

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18
November 2016, Lausanne, Switzerland

Techno-economic performance of state-of-the-art oxyfuel technology for low-CO₂ coal-fired electricity production

Mijndert van der Spek^{a*}, Nils Henrik Eldrup^b, Ragnhild Skagestad^b, Andrea Ramirez^a

^a*Copernicus Institute of Sustainable Development, Section Energy & Resources, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands.*

^b*Tel-Tek, Kjølnes ring 30, 3918 Porsgrunn, Norway.*

Abstract

This work presents a techno-economic analysis of a 2015 state-of-the art ASC PC oxyfuel power plant. This work adds to the existing body of techno-economic studies on coal oxycombustion that use less advanced oxyfuel technology and/or steam cycles. The study shows that this oxyfuel configuration has a net efficiency about 2%-pt. higher than a similar ASC PC plant with MEA postcombustion technology. This is partly due to the high gross efficiency of the oxyfuel power plant. The capital costs, LCOE, and cost of CO₂ avoided of the oxyfuel configuration are, however, slightly higher than those of the MEA configuration, despite the high efficiency of the oxyfuel plant. This means that the good technical performance of this state of the art oxy-fired coal plant is not necessarily translated into equally favourable economic performance. Rather, oxyfuel and PCC performance are rather comparable.

© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: Oxyfuel; Advanced super critical pulverised coal; techno-economic assesment; EBTF

1. Introduction

CO₂ Capture and Storage (CCS) is considered a necessary strategy to deeply decarbonise our energy system and industrial sector [1]. The last two decades have yielded many new developments in carbon capture technologies for

* Corresponding author. Tel.: +31-30-2536466

E-mail address: m.w.vanderspek@uu.nl

power plants and/or industrial sources, and some of these technologies have progressed to commercial state [2]–[5].

Oxyfuel combustion is one of the technologies for coal power plant decarbonisation that has significantly progressed over the last years. However, not all these improvements have been included in existing techno-economic performance studies, and thus modelling results of the currently best achievable performance is lacking. Therefore, this work aims to create a 2015 timestamp for coal oxy-combustion, using the most advanced power plant technology that could be purchased at the moment of writing, thereby adding to the existing body of studies that typically use somewhat less sophisticated power plant configurations [6]–[8], but without anticipating on further technology development in the coming decades (e.g. Santos 2014).

2. Approach

The approach in this study included four steps: 1) design of the oxyfuel coal power plant. State-of-the-art technologies were used in the design; 2) assessment of the oxyfuel plant's technical performance; 3) assessment of the oxyfuel plant's economic performance; and 4) comparison to the performance of a coal power plant with benchmark postcombustion (MEA) technology [10].

2.1. Oxyfuel plant design

The standard coal power plant areas (coal boiler, steam cycle) in this study were based on the design suggested by the European Benchmarking Task Force [11]. It contains an advanced supercritical (ASC) steam cycle,

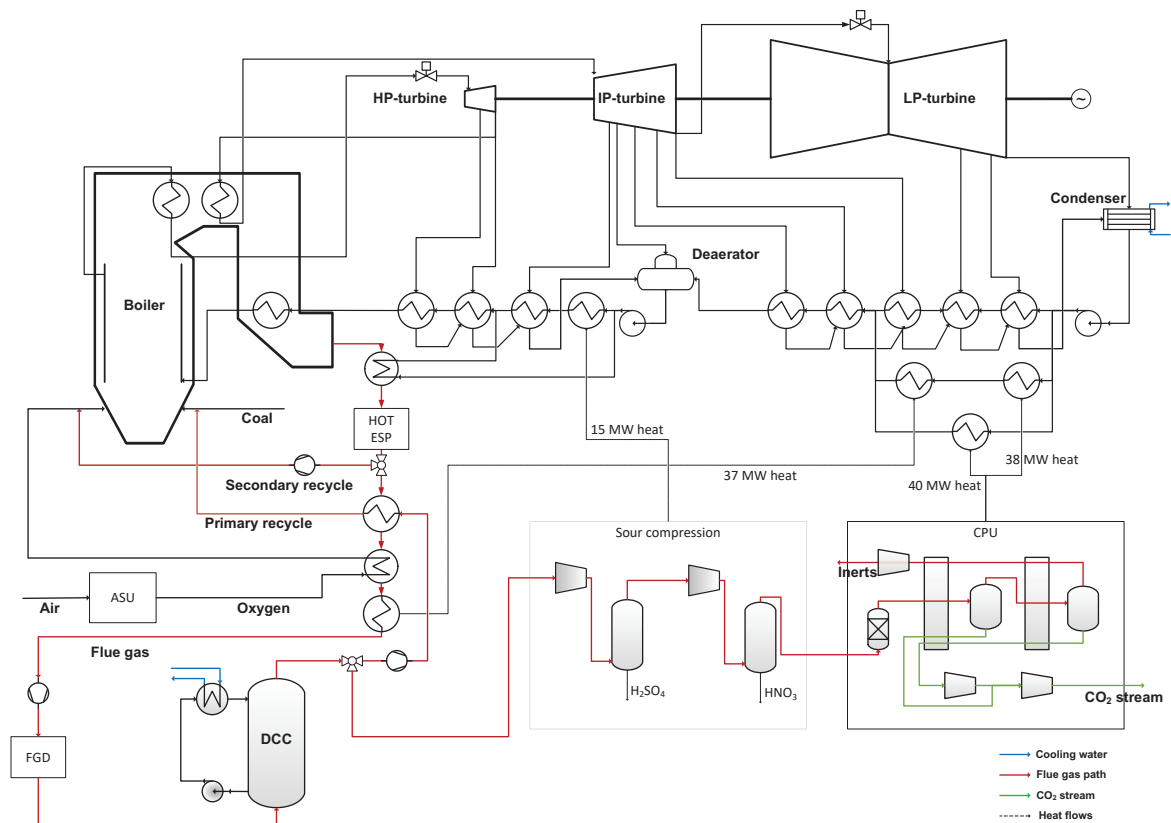


Figure 1. PFD of the oxyfuel coal power plant configuration. The figure shows the heat integration of the steam cycle with flue gas cooling, sour compression, and CPU.

Table 1. Power plant boundary conditions (based on the EBTF guidelines [11]).

Parameter	Unit	Value
Ambient Conditions		
Ambient temperature	°C	15
Ambient pressure	bar	1,01325
Ambient humidity	%	60
Cooling water temperature ¹	°C	12
Cooling water max T increase ¹	°C	7
Cooling water pressure ¹	bar	2,5
CO ₂ stream conditions		
CO ₂ capture rate	%	90
CO ₂ pressure for transport	bar	110
CO ₂ purity	%	>96
CO ₂ water content	ppmv	< 200
Emissions Settings ²		
SO ₂ (at 6% O ₂ , dry basis)	mg/m ³	85
NO _x (at 6% O ₂ , dry basis)	mg/m ³	120
Particles (at 6% O ₂ , dry basis)	mg/m ³	8

¹ [6]; ² These are the emission guidelines as stated by the European Commission for large combustion plants [11].

and the environmental controls to operate under current European emission regulations (Figure 1, Table 1). The design of the flue gas cleaning and recycle section includes a hot ESP for particulate removal. A hot ESP was selected over a cold ESP for reasons of exergy conservation, at the expense of ESP size, and thus capital costs. After the ESP a hot secondary recycle is split from the flue gas stream and returned to the boiler after combination with the ASU produced oxygen stream. The remainder of the flue gas stream continues down the cleaning section through a traditional wet flue gas desulphurisation unit (FGD, to limit the amount of Sulphur recycled to the boiler) and a direct contact cooler (DCC; to reduce the temperature of the flue gas). After the DCC the primary recycle is split from the flue gas stream. The primary recycle is reheated in the recycle preheater, and is used to dry and fluidize the coal dust entering the boiler.

Table 2. Oxyfuel specific design assumptions.

Parameter	Unit	Value	Values used in other sources
Oxygen purity	%	95 ¹	95-97 [9]; 95 [6]; 96,5 [12]
Excess Oxygen Rate (at burner)	%	13,2 ²	10 [13]
Oxygen pressure	bar	1,1	Near ambient [9]; 1,2 [12]
Specific energy demand	kWh/t O ₂	180 ¹	>140 [9]; 170 [12]; 150 [14]
Steam demand for ASU air dryer	Kg/s	8 ¹	
Oxygen concentration in oxidator	%vol	approx. 30 ³	30 [13]
Air leakage in boiler / flue gas path	%vol	2 ¹	2 [15]
Adiabatic Flame Temperature	°C	2075 ²	
Primary recycle flow for fuel feed	kg/kg coal	2,6 ⁴	2 m ³ /kg [16]
Steam demand CPU CO ₂ dryer	Kg/s	4 ⁵	

¹ [17]; ² Same value applied as in air-fired mode; ³ [18]; ⁴ [6]; ⁵ Estimated half of steam use for ASU air dryer.

The CO₂ Purification Unit (CPU) includes sour compression to 30 bar following the Air Products design [19] in which SO_x and NO_x are removed as liquid acids. Because our study assumed a relatively loose CO₂ purity of > 96% (

Table 1), the CPU design could suffice with a cryogenic dual flash inert removal system operating in a cold box at a minimum of -50°C. Therefore, we followed the CPU design presented in the recent IEAGHG report [7]. More sophisticated designs using cryogenic distillation columns are only necessary in case a higher CO₂ purity is required. After separating the inerts (O₂, N₂, Ar), the CO₂ rich stream is compressed to 110 bar. The inert stream is depressurized over an expander, producing a small additional amount of electricity. The selected air separation unit (ASU) is an energy efficient 3 column design, applying three pressure levels, and producing a 95% pure oxygen stream. The oxygen stream is preheated before being combined with the secondary recycle through heat integration with the flue gas stream. Overall, a high level of heat integration between steam cycle, FG cleaning, CPU, and ASU was used, to improve the efficiency of the oxyfuel power plant (see Figure 1).

2.2. Process modelling

The technical performance of the oxyfuel power plant was modelled in Aspen Plus V8.4 using the input specifications shown in Table 2. The advanced super critical steam cycle was modelled using the design specifications of the EBTF [11], [20], [21].

2.3. Economic evaluation

The capital costs of the power plant were calculated using a combination of the exponent method and the detailed individual factoring method [10]. The power plant block was scaled to the required coal input, gross power output, and flue gas flow rate using earlier estimates presented in the NETL cost and performance baseline (NETL 2010: case 11). The ASU was scaled to the required size using an earlier ASU cost estimate by IEAGHG [7]. The equipment costs of the hot ESP, DCC, and CPU were calculated based on equipment sizes derived from the process model using the Aspen capital cost estimator. The total cost of these equipment was calculated by multiplying its bare equipment cost with an individual factor.

Table 3. Oxyfuel power plant operating cost assumptions used in this study.

Cost item	Unit	Value
<i>Power plant</i>		
Coal	€/tonne	80 ^a
Fixed operating costs	k€/a	26.417 ^b
MU & WT chemicals	k€/a	1.345 ^b
Limestone	€/tonne	20,09 ^c
Ash disposal	€/tonne	15,08 ^c
Gypsum sales/disposal	€/tonne	0
<i>ASU, sour compression, and CPU</i>		
Maintenance	% TPC/a	4 ^d
Process water	€/m ³	1 ^e
Operators & supervision	k€/a	421,5 ^f
Plant technologist	k€/a	100 ^g
<i>Transport & Storage</i>		
Transport (180 km offshore)	€/tonne	6 ^h
Storage (offshore DOGF)	€/tonne	10 ⁱ

^a 2010–2014 average price of steam coal imported to the Netherlands from non-EU countries [23]. Validated against IEA coal information 2013 [24] (coal import prices to western Europe). ^b Costs are presented in the NETL study as US\$₂₀₀₇/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, first converted to €₂₀₀₇ using the 2007 exchange rate of 1,3705 and then converted to €₂₀₁₄ using the HCPI index (+12,9%). ^c Costs are presented in the NETL study as US\$₂₀₀₇/ton (short ton). First, they were adjusted to US\$₂₀₀₇/metric tonne, using the ratio of 0,907. Then, they were converted to €₂₀₀₇ using the 2007 exchange rate of 1,3705 and converted to €₂₀₁₄ using the HCPI index (+12,9%). ^d [25]. ^e [26]. ^f Wage information retrieved from the Norwegian Confederation of Trade Unions [27]. 1 additional operator assumed in 6 shift rotation. ^g Wage information retrieved from the Confederation of Norwegian Enterprises [28]. One additional plant technologist assumed. ^h [29]. ⁱ [30].

The final capital costs were presented as total plant cost (TPC). Following Rubin et al. [31], the TPC calculated in this study includes installed equipment costs, engineering, procurement, and contracting, and project contingencies.

Table 3 presents an overview of the operating cost items used in this study. The fixed operating costs of the oxyfuel plant were based on the NETL study [22]. The variable operating costs were calculated using the mass and energy balance of the process model, multiplying them with unit costs. CO₂ transport and storage costs of €16 per tonne CO₂ were used based on two ZEP reports [29], [30], assuming a distance of 180km for offshore transport and storage in a depleted oil and gas field (DOGF).

Levelised cost of electricity and cost of CO₂ avoided were calculated following the definitions in Rubin et al. [31], using a real discount rate of 7,5%, and a power plant lifetime of 40 years including four years for construction. Two load scenarios were calculated: a full load scenario of 7446h/a (85% CF) and a part load scenario of 4000h/a (~45% CF). Costs were calculated in 2014 Euro.

3. Results

Figure 2 presents the energy balance of the oxycombustion ASC coal power plant. As with any coal fired power plant, there are significant exergy losses during coal combustion and heat rejection in different sections of the power plant. Typical for an oxyfuel configuration are the additional electricity production by the inert gas expander and the high parasitic loads of the ASU and the CPU (mainly due to energy required for compression).

The technical performance indicators (Table 4) show that the ASC oxyfuel power plant produces electricity at a higher efficiency than an ASC pulverized coal plant using standard MEA postcombustion technology.

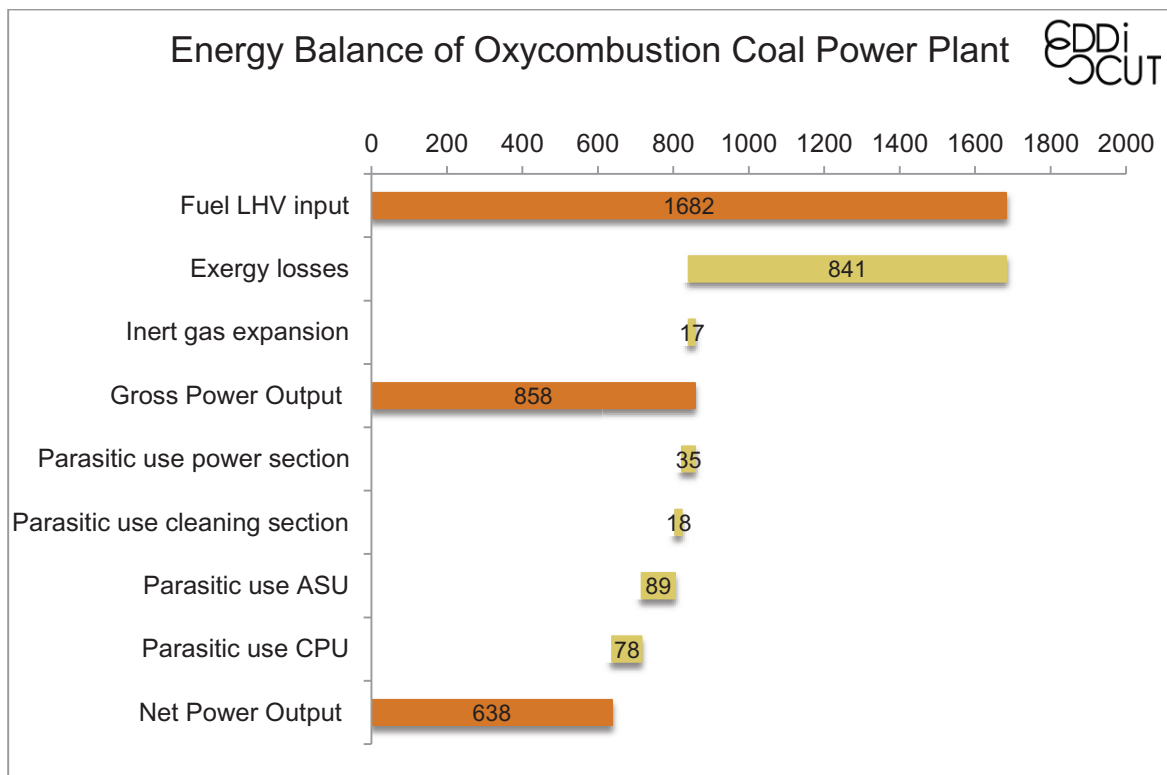


Figure 2. Water fall diagram of energy input, losses, parasitic load, and resulting output.

Table 4. Techno-economic performance of the oxyfuel ASC coal power plant compared with a reference case (w/o CCS) and a postcombustion case (MEA).

Performance indicator	w/o CCS	ASC OXY	ASC MEA
<i>Technical indicators</i>			
Gross efficiency LHV (%)	49,5	51,0	43,2
Net efficiency LHV (%)	46,1	37,9	36,2
SPECCA (GJ/t CO ₂) ¹		2,6	3,4
Specific CO ₂ intensity (kg/MWh)	734	87	94
Specific cooling water use (kg/MW _e)	34,4	50,1	55,4
<i>Economic indicators full load</i>			
Total Plant Cost (M€ ₂₀₁₄)	1.094	1.609	1.417
OPEX (M€ _{2014/a})	181	285	270
LCOE (€ ₂₀₁₄ /MWh)	49	91	88
Cost of CO ₂ Avoided (€ ₂₀₁₄ /t CO ₂)		65,3	61,8
<i>Economic indicators part load²</i>			
Total Plant Cost (M€ ₂₀₁₄)	1.094	1.609	1.417
OPEX (M€ _{2014/a})	97	174	152
LCOE (€ ₂₀₁₄ /MWh)	67	130	120
Cost of CO ₂ Avoided (€ ₂₀₁₄ /t CO ₂)		97,5	82,8

¹Specific Primary Energy Consumption per tonne of CO₂ Avoided. ²The costs of part load were calculated assuming the power plant is “on” 4000h/a, running at its maximum generating capacity, or “off” the remainder of the year, standing idle. Efficiency losses and costs of start-up and shutdown and/or flexible operation are excluded.

The gross efficiency of the oxyfuel plant is higher than the gross efficiency of the reference plant without capture, which is explained by the rigorous integration of rejected heat from the FG cleaning train, sour compression, and CPU, with the steam cycle. The net power output is over 8%-point lower than that of the reference plant, but is almost 2 %-point higher than the power plant with MEA. Because of the high level of integration of the downstream processes with the steam cycle, also the specific cooling water intensity of the oxyfuel configuration is lower than that of the postcombustion configuration. Thus, from a technical performance perspective, this state of the art oxyfuel configuration shows clear benefits over a coal plant with a standard MEA postcombustion line-up.

From a cost perspective however, oxyfuel capture is slightly more expensive than MEA capture under the given conditions (Table 4). The capital costs of the MEA case are almost 200 M€ lower than that of the oxyfuel plant. In terms of levelised costs this is partly offset by the oxyfuels’ higher net efficiency. This higher efficiency leads to a higher power output per unit of coal input, and hence lower fuel costs (included in opex) to produce a unit of energy. Also, Table 4 shows that where the calculated LCOE (and thus cost of CO₂ avoided) of oxyfuel and MEA are comparable for the full load scenario, the high capital costs start to weigh more heavily on the oxyfuel configuration in the part load scenario, leading to substantially higher levelised indicator values.

The results of this study show a slightly different outcome than the results of the IEAGHG study on oxyfuel power plants [7]. For instance, this works’ reference coal power plant and oxyfuel plant show net efficiencies that are 2%-point higher, which is explained by the use of an advanced SC steam cycle in this work, versus a normal SC steam cycle in the IEAGHG study. Also, the technical performance of the postcombustion system used in the IEAGHG study is almost similar to their oxyfuel performance; in our study the oxyfuel efficiency is clearly better. Conversely, their PCC costs are higher than their oxyfuel costs, which contradicts the findings in this work, where oxyfuel costs are higher. This may be attributed to the use of a more expensive Cansolv PCC system, instead of the “standard” MEA system. Comparison with the IEAHG study thus indicates that oxyfuel and PCC performance depend strongly on technology and design assumptions and that it would be difficult to state that one technology outperforms the other. Rather, it can be concluded that both technologies show comparable techno-economic performance and the best solution for a specific low CO₂ coal power project will depend on project specific technology requirements.

4. Conclusion

In this work we presented a techno-economic analysis of a 2015 state of the art ASC PC oxyfuel power plant. The study showed that this oxyfuel configuration has a net efficiency some 2%-pt higher than the same ASC PC plant with standard MEA postcombustion technology. This is partly due to the high gross efficiency of the oxyfuel power plant. The capital costs, LCOE, and cost of CO₂ avoided of the oxyfuel configuration are slightly higher than those of the MEA configuration, despite the high efficiency of the oxyfuel plant. This means that the good technical performance of this state of the art oxy-fired coal plant is not necessarily translated into equally favourable economic performance. Other studies may show a slightly different picture, indicating the dependence of technology performance on specific design assumptions, and also indicating that PCC and oxyfuel generally show rather similar techno-economic performance.

Acknowledgements

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, Norske Shell, and Uniper).

References

- [1] IPCC, "CLIMATE CHANGE 2014 Synthesis Report Summary for Policymakers," Geneva, 2014.
- [2] J. C. Abanades, B. Arias, A. Lyngfelt, T. Mattisson, D. E. Wiley, H. Li, M. T. Ho, E. Mangano, and S. Brandani, "Emerging CO₂ capture systems," *Int. J. Greenh. Gas Control*, 2015.
- [3] Z. (Henry) Liang, W. Rongwong, H. Liu, K. Fu, H. Gao, F. Cao, R. Zhang, T. Sema, A. Henni, K. Sumon, D. Nath, D. Gelowitz, W. Srisang, C. Saiwan, A. Benamor, M. Al-Marri, H. Shi, T. Supap, C. Chan, Q. Zhou, M. Abu-Zahra, M. Wilson, W. Olson, R. Idem, and P. (Pt) Tontiwachwuthikul, "Recent progress and new developments in post-combustion carbon-capture technology with amine based solvents," *Int. J. Greenh. Gas Control*, vol. 40, pp. 26–54, 2015.
- [4] R. Idem, T. Supap, H. Shi, D. Gelowitz, M. Ball, C. Campbell, and P. Tontiwachwuthikul, "Practical experience in post-combustion CO₂ capture using reactive solvents in large pilot and demonstration plants," *Int. J. Greenh. Gas Control*, vol. 40, pp. 6–25, 2015.
- [5] T. Wall, R. Stanger, and S. Santos, "Demonstrations of coal-fired oxy-fuel technology for carbon capture and storage and issues with commercial deployment," *Int. J. Greenh. Gas Control*, vol. 5, no. SUPPL. 1, 2011.
- [6] IEAGHG, "Water Usage and Loss Analysis of Bituminous Coal Fired Power Plants with CO₂ Capture, 2010/05," Stoke Orchard, 2010.
- [7] IEAGHG, "CO₂ CAPTURE AT COAL BASED POWER AND HYDROGEN PLANTS. Report 2014/3," Cheltenham, 2014.
- [8] J. Ciferno, J. Haslbeck, J. Black, N. Kuehn, E. Lewis, M. Rutkowski, M. Woods, and V. Vaysman, "Pulverized Coal Oxycombustion Power Plants Volume 1 : Bituminous Coal to Electricity Final Report," 2008.
- [9] S. Santos, "Oxy-Coal Combustion Power Plant with CCS Current Status of Development," in *7th Dutch CCS Symposium*, 2014, no. June.
- [10] M. van der Spek, E. Sanchez Fernandez, N. H. Eldrup, R. Skagestad, A. Ramirez, and A. Faaij, "Unravelling uncertainty and variability in early stage techno-economic assessments of carbon capture technologies," *Int. J. Greenh. Gas Control*.
- [11] Cesar, "D2.4.3. European Best Practice Guidelines for Assessment of CO₂ capture technologies," Brussels, 2011.
- [12] L. Strömberg, "Discussion on the ' big picture ' for the development of the Oxyfuel technology," in *The 5th oxyfuel capacity building course*, 2013, no. September.
- [13] M. B. Toftegaard, J. Brix, P. a. Jensen, P. Glarborg, and A. D. Jensen, "Oxy-fuel combustion of solid fuels," *Prog. Energy Combust. Sci.*, vol. 36, no. 5, pp. 581–625, 2010.
- [14] N. Perrin, R. Dubettier, F. Lockwood, J.-P. Tranier, C. Bourhy-Weber, and P. Terrien, "Oxycombustion for coal power plants: Advantages, solutions and projects," *Appl. Therm. Eng.*, vol. 74, pp. 75–82, 2014.
- [15] I. Pfaff and A. Kather, "Comparative thermodynamic analysis and integration issues of CCS steam power plants based on oxy-combustion with cryogenic or membrane based air separation," *Energy Procedia*, vol. 1, no. 1, pp. 495–502, Feb. 2009.
- [16] I. Pfaff, "Information on oxyfuel power plants. Personal communication." 2015.
- [17] J. Dickmeis and a. Kather, "The Coal-fired Oxyfuel-process with Additional Gas Treatment of the Ventgas for Increased Capture Rates," *Energy Procedia*, vol. 63, pp. 332–341, 2014.
- [18] T. Wall, Y. Liu, C. Spero, L. Elliott, S. Khare, R. Rathnam, F. Zeenathal, B. Moghtaderi, B. Buhre, C. Sheng, R. Gupta, T. Yamada, K.

- Makino, and J. Yu, "An overview on oxyfuel coal combustion-State of the art research and technology development," *Chem. Eng. Res. Des.*, vol. 87, no. November 2008, pp. 1003–1016, 2009.
- [19] V. White, L. Torrente-Murciano, D. Sturgeon, and D. Chadwick, "Purification of oxyfuel-derived CO₂," *Int. J. Greenh. Gas Control*, vol. 4, no. 2, pp. 137–142, 2010.
- [20] M. Van der Spek, R. Arendsen, A. Ramirez, and A. Faaij, "Model development and process simulation of postcombustion carbon capture technology with aqueous AMP/PZ solvent," *Int. J. Greenh. Gas Control*, vol. 47, pp. 176–199, 2016.
- [21] M. Van der Spek, A. Ramirez, and A. Faaij, "Improving model uncertainty evaluation by using pedigree matrices. A case study on CO₂ capture with Monoethanolamine," *Comput. Chem. Eng.*, vol. 85, pp. 1–15, 2016.
- [22] NETL, "Cost and Performance Baseline for Fossil Energy Plants Volume 1 : Bituminous Coal and Natural Gas to Electricity Revision 2, November 2010," 2010.
- [23] CBS, "Steam coal; import price from non-EU countries," *Centraal Bureau voor de Statistiek*, 2015. [Online]. Available: <http://statline.cbs.nl/StatWeb/publication/?DM=SLEN&PA=37215ENG>. [Accessed: 02-Sep-2015].
- [24] IEA, "Coal information 2013," Paris, 2013.
- [25] T. Melien and S. Brown-Roijen, "Economics," in *Carbon dioxide capture for storage in deep geologic formations - results from the CO₂ capture project. Volume three: advances in CO₂ capture and storage technology. Results (2004-2009)*, First Edit., L. I. Eide, Ed. Newbury, UK: CPL Press, 2009, p. 470.
- [26] R. K. Sinnott, *Coulson & Richardson's Chemical Engineering Volume 6.*, Fourth Edi. Oxford: Butterworth-Heinemann, 2004.
- [27] LO, "Wage information Norway," *Norwegian confederation of trade unions*, 2014. [Online]. Available: www.lo.no/lonn--tariff. [Accessed: 04-Sep-2015].
- [28] NHO, "Information about wages in Norway," *Organisation of Norwegian Employers*, 2014. [Online]. Available: <https://www.nho.no/en>. [Accessed: 04-Sep-2015].
- [29] Zep, "The Costs of CO₂ Transport. Post-demonstration CCS in the EU," Brussels, 2011.
- [30] Zep, "The Costs of CO₂ Storage: Post-demonstration CCS in the EU," Brussels, 2011.
- [31] E. S. Rubin, C. Short, G. Booras, J. Davison, C. Ekstrom, M. Matuszewski, and S. McCoy, "A proposed methodology for CO₂ capture and storage cost estimates," *Int. J. Greenh. Gas Control*, vol. 17, pp. 488–503, 2013.