€ <sub>2013</sub> /kWh)	€ 55,20	€ 55,20	€ 46,31	€ 52,00
LCOE with CCS (€ <sub>2013</sub> /kWh)	€ 91,57	€ 93,67	€ 75,60	€ 94,70
<b>LCOE increase (€<sub>2013</sub>/kWh)</b>	<b>€ 36,37</b>	<b>€ 38,47</b>	<b>€ 29,29</b>	<b>€ 42,70</b>
Cost of CO <sub>2</sub> avoided (€ <sub>2013</sub> /t CO <sub>2</sub> )	€ 56,53	€ 59,82	€ 42,92	€ 65,40



**Fig. 7.** Sensitivity of Levelised Cost of Electricity (LCOE) to a  $\pm 50\%$  variation of CCS input parameters. The efficiency penalty is the decrease in net power plant efficiency due to capture and compression. Study 1 (top) and study 2 (bottom).

Would they have been aggregated, the order of sensitivities would be the same as for study 2.

Last, note that this sensitivity analysis was done for the high utilisation scenario. In case of a low utilisation scenario, sensitivity to changes in capital costs will increase, while sensitivity to changes in variable operational costs will remain in the same order.

### 3.5.2. Pedigree analysis

Table 10 presents the pedigree results of the input parameters to study 1. The table shows a mixed picture, without any parameter assigned very high scores. Efficiency penalty scores best as it is a directly calculated quantity rather than a proxy, and because the parameter is complete (it is based on all relevant flows and data). The equipment costs of the columns score worst, because they

were based on 30-year-old empirical relations for FGD columns, which have a different design than modern day absorber/desorber columns. In addition, the relations were derived from an industry journal, but not from a peer reviewed source, or an official industrial database.

Also T&S costs scored relatively low. T&S costs mostly scored values of 2 because the reviewers felt the used figure was a generic figure rather than an exact cost study for a specific location. Also, the cost figure was based on one source only (ZEP) and although this source includes inputs from industrial partners, it is explicitly not an industrial quote. Also, due to a lack of real project data on CO<sub>2</sub> transport and storage, the validation of the T&S costs was deemed weak, hence the score of 1.

All other parameters were assigned intermediate scores (some scores of 2 and some of 3). Note that in general the scores for validation process were low for study 1: for most parameters there was hardly any explicit validation done, or the validation was done using sources that were not independent.

Table 11 shows the pedigree results of the input parameters to study 2. The pedigree scores of the equipment costs and escalation factors are high: the reviewers felt that the equipment costs were derived from a reliable and complete source (Aspen capital cost estimator) and were validated against other cost studies. The factors also received high scores because they are derived from official/measured industrial and vendor data and because they rely on a large sample of measured cost quotes.

The factor scores could be further improved if the database would be updated with more recent costing data and if the database would be validated with cost data from more and different manufacturing companies.

Solvent price and T&S costs show the lowest pedigree scores; for solvent price, the reported costs for the MHI KS1 solvent were used. The reviewers reasoned that although KS1 is believed to be a blend of AMP and PZ, this is not certain, hence it remains a proxy. In addition, the costs were derived from a 2004 MHI company presentation that may not be that reliable, or may not represent the actual current costs. Therefore, low scores for *reliability of source* and *completeness* were assigned.

Owner's costs and IDC was considered relatively certain, because based on the IEAGHG report, but still a proxy because a generic factor was derived from this report rather than estimating each owner's costs individually. Also, although IEAGHG is a highly regarded source, the experts were unable to verify in how far the IEAGHG owner's costs and IDC estimates were based on actual industrial data, hence the score of 2 for *reliability of source*.

Last, efficiency penalty was judged relatively certain, represented by scores of 2 and 3 and based on the pedigree scores for the AMP/PZ performance model presented in Van der Spek et al. (2016a).



**Table 10**

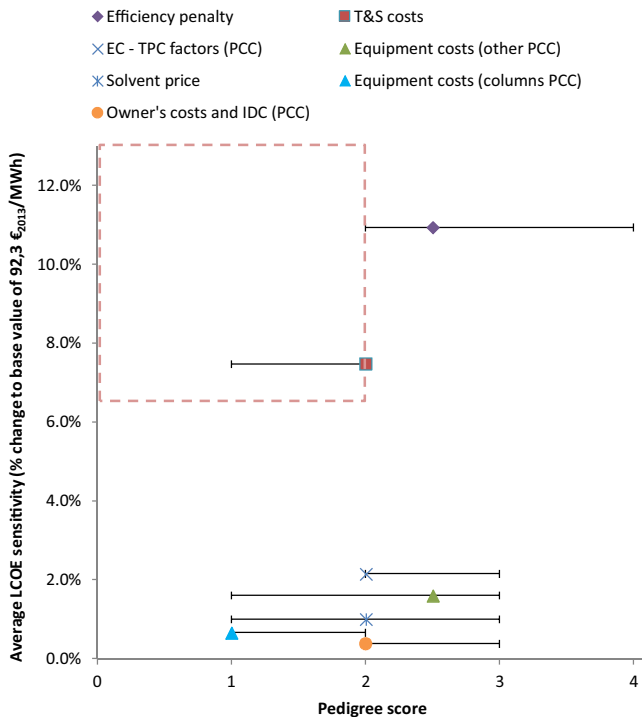
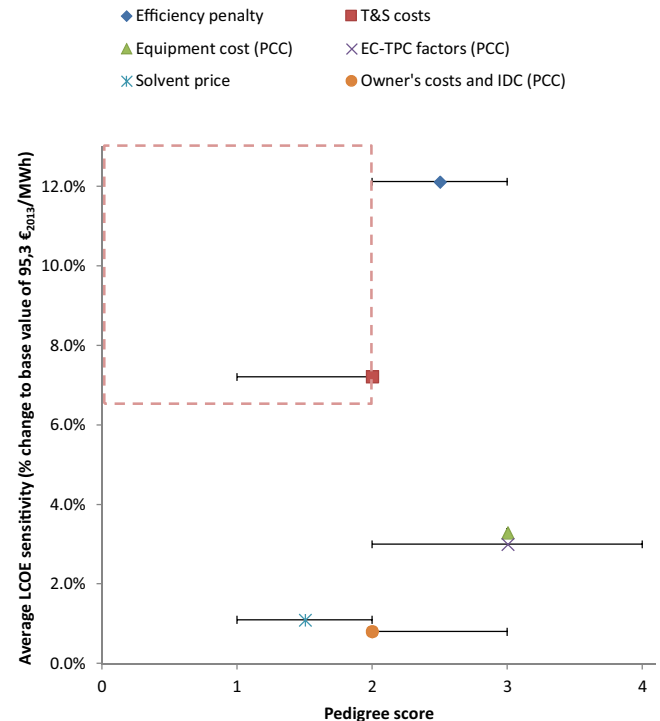
Study 1: pedigree scores of the input data of the economic model. Colours used for visual aid.

Input parameter quality indicators AMP/PZ model study 1				
	Proxy	Reliability of Source	Completeness	Validation process
Efficiency penalty	4	2	3	2
T&S costs	2	2	2	1
EC-TPC factors (PCC)	3	2	2	2
Equipment costs (other PCC)	3	3	2	1
Solvent price	3	3	1	1
Equipment costs (columns PCC)	2	1	1	1
Owner's costs and IDC	2	2	3	2

**Table 11**

Study 2: pedigree scores of the input data of the economic model. Colours used for visual aid.

Input parameter quality indicators AMP/PZ model study 2				
	Proxy	Reliability of Source	Completeness	Validation process
Efficiency penalty	3	2	2	3
T&S costs	2	2	2	1
Equipment cost (PCC)	3	3	3	3
EC-TPC factors (PCC)	3	4	3	2
Solvent price	2	1	1	2
Owner's costs and IDC	2	2	3	2

**Fig. 8.** Study 1: diagnostic diagram of the models for the LCOE. The red dashed quadrant includes parameters to which LCOE is most sensitive and that are highly uncertain, indicating weakness in the economic model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)**Fig. 9.** Study 2: diagnostic diagram of the models for the CCA. The red dashed quadrant includes parameters to which CCA is most sensitive and that are highly uncertain, indicating weakness in the economic model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 3.5.3. Diagnostic diagram

Figs. 8 and 9 combine the results of the sensitivity analysis and pedigree analysis in so-called diagnostic diagrams, see e.g. van der Sluijs et al. (2005). On the x-axis, these diagrams show the median

pedigree scores of the parameters, including the minimum and maximum values; on the y-axis, they show the average sensitivity of the LCOE to the same parameters, displayed as a percentage

change to its base value. The diagnostic diagrams thus provide a single overview of the sensitivity of the economic indicator to the parameters, as well as the strength of the parameters. Note that the upper left quadrant of the diagnostic diagram is marked with a dotted red line. This quadrant represents the zone in which parameters are least robust (red zone or red quadrant), because the output indicator is very sensitive to input parameters lying in this quadrant, and the strength of these indicators is low.<sup>4</sup> In this way, the diagnostic diagram has the ability to provide a clear and single overview of the robustness of economic indicators and clearly pinpoint potential weaknesses. This in turn allows for easy interpretation and communication of the robustness of techno-economic results.

The diagnostic diagrams for study 1 and 2 show a similar picture, but there are also some apparent differences. First, for both studies, only one parameter is located inside the red quadrant: *T&S costs*. Although not at the core of this study on PCC costing, it does provide a clear weakness in these LCOE estimates. Second, *efficiency penalty* is located nicely outside the red quadrant, which is favourable since this parameter contributes most to LCOE.

Continuing, the low strength of the parameters *equipment costs* (*columns PCC*) (study 1) and *solvent price* (study 2) present only little risk for the respective LCOE estimates, because sensitivity to these parameters is low; they are located well below the red zone in the diagnostic diagram.

Looking at the differences between study 1 and 2, the diagnostic diagrams indicate that study 1 is slightly less robust than study 2, with more parameters extending into the low pedigree scores. For the reliability of LCOE, this need not be a problem, given the low sensitivity of LCOE to these parameters. Last, note that in the presented uncertainty analyses of the high utilisation LCOE, the PCC capital costing parameters contribute relatively little to the LCOE, which was also shown in Section 3.3. However, this does not mean that the capital costs are an unimportant part of CCS power plant costing, because capital cost is a relevant performance indicator itself. If a diagnostic diagram were made for TCR, the sensitivity to the capital cost parameters would have been much higher, showing that the TCR estimate of e.g. study 1 would be on the weak side.

#### 4. Conclusions

This paper presented an analysis of uncertainties and variability of early stage techno-economic studies of CCS technologies. This was done by: (1) a detailed comparison of two techno-economic studies on AMP/PZ postcombustion capture from the same coal fired power plant; (2) comparison of these results with the results of other NGO/vendor published techno-economic studies; and (3) by uncertainty analysis using a combination of sensitivity analysis and pedigree analysis.

The results of this study showed a 65% difference in total capital requirement when comparing the two different AMP/PZ PCC studies, while both followed established capital costing procedures. This confirms that uncertainty in early stage capital cost estimates can be substantial and is likely inherent to this type of estimate. The capex uncertainties propagate only mildly into uncertainties in LCOE and CCA. This effect is stronger in case of low utilisation scenarios.

The analyses in this work further confirmed that the uncertainty and variability in capital cost estimates are present in every stage of

the assessment: from process modelling to equipment sizing and costing and contingency selection. In this particular case, variability in the capital costs was especially caused by differences in equipment sizing assumptions and equipment cost estimating methods, and to a lesser extent by differences in the results of the process model, the equipment included in the capture plant, and the factoring methods used. Uncertainties in the process model did however propagate strongly to LCOE, because of their strong influence on fuel costs and O&M costs.

It was also found hard to compare the values of our PCC equipment cost with NGO/vendor equipment cost estimates; the first may be less inclusive due to less experience with real process design, while the latter are often supplied as a lump sum, leaving out details that are relevant for comparison. Although the latter is understandable from an intellectual property perspective, it may prevent the scientific community to learn from industrial cost estimates.

We also showed that a combination of sensitivity analysis and pedigree analysis is a good means to provide insight into the impact of input parameters on techno-economic performance indicators, and to understand the strength and/or quality of those input parameters, clearly indicating the strengths and weaknesses of the techno-economic study as a whole. The benefit of using pedigree analysis complementary to quantitative uncertainty analysis is its ability to provide a figure of merit to a parameter, a feature that sensitivity analysis alone cannot do. Combination of the two in a diagnostic diagram allows easy to interpret communication of the robustness of a techno-economic performance indicator. The diagnostic diagrams showed that the LCOE estimates of study 1 and study 2 were robust, despite weaknesses in *equipment costs* (*columns PCC*) (study 1) and *solvent price* (study 2), because these only have a small influence on LCOE.

Based on the findings in this work we conclude that the simulation model is the most important part of estimating the costs (LCOE) of a novel PCC capture process, through its effect on the power plant efficiency and hence the fuel costs. Transport and storage costs are also of significant importance and are recommended to be estimated in much more detail than is done in current practice. For the purpose of early stage cost assessment, currently used capture and compression plant capital costing methods are reliable enough because they have little influence on the LCOE, despite their –30% +50% uncertainty margins.

#### Acknowledgments

This work is part of the European project EDDiCCUT, which is supported by the Norwegian Research Council under project number 218952 and by an industrial consortium (Bharat Petroleum, Uniper, and Norske Shell). We would like to thank Giampaolo Manzolini (Politecnico di Milano) and Wouter Shakel (Utrecht University) for their contribution to the pedigree analysis. Eva Sanchez and Andrea Ramirez were the other expert reviewers for the pedigree analysis. We would also like to thank Svein Bjørnsen, Dennis Jong, and Leon Pulle for their valuable discussions on capital cost estimation, project finance, and project evaluation.

#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ijggc.2016.11.021>.

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<sup>4</sup> Note that in this study it was chosen to place the borders of the red quadrant at 50% of max average sensitivity and at a pedigree score of 2 (also 50% of maximum). This is common practice in diagnostic diagrams (van der Sluijs et al., 2005), but exceptions can be made. For instance, if a certain indicator overrun is assumed unacceptable, than the placement of the quadrant's lower border can be adjusted accordingly, to show which parameters may cause such overrun.

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