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Report

Understanding the Cost of Retrofitting CO2 capture in an Integrated Oil Refinery

Cost estimation and economic evaluation of CO2 capture options for refineries

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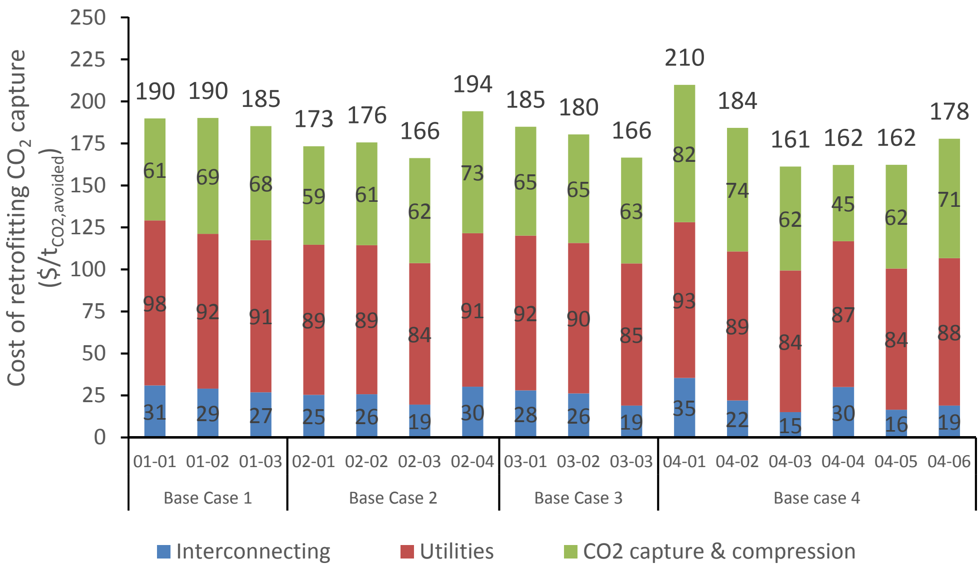

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ABSTRACT

Post combustion capture with MEA from four generic refineries was modelled and simulated. Altogether 16 different capture cases were evaluated (3-6 per generic refinery) for four refineries with nominal capacity of 100 000-350 000 bbl/day and CO_2 emissions of 729-3350 ktonnes/year. The cost of integrating CO_2 capture into the refinery including utilities plant costs and ducting and clearing space for absorbers and FGDs is assessed for each of the 16 capture cases.

The cost lies between 160 and 210 $\$/t_{CO2,avoided}$ with significant variations between capture and refinery cases. The cost variations between captures cases are linked to flue gas CO_2 content, amount of CO_2 capture, interconnecting characteristics strategy, CO_2 emission source location in the refinery, etc. Through the difference cases, the overall CO_2 avoided cost breakdown is as follows: 30-40% of costs linked to CO_2 capture and conditioning, 45-55% linked to utilities, and 10-20% linked to interconnecting costs. Furthermore, the total capital requirement lies between 200 and 1 500 M$ depending especially on the amount of CO_2 captured.

Sensitivity analyses reveal that reducing the large utilities costs through reduced spare capacity and advanced solvents could improve the competitiveness of retrofitting CO_2 capture to integrated oil refineries.

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Table of contents

Summary

Report approach

This report describes and analyses the cost of retrofitting CO_2 capture from refineries. The costs of retrofitting CO_2 capture of 16 CO_2 capture cases, developed and designed for four generic integrated oil refineries, are assessed and analysed considering Mono Ethanol Amine (MEA) based CO_2 capture.

Compared to other studies on CO_2 capture, the assessments performed in this report focuses on retrofit costs including modifications in the refineries, interconnections, and additional CHP and utility facilities. The main focus is on CO_2 capture from refinery Base Case 4, which is seen as the most relevant reference for existing European refineries of interest for CO_2 capture retrofit. Considering the large number of cases (16) and their complexity, a hybrid methodology is used in order to evaluate the cost of the sections (CO_2 capture and compression, utilities, and interconnecting) of the concept. In this approach, four of the 16 capture cases are selected to represent a wide range of CO_2 capture capacity and flue gas CO_2 content and assessed in detail, based on the cost methodology presented in *Technical Design Basis and Economic Assumptions*. These detailed cost assessments form, based on subsequent scaling, the basis for the assessment of the other cases.

Finally, sensitivity analyses are carried out for each of the 16 CO_2 capture cases in order to quantify the impact of the expect cost range accuracy, key parameter assumptions and project valuation parameters.

A review of the IEAGHG technical report "Techno-Economic Evaluation of SMR based standalone (merchant) hydrogen plant with CCS" was performed and compared to capture Case 04-04 (a case with CO_2 capture from the refinery SMR only). Insights on the effects of tight integration of the hydrogen plant with the refinery and additional CHP plant are provided.

Results

The results of the cost evaluation of the 16 CO_2 capture cases shows that the cost of retrofitting CO_2 capture lies between 160 and 210 $\$/t_{CO2,avoided}$ as shown in Figure 1. These estimates are significantly larger than estimates available in the literature on CO_2 capture for other sources (natural gas and coal power generation, cement, steel, etc.). Three main reasons for this difference are:

- The inclusion of the retrofit costs such as interconnection costs.
- The utilities cost is based on the installation of an additional CHP plant, cooling water towers and waste water plant which are all designed with significant spare capacity in some cases (up to 30% overdesign).
- Most of the CO_2 capture cases considered include small to medium CO_2 emission point sources and/or low to medium flue gas CO_2 content (7 of the 16 cases considered include only flue gases with CO_2 contents below or equal to 11.3%vol).

Although the cost distribution is specific to each case considered, the overall breakdown is as follows: 30-40% of costs linked to CO_2 capture and conditioning, 45-55% linked to utilities production, and 10-20% linked to interconnecting costs.

In terms of investment cost, the estimations show that the total capital requirement lies between 200 and 1500 M$ for the different case as shown in Figure 2. The main reasons for this wide range is mainly the differences in the amount of CO_2 captured between the cases. It is worth noting that although a case may be cheaper in terms of normalised cost ($\$/t_{CO2,avoided}$), high total capital requirement could make it less attractive.

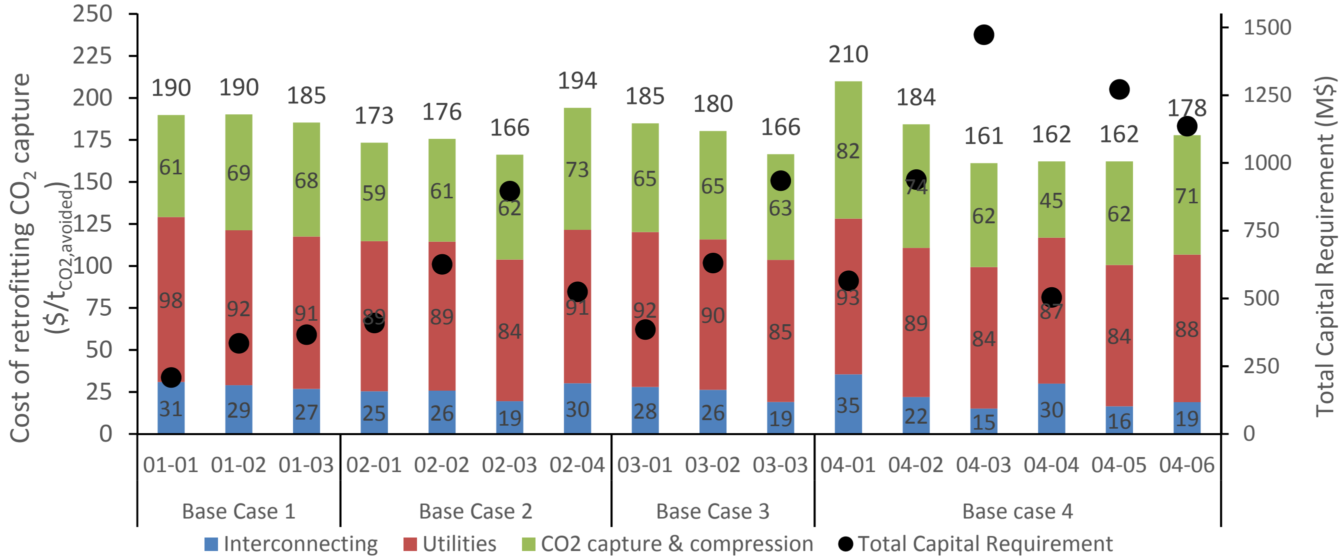


Figure 1. Cost of retrofitting CO_2 capture of all cases considered for the four refinery base cases with breakdown by section

When looking more in detail on the differences between the cases, the results show that cases in which the amount of CO_2 avoided is the largest tend to lead to lower costs of retrofitting the CO_2 capture as shown in Figure 2. However, it is important to understand that the differences between the cases are significantly more complex than differences in scale. Indeed, the different cases have significant differences in for example flue gas CO_2 concentration, number of flue gas desulphurisation units, interconnecting distances and capture capacity.

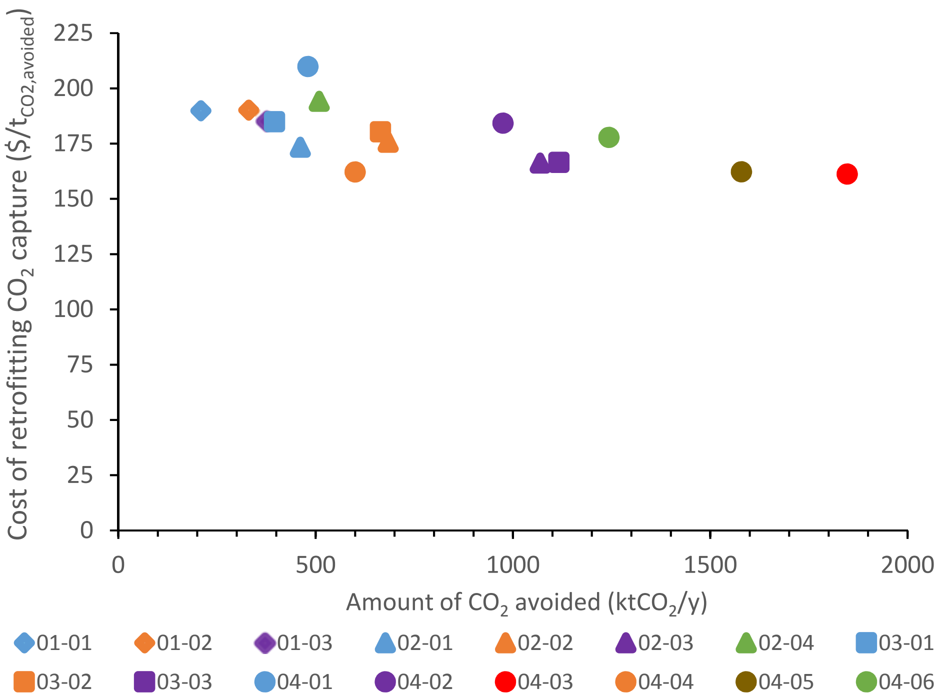


Figure 2. Costs of retrofitting CO_2 capture compared to amount of CO_2 avoided

In sum, the CO_2 avoidance cost depends on many parameters. However, given the relatively large number of cases and capture options studied in this work, it is possible to provide an overview or trend of the CO_2 avoidance cost of different CO_2 capture cases with different characteristics. Table 1 provides a range CO_2 avoidance costs for capture characteristics such as flue gas CO_2 concentration, amount of CO_2 captured and fraction of gas that requires desulphurisation treatment. This table will allow the reader to establish a very rough estimate of the cost if retrofitting CO_2 capture in a refinery given these characteristics. This along with the cost laws to estimate the CAPEX of the CO_2 capture plant, utilities and interconnecting section provide tools to interpolate or if required extrapolate from the results presented in this report.

Table 1. Overview of CO_2 avoidance cost and related characteristics

CO_2 avoidance cost ($\$/t_{CO2,avoided}$)	Characteristics	Capture Cases
210	Very low CO_2 concentration in flue gas (4-5%) coupled with a small amount of CO_2 captured (around 750 kt_{CO2}/y)	04-01
200-180	Low to medium CO_2 concentration in flue gas (6-9%), very low amount of CO_2 captured (300-600 kt_{CO2}/y), significant fraction of the flue gases require FGD (50-100%) or a combination of these factors	02-04, 01-02, 01-01, 03-01, 01-03, 04-02
180-170	Low to medium CO_2 concentration in flue gas (6-9%), low amount of CO_2 captured (600-750 kt_{CO2}/y), small fraction of the flue gases require FGD (20-50%) or a combination of these factors	03-02, 04-06, 02-02, 02-01
170-160	medium to high CO_2 concentration in flue gas (10-18%), large amount of CO_2 captured (2000-3000 kt_{CO2}/y), small fraction of the flue gases require FGD (<10%) or a combination of these factors	03-03, 02-03, 04-05, 04-04, 04-03

Topics for further investigation

Sensitivity analyses show that there are opportunities to reduce the cost of utilities that merit further investigation, for example:

- With the objective to *reduce the steam* (and if possible power) *requirement* for CO_2 capture and compression: Evaluation of advanced solvents with lower specific heat requirement as well as other CO_2 capture technologies[1].
- *Use of readily available waste heat* within the refinery plant as well as (when relevant) from nearby industries in combination with purchase of the necessary power for CO_2 capture and compression from the grid, preferably from renewable power or large efficient thermal power plants with CO_2 capture.
- *Lower utilities investment cost through reduced design margins:* The design of CHP plant has been performed considering significant overdesign in some cases (up to 30%). In practice, this over-design of the additional CHP, included to provide the steam and power required for CO_2 capture, might be reduced.
- *Operation at full load of existing CHP plants in a refinery*. This would mean to accept temporary shut-down of CO_2 capture when there is a CHP plant failure since refinery production has priority. This approach could be evaluated with the following steps:
    1. Determine maximum additional steam production in refinery if installed CHP capacity is fully used
    2. Knowing this additional steam production, and for selected solvent(s): Determine approximately how much CO_2 can be captured (i.e. what thermal power can be made available in the reboiler)
    3. Assess the different options in the refinery to capture this amount of CO_2 (i.e. the emission points that CO_2 could be captured from, where capture rate may be other than the 90% assumed in this work)
    4. Evaluate how practical different capture options are to implement, and how much they will cost.

[1] Such as membrane technologies, adsorption, hybrid technology concepts, etc.

1 Introduction

The aim of this study is to describe and analyse the cost of retrofitting CO_2 capture from refineries. Based on four generic refinery Base Cases developed and described by Amec FW in the document *Performance Analysis – Refinery Reference Plants*, 16 CO_2 capture cases have been designed and assessed by SINTEF ER and Amec FW in the document *Performance analysis of CO_2 capture options.* A brief overview of refinery cases and CO_2 capture cases is presented in Table 2.

Table 2. Summary of the refinery cases and CO_2 capture cases

Refinery	CO_2 capture cases	List of CO_2 capture emissions sources[1]	CO_2 concentration range (%vol)		
			Lowest	Average	Highest
Base Case 1 Nominal capacity: 100 000 bbl/d Simple refinery	01-01	POW	8.4	8.4	8.4
	01-02	POW + CDU	8.4	9.2	11.3
	01-03	POW + CDU + CRF	8.4	9.1	11.3
Base Case 2 Nominal capacity: 220 000 bbl/d Medium complexity	02-01	POW	8.3	8.3	8.3
	02-02	POW + FCC	8.3	9.9	16.6
	02-03	POW + FCC + CDU-B /VDU-B + CDU-A + SMR	8.3	10.7	17.8
	02-04	FCC + CDU-B /VDU-B + CDU-A	11.3	13.1	16.6
Base Case 3 Nominal capacity: 220 000 bbl/d High complexity	03-01	POW (NGCC) + POW (B)	4.9	6.6	8.1
	03-02	POW (NGCC) + POW (B) + FCC	4.9	8.7	16.6
	03-03	POW (NGCC) + POW (B) + FCC + CDU-B /VDU-B + CDU-A + SMR	4.9	10	17.7
Base Case 4 Nominal capacity: 350 000 bbl/d High complexity	04-01	POW (NGCC) + POW (B)	4.2	4.7	8.1
	04-02	POW (NGCC) + POW (B) + CDU-A /VDU-A + CDU-B/ VDU-B	4.2	6.7	11.3
	04-03	POW (NGCC) + POW (B) + FCC + CDU-A /VDU-A + CDU-B/ VDU-B + SMR	4.2	9.4	17.7
	04-04	SMR	17.7	17.7	17.7
	04-05	POW (NGCC) + POW (B) + CDU-A /VDU-A + CDU-B/ VDU-B + SMR	4.2	8.7	17.7
	04-06	POW (NGCC) + POW (B) + FCC + CDU-A /VDU-A + CDU-B/ VDU-B	4.2	7.7	16.6

[1]Reference should be made to section 1.1.1 in report *Performance analysis – Refinery reference plants* for explanation of abbreviations POW, CDU, CRF, FCC, SMR, and VDU.

The costs of retrofitting CO_2 capture of these 16 cases are assessed and analysed based on the technical assessments of Mono Ethanol Amine (MEA) CO_2 capture performed in the document *Performance analysis of CO_2 capture options*. Compared to other studies on CO_2 capture[2,3,4,5,6], the assessments performed in this report focused also on retrofit costs including modifications in the refineries, interconnections, additional CHP and utility facilities.

The main focus is on CO_2 capture from refinery Base Case 4, which is seen as the most relevant reference for existing European refineries of interest for CO_2 capture retrofit. The aim is that the work presented in this report should be a useful basis for the European refinery industry to estimate their range of costs of retrofitting CO_2 capture.

[2] IEAGHG, CO_2 capture in the cement industry, 2008/3., 2008.
[3] IEAGHG, Deployment of CCS in the Cement industry, 2013/19., 2013.
[4] IEAGHG, Iron and steel CCS study (Techno-economic integrated steel mill), 2013/4, 2013.
[5] IEAGHG, CO_2 Capture at Coal Based Power and Hydrogen Plants, 2014/3., 2014.
[6] R. Anantharaman, O. Bolland, N. Booth, E.V. Dorst, C. Ekstrom, F. Franco, E. Macchi, G. Manzolini, D. Nikolic, A. Pfeffer, M. Prins, S. Rezvani, L. Robinson, D4.9 European best practice guidelines for assessment of CO_2 capture technologies, DECARBit Project, 2011.

A review of the IEAGHG technical report "Techno-Economic Evaluation of SMR based standalone (merchant) hydrogen plant with CCS" was performed and compared to Case 04-04. Insights on the effects of tight integration of the hydrogen plant with the refinery and additional CHP plant are provided in section 3.

1.1 Cost evaluation methodology

The overall cost evaluation methodology used for the assessment of the CO_2 capture cases can be found in the document *Technical Design Basis and Economic Assumptions*. Considering the large number of cases considered (16) and their complexity, a hybrid methodology is used in order to evaluate the cost of the sections (CO_2 capture and compression, utilities, and interconnecting) of the concept. In this approach, four of the 16 cases are assessed in detail, based on the cost methodology presented in *Technical Design Basis and Economic Assumptions*. These detailed cost assessments are used to develop cost functions that form the basis for the assessment of the other cases based on subsequent scaling as illustrated in Figure 3.

The four CO_2 capture cases, which were selected for detailed cost assessment, are the cases 01-03, 02-02, 04-03 and 04-04. The cases 01-03, 02-02 and 04-03 were selected in order to represent the wide range of the CO_2 capture capacity and flue gas CO_2 content considered: 04-03 being the largest of all the cases, 02-02 being of intermediate size and 04-04 being one of the smallest cases. Meanwhile, case 01-03 is also selected as it is the only case considering CO_2 capture from a CRF unit. For all these four cases, detailed equipment lists including each equipment and its key characteristics are developed, as shown in Appendix A. These form the basis of the investment cost evaluation. The CO_2 capture and compression equipment list and corresponding equipment costs are prepared by SINTEF ER while Amec FW prepared the equipment lists and equipment cost for the utilities and interconnecting section. Amec FW then estimated additional costs required to evaluate direct materials, direct field cost, and total installed cost that form the basis to calculate the total capital requirement. In addition, operating costs are calculated based on the estimated number of employees, utility and mass balances, and the plant performances.

The investment cost of the other twelve cases are assessed by subsequent scaling-based cost functions presented in Appendix B and developed from the four cases evaluated in detail. Meanwhile operating costs are calculated based on the estimated number of employees, utility and mass balances, and the plant performances of each case. In order to ensure accurate and reliable estimates, the investments cost of the 3 sections are divided in 8 subsections: CO_2 capture and compression (flue gas desulphurisation unit, absorber section, regeneration section, and CO_2 compression), utilities (CHP plant, cooling towers, and waste water treatment), and interconnecting (no subsections). The overall cost breakdown, key performance indicators and sensitivity analyses are then evaluated for each case based on the excel model for evaluation of CO_2 capture from refineries developed by SINTEF ER and available in Appendix B.

It is worth noting that absolute costs (CAPEX and OPEX) are given in Appendix D, whereas the costs of the CO_2 capture options presented and discussed in the main text of this report focus on normalised estimates ($\$/t_{CO2,avoided}$).

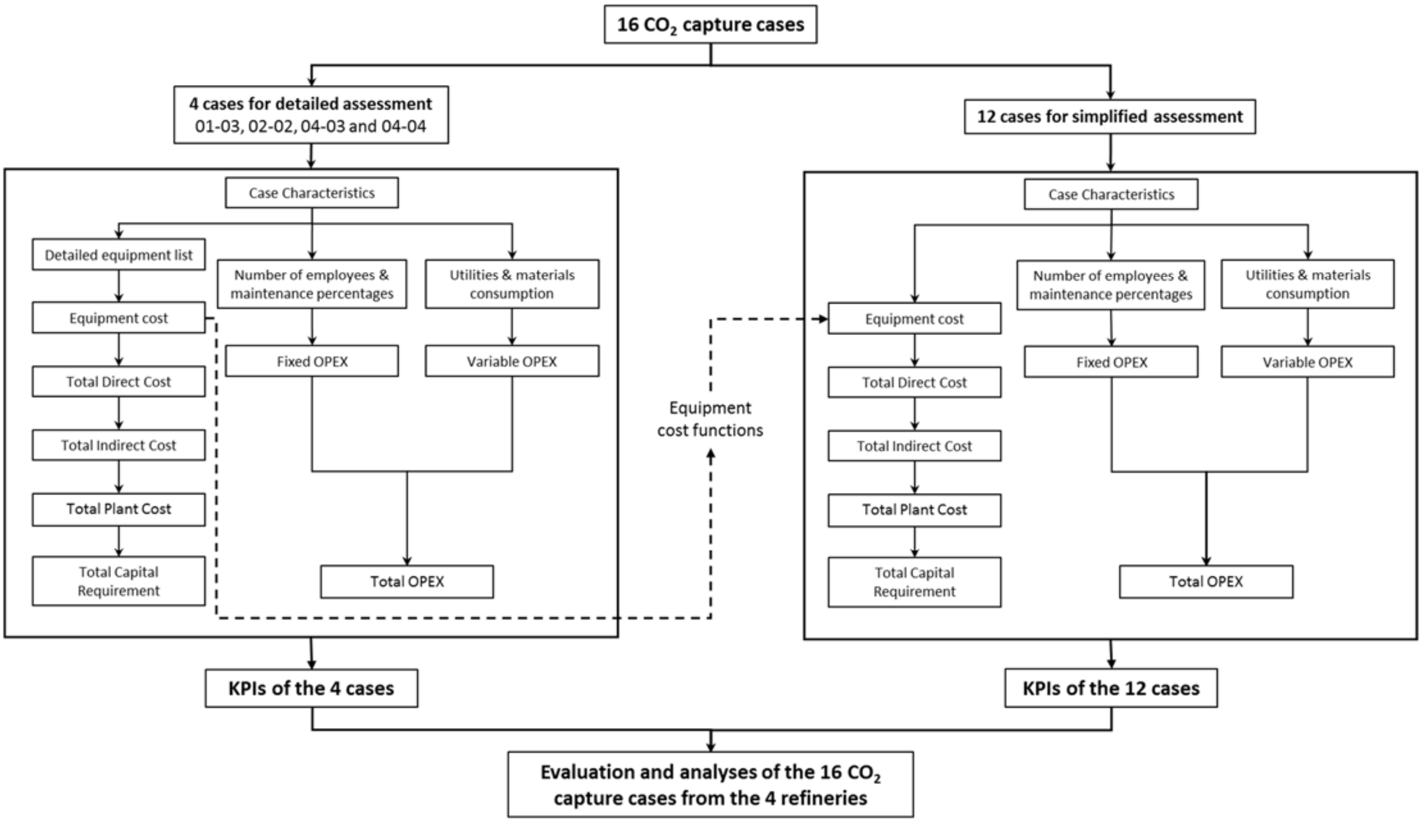


Figure 3. Representation of the methodology used to evaluate and analyse the 16 CO_2 capture cases

1.2 Sensitivity analyses

Sensitivity analyses on the cost of retrofitting CO_2 capture ($\$/t_{CO2,avoided}$) are carried out for each of the 16 CO_2 capture cases considered in order to quantify the impact of the cost range accuracy, key parameter assumptions and project valuation parameters.

The variation range considered for investment cost (CAPEX), operating cost and fuel cost are based on the expected accuracy of the cost estimation. In addition, the impact of variations of cost by section (CO_2 capture and compression, utilities, and interconnecting) are presented. Furthermore, variations on the CHP plant investment cost (CAPEX) and steam requirement for the CO_2 capture are also considered. Variations on the CHP plant investment are considered to assess the cost cutting potential which could be achieved by reducing the significant overdesign, in some cases[7], of the additional CHP plant built to supply steam and power for the implementation of CO_2 capture. Variations on the steam consumption are also included in order to assess the potential of reducing the specific reboiler duty of the CO_2 capture process through advanced solvents and or process configurations. The variation ranges considered on cost accuracy and key parameters assumptions are gathered in Table 3.

Finally, the range of values considered for the project valuation parameters (project duration, discount rate and utilisation rate) are presented in Table 4.

[7] The design of CHP plant in some cases results in overdesigns up to 30%.

Table 3. Variation range considered on cost accuracy and key parameter assumptions

Parameter	Variation range	
	Lower range	Higher range
Total CAPEX	-15%	+35%
Fixed and variable operating cost	-20%	+20%
Fuel cost	-30%	+30%
CO_2 capture and compression	-20%	+20%
Utilities	-20%	+20%
Interconnecting	-20%	+20%
CHP plant CAPEX	-25%	+0%
Steam consumption	-30%	+0%

Table 4. Variations considered on the project valuation parameters

Parameter	Default value	Variation range	
		Lower range	Higher range
Project duration (y)	25	10	40
Discount rate (%)	8	4	12
Utilisation rate (%)	96	70	100

2 Results for post-combustion capture from refineries

This section presents and analyses the cost of the CO_2 capture options on a normalised basis ($/$t_{CO2,avoided}$). The absolute costs (CAPEX and OPEX) of each CO_2 capture case are presented in Appendix D.

2.1 Base Case 1

The cost of retrofitting CO_2 capture for Base Case 1 are presented in Figure 4 with a breakdown between the costs of interconnecting, utilities (CHP plant, cooling water tower, and waste water treatment) and CO_2 capture and conditioning (flue gas desulphurisation unit, absorption section, desorption section and CO_2 compression section). Meanwhile, a more detailed cost breakdown including investment and operating costs is presented in Table 5.

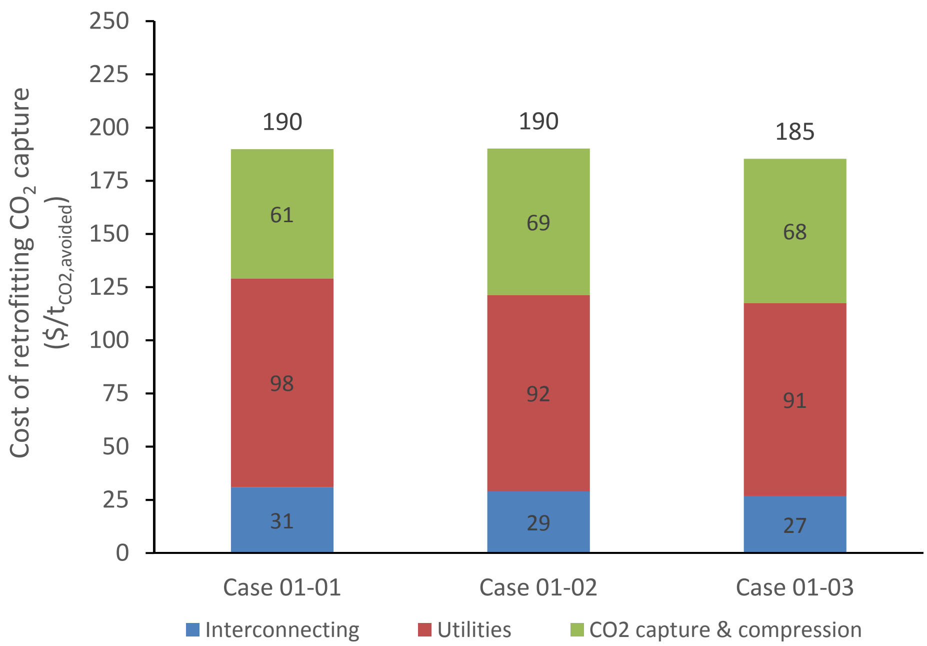


Figure 4. Costs of retrofitting CO_2 capture for Base Case 1

Table 5. Detailed cost breakdowns [$/$t_{CO2,avoided}$] of retrofitting CO_2 capture cases for Base Case 1

		Case 01-01	Case 01-02	Case 01-03
CO_2 capture & compression		**60.7**	**68.9**	**67.9**
	CAPEX	*35.7*	*42.2*	*41.7*
	Fixed OPEX	*16.3*	*18.5*	*17.9*
	Variable OPEX	*8.7*	*8.3*	*8.3*
Utilities		**98.2**	**92.2**	**90.6**
	CAPEX	*24.8*	*21.4*	*20.6*
	Fixed OPEX	*13.5*	*10.8*	*10.2*
	Natural gas cost	*59.3*	*59.4*	*59.3*
	Variable OPEX	*0.6*	*0.5*	*0.5*
Interconnecting		**30.9**	**29.0**	**26.8**
	CAPEX	*25.8*	*24.2*	*22.4*
	Fixed OPEX	*5.1*	*4.8*	*4.5*
	Variable OPEX	*0.0*	*0.0*	*0.0*
Total		**190**	**190**	**185**

In order to further understand the cost results of the different cases of Base Case 1, the costs of retrofitting the CO_2 capture depending on the amount of CO_2 avoided and the key technical characteristics of the three cases are presented in Figure 5 and Table 6. It should be noted that the percentage of refinery emissions avoided refers to the entire refinery, including the CO_2 emissions from stacks where CO_2 capture was not investigated. However, it can be recalled here that the CO_2 capture system is always designed to ensure a CO_2 capture ratio of 90% from the stacks considered for capture. Furthermore, due to the CO_2 emissions from the new CHP plant that is associated with steam and power consumption for the CO_2 capture, the net CO_2 avoided for the Base Case 1 capture cases remains below 55%.

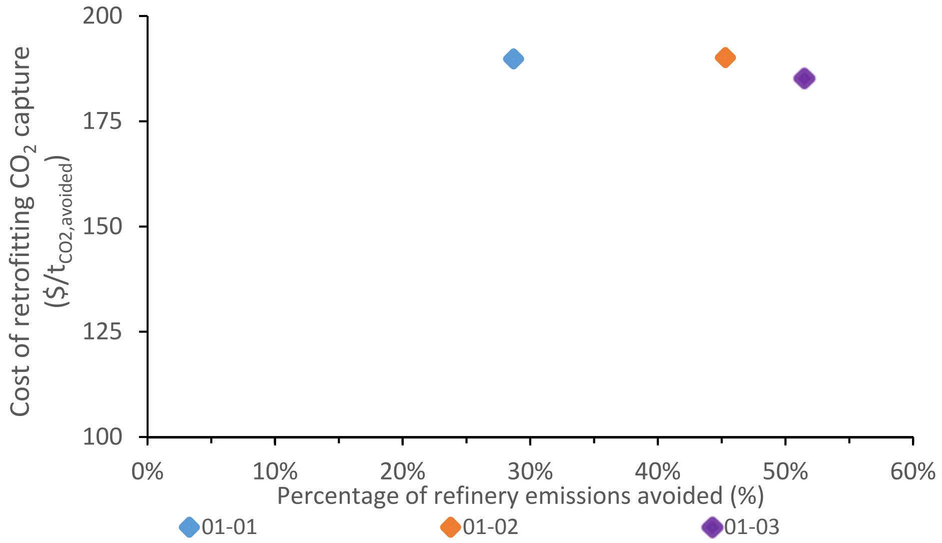
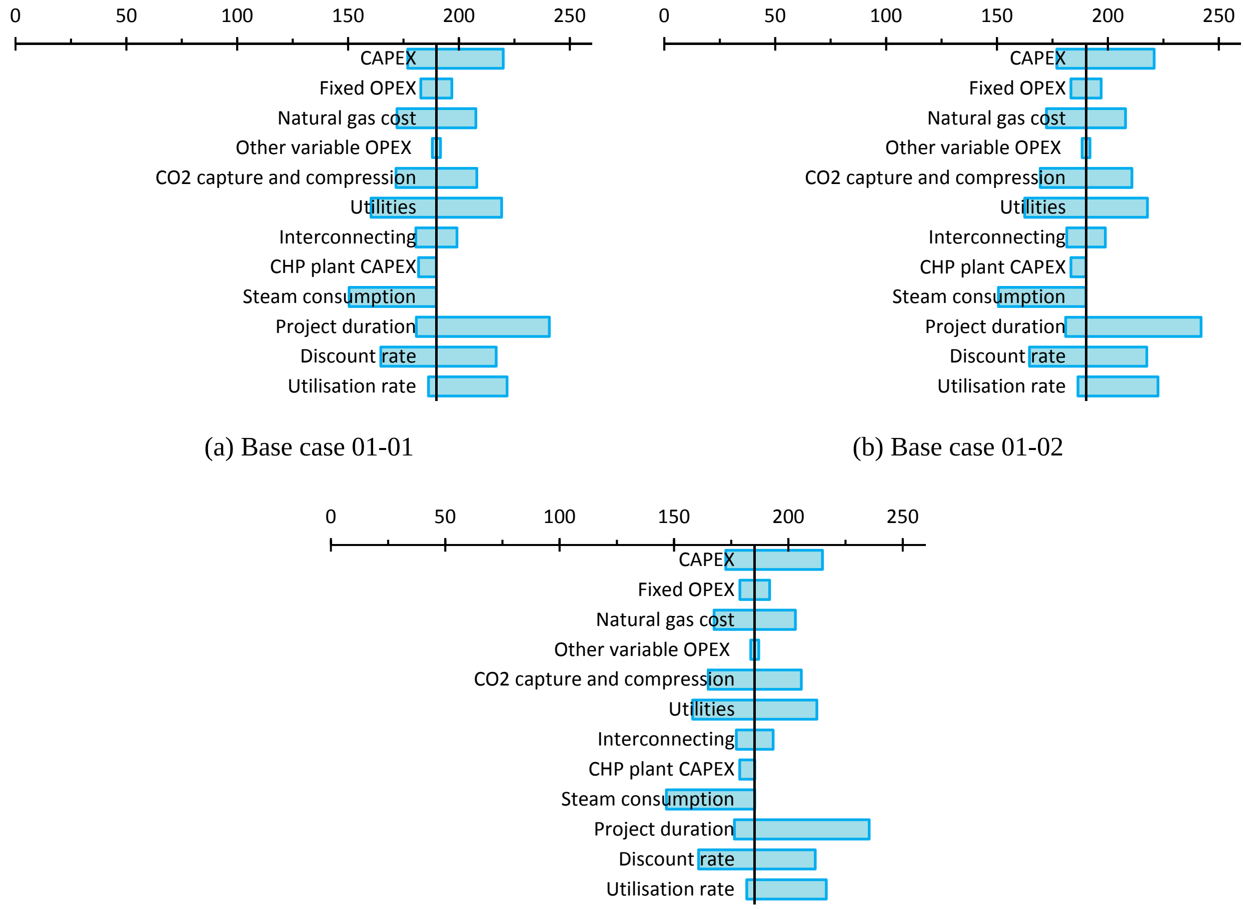


Figure 5. Costs of retrofitting CO_2 capture compared to percentage of emissions avoided for Base Case 1

Table 6. Key technical characteristics of the CO_2 capture cases for Base Case 1

	Case 01-01	Case 01-02	Case 01-03
Units considered for CO_2 capture	A1	A1+A2	A1+A2+A3
Amount of CO_2 captured (kt_{CO2}/y)	316	499	566
Percentage of refinery emissions captured (%)	43.3	68.4	77.7
Amount of CO_2 avoided (kt_{CO2}/y)	209	330	375
Percentage of refinery emissions avoided (%)	28.7	45.3	51.5
Average CO_2 content in the flue gas (%vol)	8.4	9.2	9.1
Number of absorbtion section(s)	1	2	3
Number of FGD unit(s)	0	1	1
Number of desorbtion section(s)	1	1	1
Specific reboiler duty ($GJ/t_{CO2,avoided}$)	3.66	3.67	3.67
Specific power ($kWh/t_{CO2,captured}$)	149	158	157
Cooling duty ($GJ/t_{CO2,captured}$)	4.36	3.96	3.99
MEA make-up (kg_{MEA}/t_{CO2})	2.28	2.09	2.09

Sensitivity analyses of the main parameters with the variation range presented in Table 3 and Table 4 are presented to increase the understanding of the impact different parameters (cost estimates' accuracy, project valuation assumptions and key assumptions). The results of the sensitivity analyses are presented in Figure 6(a) to (c) for each of the capture cases of Base Case 1.



(a) Base case 01-01

(b) Base case 01-02

(c) Base case 01-03

Figure 6. Sensitivity analyses of the cost of retrofitting CO_2 capture (\$/$t_{CO2,avoided}$) of the cases (a) 01-01 (b) 01-02 (c) 01-03

2.2 Base Case 2

The cost of retrofitting CO_2 capture for Base Case 2 are presented in Figure 7 with a breakdown between the costs of interconnecting, utilities and CO_2 capture and conditioning. Meanwhile, a more detailed cost breakdown including also investment and operating costs is presented in Table 7.

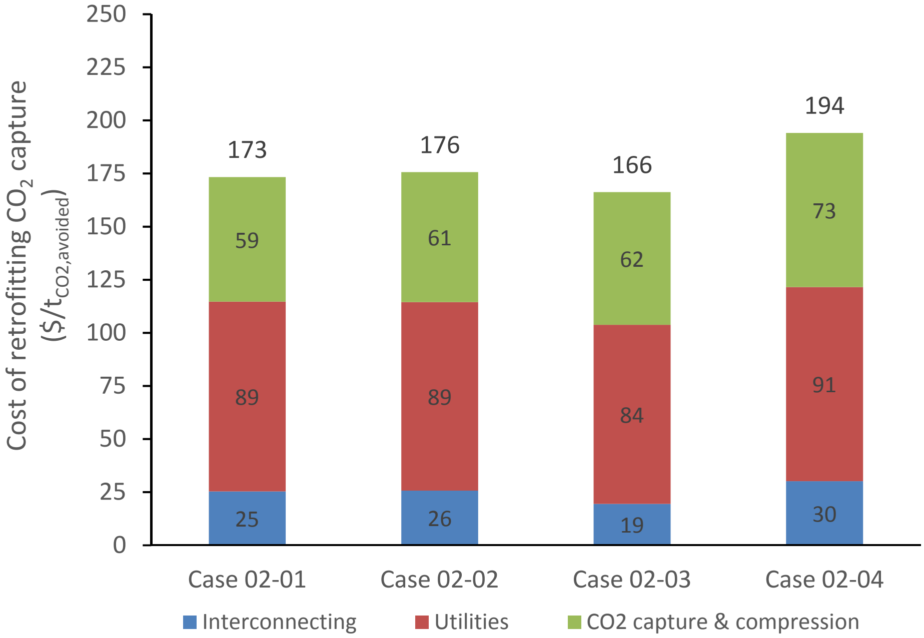


Figure 7. Costs of retrofitting CO_2 capture for Base Case 2

Table 7. Detailed cost breakdowns [$/$t_{CO2,avoided}$] of retrofitting CO_2 capture cases for Base Case 2

		Case 02-01	Case 02-02	Case 02-03	Case 02-04
CO_2 capture & compression		**58.6**	**61.2**	**62.5**	**72.6**
	CAPEX	*36.1*	*37.9*	*39.0*	*45.8*
	Fixed OPEX	*14.4*	*15.1*	*15.2*	*18.4*
	Variable OPEX	*8.1*	*8.2*	*8.3*	*8.4*
Utilities		**89.3**	**88.7**	**84.2**	**91.3**
	CAPEX	*19.8*	*20.1*	*17.5*	*18.5*
	Fixed OPEX	*9.4*	*9.0*	*7.6*	*8.8*
	Natural gas cost	*59.6*	*59.0*	*58.6*	*63.5*
	Variable OPEX	*0.6*	*0.6*	*0.5*	*0.5*
Interconnecting		**25.4**	**25.7**	**19.5**	**30.2**
	CAPEX	*21.1*	*21.4*	*16.2*	*25.2*
	Fixed OPEX	*4.2*	*4.3*	*3.2*	*5.0*
	Variable OPEX	*0.0*	*0.0*	*0.0*	*0.0*
Total		**173**	**176**	**166**	**194**

In order to further understand the cost results of the different cases of Base Case 2, the costs of retrofitting the CO_2 capture depending on the amount of CO_2 avoided and the key technical characteristics of the four cases are presented in Figure 8 and Table 8. For the reasons discussed previously, it is worth noting that the net CO_2 avoided for the Base Case 2 capture cases remains below 50%.

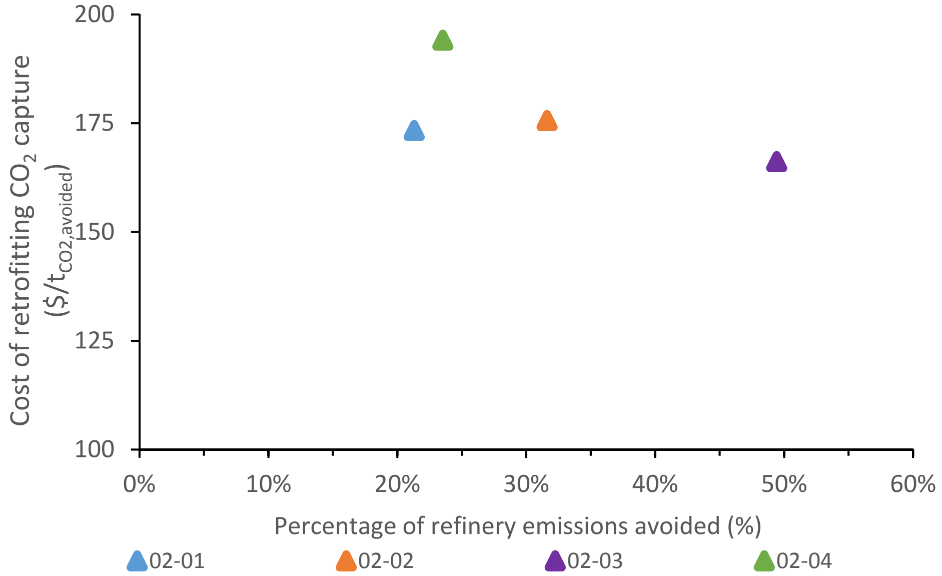


Figure 8. Costs of retrofitting CO_2 capture compared to percentage of emissions avoided for Base Case 2

Table 8. Key technical characteristics of the CO_2 capture cases for Base Case 2

	Case 02-01	Case 02-02	Case 02-03	Case 02-04
Units considered for CO_2 capture	B1	B1+B2	B1+B2+B3+B4+B5	B2+B3+B4
Amount of CO_2 captured (kt_{CO2}/y)	697	1,030	1,607	765
Percentage of refinery emissions captured (%)	32.2	47.6	74.3	35.4
Amount of CO_2 avoided (kt_{CO2}/y)	461	684	1,069	509
Percentage of refinery emissions avoided (%)	21.3	31.6	49.4	23.5
Average CO_2 content in the flue gas (%vol)	8.3	9.9	10.7	13.1
Number of absorbtion section(s)	1	2	4	2
Number of FGD unit(s)	0	1	2	2
Number of desorbtion section(s)	1	1	1	1
Specific reboiler duty ($GJ/t_{CO2,avoided}$)	3.68	3.66	3.65	3.64
Specific power ($kWh/t_{CO2,captured}$)	149	155	164	185
Cooling duty ($GJ/t_{CO2,captured}$)	4.24	4.05	3.85	3.62
MEA make-up (kg_{MEA}/t_{CO2})	2.09	2.09	2.09	2.08

The results of the sensitivity analyses are presented in Figure 9(a) to (d) for each of the capture cases of Base Case 2.

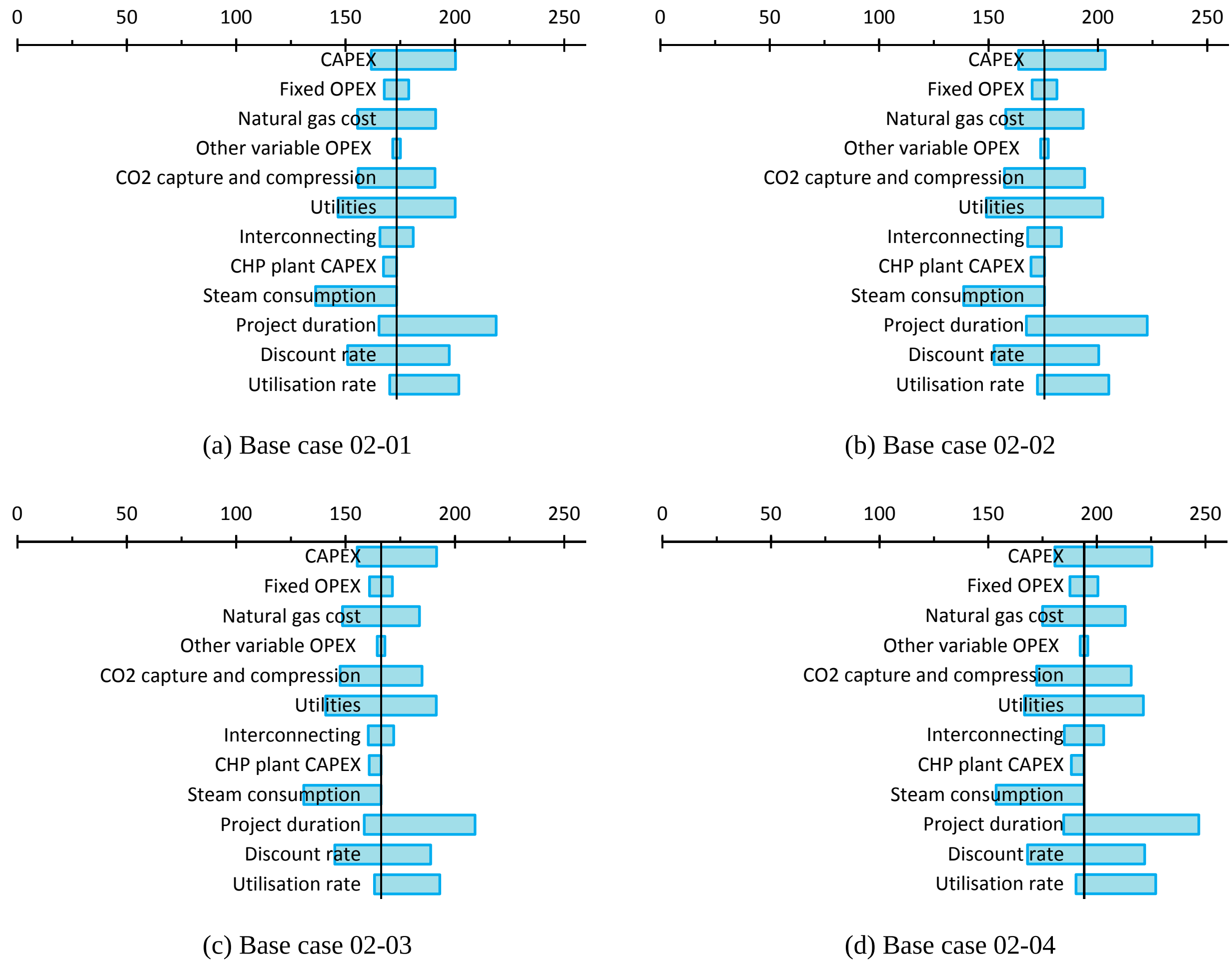


Figure 9. Sensitivity analyses of the cost of retrofitting CO_2 capture of the cases (a) 02-01 (b) 02-02 (c) 02-03 (d) 02-04

2.3 Base Case 3

The cost of retrofitting CO_2 capture for Base Case 3 are presented in Figure 10 with a breakdown between the costs of interconnecting, utilities and CO_2 capture and conditioning. Meanwhile, a more detailed cost breakdown including also investment and operating costs is presented in Table 9.

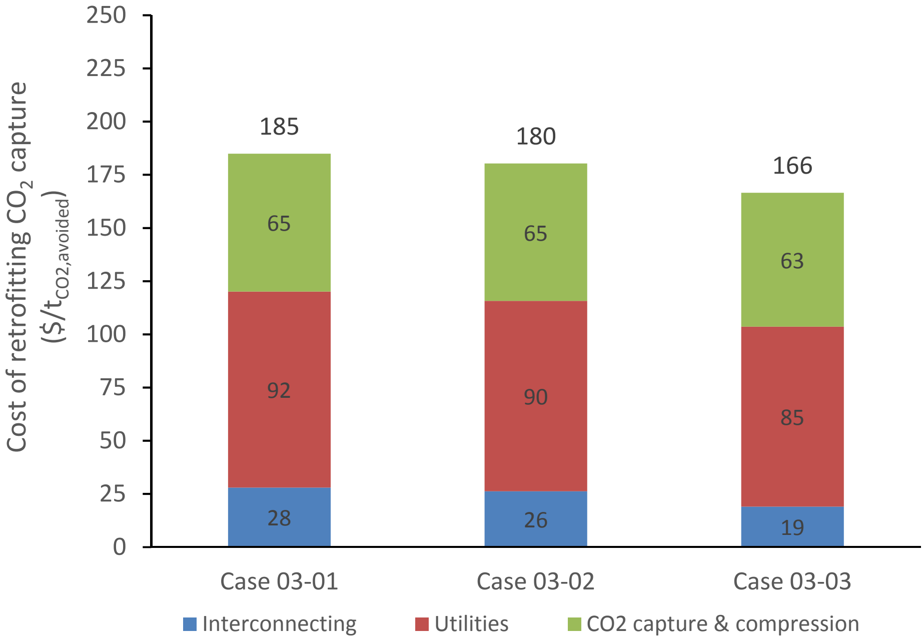


Figure 10. Costs of retrofitting CO_2 capture for Base Case 3

Table 9. Detailed cost breakdowns [$/t$_{CO2,avoided}$] of retrofitting CO_2 capture cases for Base Case 3

		Case 03-01	Case 03-02	Case 03-03
CO_2 capture & compression		**64.8**	**64.6**	**62.9**
	CAPEX	*40.4*	*40.4*	*39.4*
	Fixed OPEX	*16.2*	*16.0*	*15.3*
	Variable OPEX	*8.1*	*8.2*	*8.2*
Utilities		**92.1**	**89.5**	**84.6**
	CAPEX	*20.7*	*20.2*	*17.4*
	Fixed OPEX	*10.1*	*9.2*	*7.5*
	Natural gas cost	*60.8*	*59.6*	*59.2*
	Variable OPEX	*0.5*	*0.5*	*0.5*
Interconnecting		**27.9**	**26.2**	**19.0**
	CAPEX	*23.3*	*21.9*	*15.8*
	Fixed OPEX	*4.6*	*4.4*	*3.2*
	Variable OPEX	*0.0*	*0.0*	*0.0*
Total		**185**	**180**	**166**

In order to further understand the cost results of the different cases of Base Case 3, the costs of retrofitting the CO_2 capture depending on the amount of CO_2 avoided and the key technical characteristics of the three cases are presented in Figure 11 and Table 10. For the reasons discussed previously, it is worth noting that the net CO_2 avoided for the Base Case 3 capture cases remains below 50%.

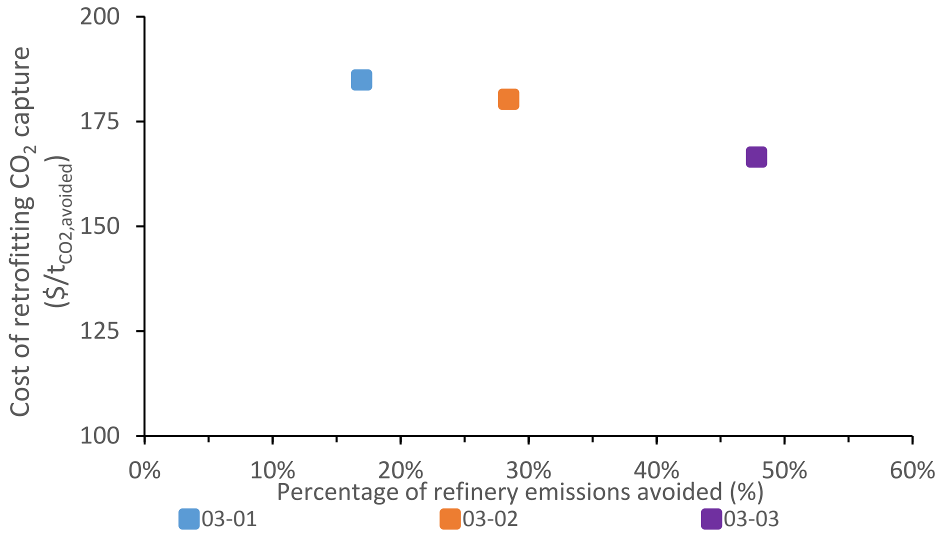
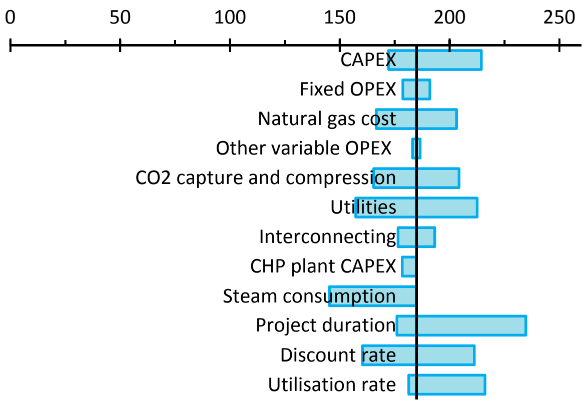


Figure 11. Costs of retrofitting CO_2 capture compared to percentage of emissions avoided for Base Case 3

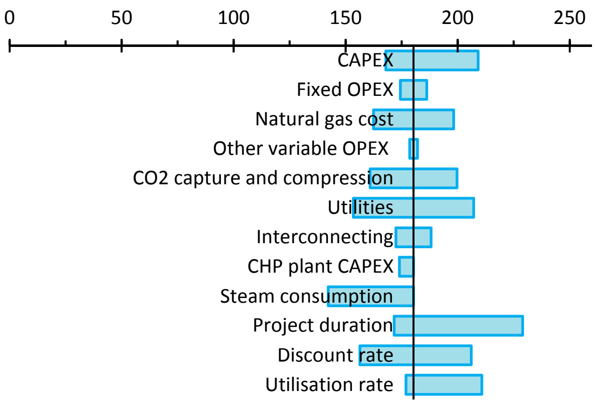
Table 10. Key technical characteristics of the CO_2 capture cases for Base Case 3

	Case 03-01	Case 03-02	Case 03-03
Units considered for CO_2 capture	C1	C1+C2	C1+C2+C3+C4+C5
Amount of CO_2 captured (kt$_{CO2}$/y)	*602*	*1,004*	*1,681*
Percentage of refinery emissions captured (%)	*25.8*	*43.0*	*72.0*
Amount of CO_2 avoided (kt$_{CO2}$/y)	*396*	*664*	*1,116*
Percentage of refinery emissions avoided (%)	*16.9*	*28.4*	*47.8*
Average CO_2 content in the flue gas (%vol)	6.6	8.7	10
Number of absorbtion section(s)	2	3	4
Number of FGD unit(s)	0	1	2
Number of desorbtion section(s)	1	1	1
Specific reboiler duty (GJ/t$_{CO2,avoided}$)	3.74	3.69	3.67
Specific power (kWh/t$_{CO2,captured}$)	159	162	166
Cooling duty (GJ/t$_{CO2,captured}$)	4.03	3.89	3.86
MEA make-up (kg$_{MEA}$/t$_{CO2}$)	2.08	2.08	2.08

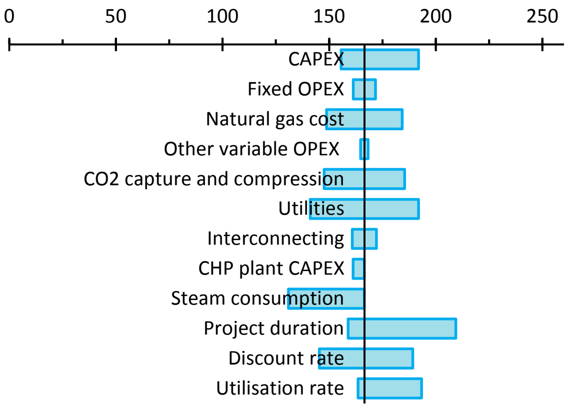
The results of the sensitivity analyses are presented in Figure 12(a) to (c) for each of the capture cases of Base Case 3.



(a) Base case 03-01



(b) Base case 03-02



(c) Base case 03-03

Figure 12. Sensitivity analyses of the cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$) of the cases (a) 03-01 (b) 03-02 (c) 03-03

2.4 Base Case 4

The cost of retrofitting CO_2 capture for Base Case 4 are presented in Figure 13 with a breakdown between the costs of interconnecting, utilities and CO_2 capture and conditioning. Meanwhile, a more detailed cost breakdown including also investment and operating costs is presented in Table 11.

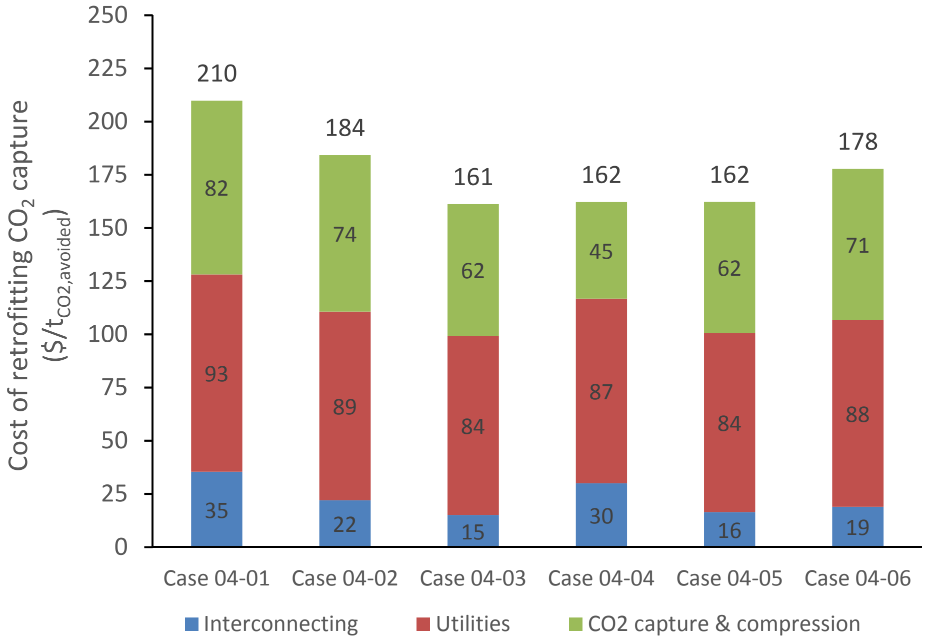


Figure 13. Costs of retrofitting CO_2 capture for Base Case 4

Table 11. Detailed cost breakdowns [$/t$_{CO2,avoided}$] of retrofitting CO_2 capture cases for Base Case 4

		Case 04-01	Case 04-02	Case 04-03	Case 04-04	Case 04-05	Case 04-06
CO_2 capture & compression		**81.7**	**73.5**	**61.9**	**45.4**	**61.7**	**71.1**
	CAPEX	*53.1*	*47.3*	*39.0*	*26.8*	*38.7*	*45.5*
	Fixed OPEX	*20.3*	*17.9*	*14.6*	*10.7*	*14.6*	*17.3*
	Variable OPEX	*8.3*	*8.3*	*8.3*	*7.9*	*8.3*	*8.3*
Utilities		**92.7**	**88.7**	**84.2**	**86.8**	**84.1**	**87.8**
	CAPEX	*19.4*	*17.9*	*17.6*	*21.1*	*17.4*	*18.0*
	Fixed OPEX	*9.3*	*7.9*	*7.5*	*9.7*	*7.4*	*7.8*
	Natural gas cost	*63.5*	*62.4*	*58.6*	*55.5*	*58.8*	*61.4*
	Variable OPEX	*0.5*	*0.5*	*0.5*	*0.4*	*0.5*	*0.5*
Interconnecting		**35.4**	**22.0**	**15.1**	**30.0**	**16.4**	**18.9**
	CAPEX	*29.5*	*18.3*	*12.6*	*25.0*	*13.7*	*15.8*
	Fixed OPEX	*5.9*	*3.6*	*2.5*	*5.0*	*2.7*	*3.1*
	Variable OPEX	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Total		**210**	**184**	**161**	**162**	**162**	**178**

In order to further understand the cost results of the different cases of Base Case 4, the costs of retrofitting the CO_2 capture depending on the amount of CO_2 avoided and the key technical characteristics of the six cases are presented in Figure 14 and Table 12. For the reasons discussed previously, it is worth noting that the net CO_2 avoided for the Base Case 4 capture cases remains below 50%.

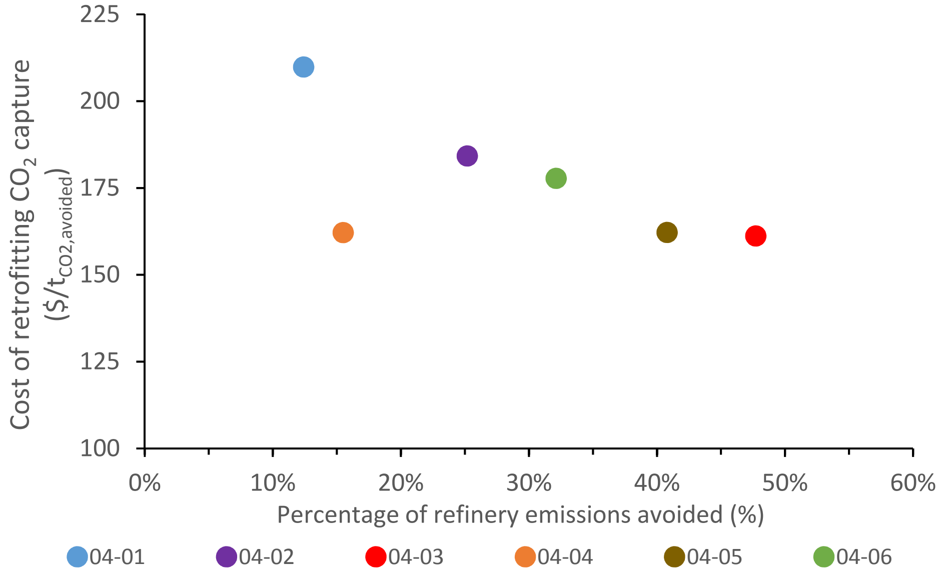
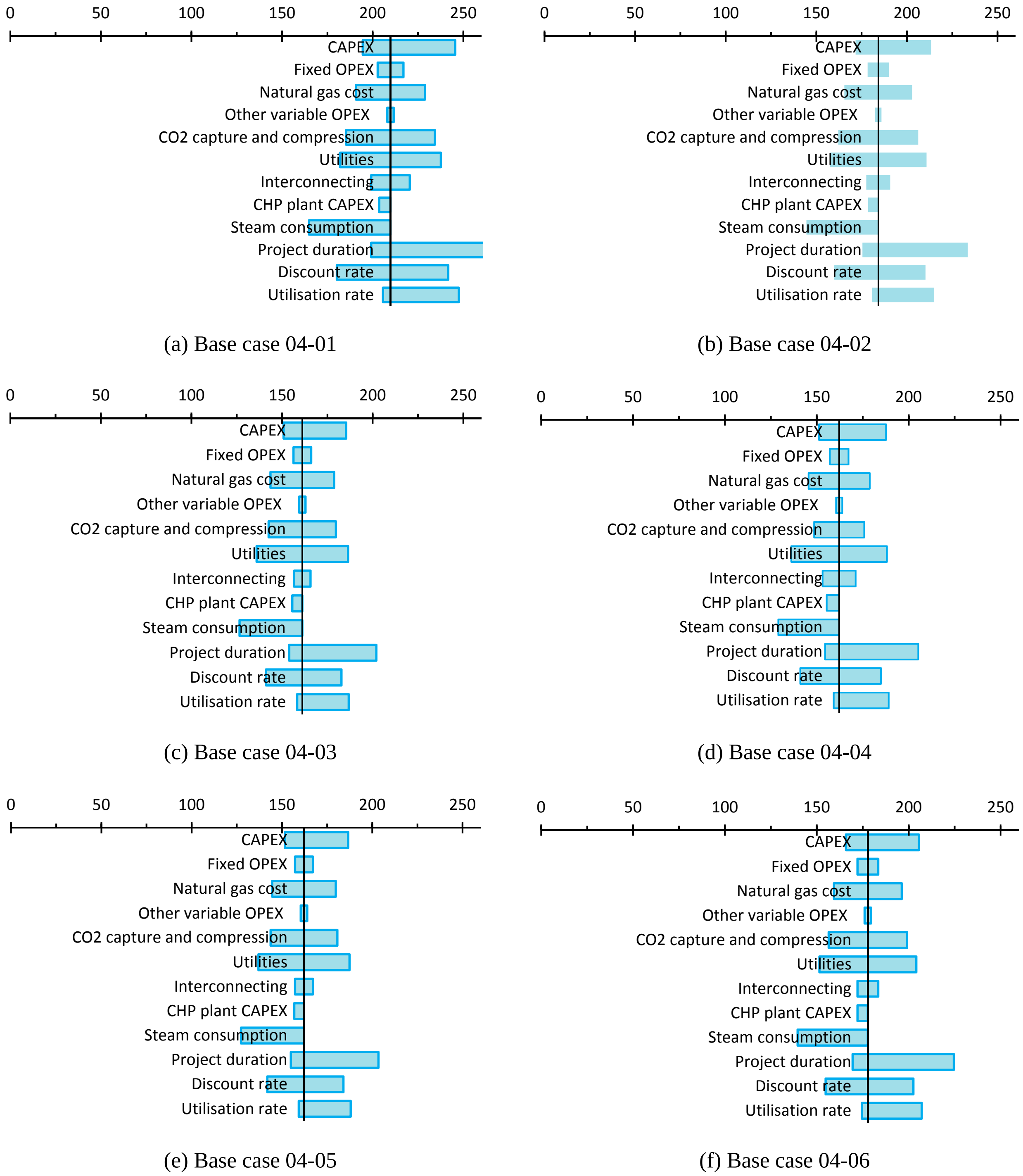


Figure 14. Costs of retrofitting CO_2 capture compared to percentage of emissions avoided for Base Case 4

Table 12. Key technical characteristics of the CO_2 capture cases for Base Case 4

	Case 04-01	Case 04-02	Case 04-03	Case 04-04	Case 04-05	Case 04-06
Units considered for CO_2 capture	D1	D1+D3+D4	D1+D2+D3 +D4+D5	D5	D1+D3 +D4+D5	D1+D2 +D3+D4
Amount of CO_2 captured (kt_{CO2}/y)	740	1,485	2,777	886	2,376	1,886
Percentage of refinery emissions captured (%)	*19.1*	*38.4*	*71.7*	*22.9*	*61.4*	*48.7*
Amount of CO_2 avoided (kt_{CO2}/y)	481	975	1,847	600	1,579	1,243
Percentage of refinery emissions avoided (%)	*12.4*	*25.2*	*47.7*	*15.5*	*40.8*	*32.1*
Average CO_2 content in the flue gas (%vol)	4.7	6.7	9.4	17.7	8.7	7.7
Number of absorbtion section(s)	2	2	4	1	3	3
Number of FGD unit(s)	0	1	2	0	1	2
Number of desorbtion section(s)	1	1	1	1	1	1
Specific reboiler duty ($GJ/t_{CO2,avoided}$)	3.85	3.76	3.68	3.57	3.69	3.65
Specific power ($kWh/t_{CO2,captured}$)	183	184	162	123	161	180
Cooling duty ($GJ/t_{CO2,captured}$)	3.54	3.64	3.55	3.24	3.52	3.72
MEA make-up (kg_{MEA}/t_{CO2})	2.09	2.09	2.09	2.09	2.09	2.09

The results of the sensitivity analyses are presented in Figure 15(a) to (f) for each of the capture cases of Base Case 4.



(a) Base case 04-01 (b) Base case 04-02 (c) Base case 04-03 (d) Base case 04-04 (e) Base case 04-05 (f) Base case 04-06

Figure 15. Sensitivity analyses of the cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$) of the cases (a) 04-01 (b) 04-02 (c) 04-03 (d) 04-04 (e) 04-05 (f) 04-06

2.5 Discussions and overall comparison

The evaluations show that the cost obtained for the 16 cases range between 160 and 210 $\$/t_{CO2,avoided}$, as shown in Figure 16, which is significantly larger than general CO_2 capture and conditioning estimates available in the literature for other sources (natural gas and coal power generation, cement, steel, etc.)[8,9,10,11,12]. Several reasons can be used to explain this difference. First, the present study is aimed at including the retrofit costs, of such as interconnection costs. Furthermore, the utilities cost is based on the installation of an additional CHP plant, cooling water towers and waste water plant which are all designed with significant spare capacity in some cases (up to 30% overdesign). Finally, most of the CO_2 capture cases considered include small to medium CO_2 emission point sources with low to medium flue gas CO_2 content (7 of the 16 cases considered only flue gases with a CO_2 content below 11.3%vol).

Although the cost distribution is specific to each case considered, the overall breakdown between the different sections is as follow. 30-40% of costs linked to CO_2 capture and conditioning, 45-55% linked to utilities production, and 10-20% linked to interconnecting costs. When looking at the more detailed cost breakdowns, the results show that the main elements, which vary between the 16 cases, are the investment and thus fixed operation costs of the three sections and the operating costs linked to natural gas consumption.

In term of investment, the estimations show that the total capital requirement lies between 200 and 1500 M$ for the different case as shown in Figure 16. The main reasons for this wide range is mainly the differences in amount of CO_2 captured between the cases. It is worth noting that although a case may be cheaper in term of normalised cost ($\$/t_{CO2,avoided}$), high total capital requirement could make it less attractive.

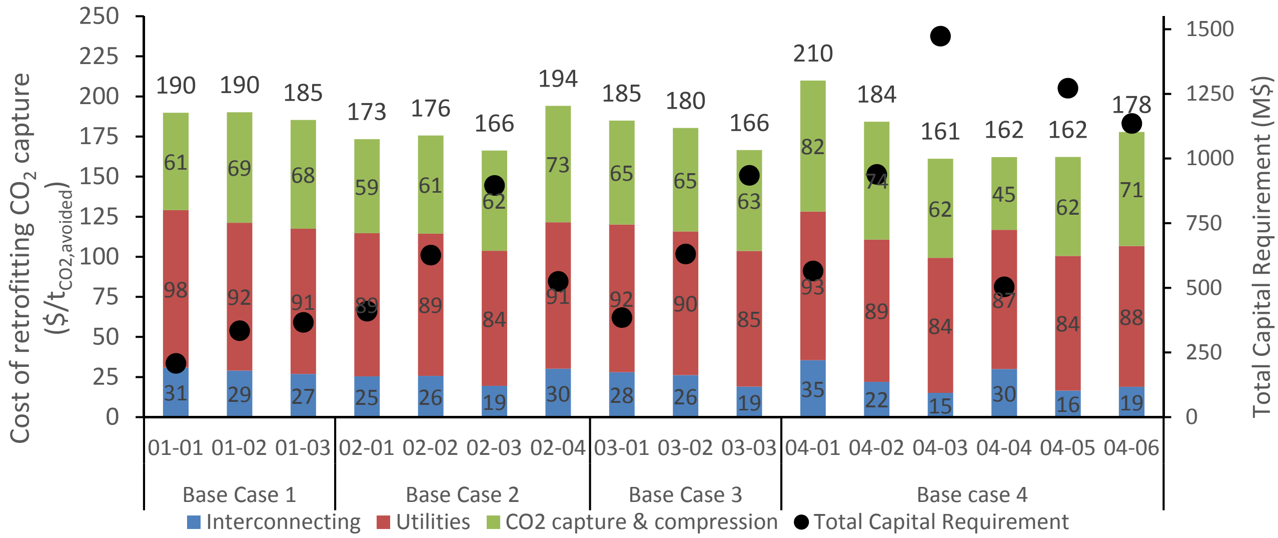


Figure 16. Cost of retrofitting CO_2 capture of all cases considered for the four refinery base cases by section

Figure 17 seems to indicate that, apart from few cases, the capture cases with higher amount of CO_2 avoided results in lower costs. However, it is important to understand that here the differences between the cases are significantly more complex than difference in scale. Indeed, as shown in the key characteristics of each cases,

[8] IEAGHG, CO_2 capture in the cement industry, 2008/3., 2008.
[9] IEAGHG, Deployment of CCS in the Cement industry, 2013/19., 2013.
[10] IEAGHG, Iron and steel CCS study (Techno-economic integrated steel mill), 2013/4, 2013.
[11] IEAGHG, CO_2 Capture at Coal Based Power and Hydrogen Plants, 2014/3., 2014.
[12] R. Anantharaman, O. Bolland, N. Booth, E.V. Dorst, C. Ekstrom, F. Franco, E. Macchi, G. Manzolini, D. Nikolic, A. Pfeffer, M. Prins, S. Rezvani, L. Robinson, D4.9 European best practice guidelines for assessment of CO_2 capture technologies, DECARBit Project, 2011.

the different cases have significant differences in for example flue gas CO_2 concentrations, absorption and desorption columns height, number of flue gas desulphurisation (FGD) units, specific utilities consumptions, number of absorption section, and interconnecting distances and capacity.

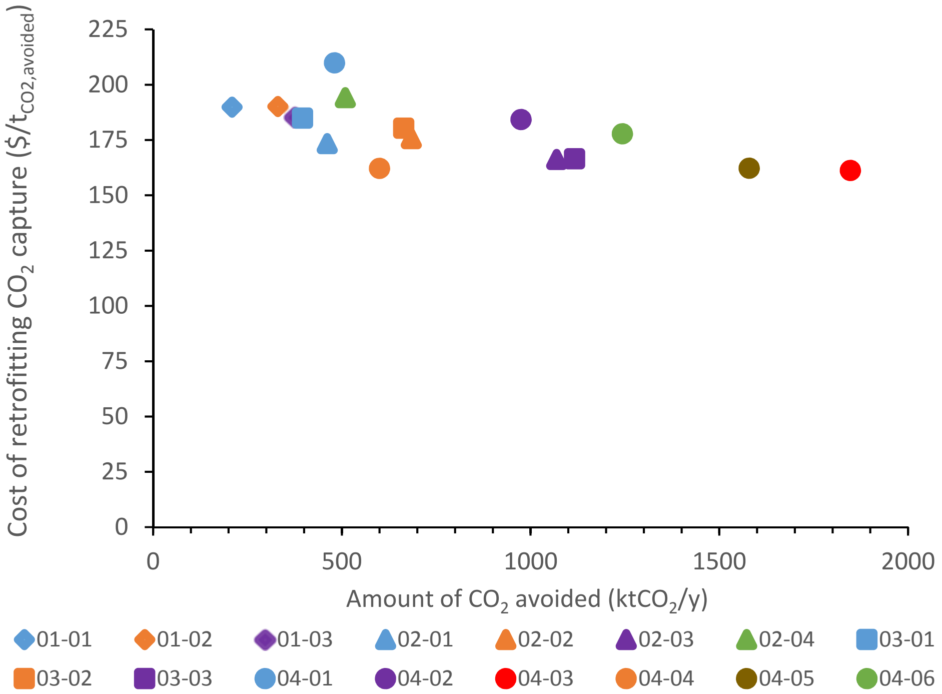


Figure 17. Costs of retrofitting CO_2 capture compared to amount of CO_2 avoided

Case 1 appears to follow the trend of economy of scale. However, while Case 01-02 captures more CO_2, the addition of a FGD unit balances the effect of economies of scale.

The CO_2 avoidance cost trends of Case 2 are similar to Case 1 for capture cases 02-01, 02-02 and 02-03. However, the effect of the additional FGD unit is greater than the economy of scale effect and the CO_2 avoidance cost of case 02-02 is thus slightly higher than case 01-01. The inclusion of case 02-04 is interesting in that this case involved CO_2 capture from flue gases of the crude/vacuum distillation units and fluidised catalytic cracker units. The flue gases from these units have a higher CO_2 concentration that the flue gas from the CHP unit considered for capture in Case 02-01. The CO_2 avoidance cost generally decreases with an increase in CO_2 concentration. However the CO_2 avoidance cost of case 02-04 is higher than case 02-01. This is due to the fact that both the crude/vaccum distillation and fluid catalytic cracker flue gases required a separated FGD unit prior to the absorption process. This results in a significant increase in cost that is not counterbalanced by the weak effect of increase in concentration of the flue gas. Cases 02-01 and 02-04 capture similar amounts of CO_2 and thus the difference between the CO_2 avoidance numbers for these two cases is indicative of the effect of FGD on the CO_2 avoidance cost.

The CO_2 capture cases in Case 3 follow the economy of scale trend. The CHP plant of base case 3 includes an additional natural gas combined cycle plant that decreases the average CO_2 concentration of flue gases from case 03-01 compared to cases 01-01 and 02-01. This results in an increase cost of CO_2 avoidance for case 03-01 compared to Case 02-01.

Cases 04-01 results in the highest cost due to both the lower amount of CO_2 capture and the low CO_2 content in the flue gas (around 5%vol) despite for example smaller desorption columns. Case 04-02, similar to earlier trends of Case 3, has a lower cost than case 04-01 but higher than all other subsequent cases. Case 04-04 being one of the cases with the lowest amount of CO_2 captured in Base Case 4 could be expected to lead to significantly higher costs. For example, high interconnecting costs are obtained as interconnecting costs are not proportional to the capacity as shown in Appendix B. However, as no flue gas desulphurisation unit is required and due to the high flue gas CO_2 content (around 18%vol) which significantly reduce utilities consumption and CO_2 capture investment costs, this case is among the cheapest of Base Case 4.

Meanwhile cases 04-03 and 04-05 benefit from both economies of scale due to the large amount of CO_2 captured and from a medium average CO_2 concentration in the flue gas (around 9%vol) due to the presence of the SMR as one of the emission sources with high CO_2 concentration. This appears to result in costs among the lowest in Base Case 4 despite for example longer interconnecting and taller desorption column. Case 04-06 also benefits from the economy of scale, but has a lower average CO_2 concentration in the flue gas and is hence slightly more expensive than cases 04-03 and 04-05.

Finally, the above discussion indicates the CO_2 avoidance cost depends on a lot of parameters. However, given the relatively large number of cases and capture options studied in this work, it is possible to provide an overview or trend of the CO_2 avoidance cost of different CO_2 capture cases with different characteristics. Table 13 provides a range CO_2 avoidance cost for capture characteristics such as flue gas CO_2 concentration, amount of CO_2 captured and fraction of gas that requires desulphurisation treatment. This table will allow the reader to establish a rough initial estimate of the cost if retrofitting CO_2 capture in a refinery given these characteristics. This along with the cost laws to estimate the CAPEX of the CO_2 capture plant, utilities and interconnecting section provide tools to interpolate or if required extrapolate from the results obtained in this work.

Table 13. Overview of CO_2 avoidance cost and related characteristics

CO_2 avoidance cost ($/t$_{CO2,avoided}$)	Characteristics	Capture Cases
210	Very low CO_2 concentration in flue gas (4-5%) coupled with a small amount of CO_2 captured (around 750 kt$_{CO2}$/y)	04-01
200-180	Low to medium CO_2 concentration in flue gas (6-9%), very low amount of CO_2 captured (300-600 kt$_{CO2}$/y), significant fraction of the flue gases require FGD (50-100%) or a combination of these factors	02-04, 01-02, 01-01, 03-01, 01-03, 04-02
180-170	Low to medium CO_2 concentration in flue gas (6-9%), low amount of CO_2 captured (600-750 kt$_{CO2}$/y), small fraction of the flue gases require FGD (20-50%) or a combination of these factors	03-02, 04-06, 02-02, 02-01
170-160	medium to high CO_2 concentration in flue gas (10-18%), large amount of CO_2 captured (2000-3000 kt$_{CO2}$/y), small fraction of the flue gases require FGD (<10) or a combination of these factors	03-03, 02-03, 04-05, 04-04, 04-03

As expected, similar overall trends are observed for the 16 cases in terms of sensitivity analyses. The sensitivity analyses show that the cost items which have the strongest impact on the cost of retrofitting CO_2 capture are the overall investment cost, the natural gas cost, the CO_2 capture and conditioning costs, and the utilities costs. Due to high contribution of the investment costs to the cost of retrofitting CO_2 capture (40-50%), the parameters used for the project valuation (project duration, discount rate, and utilisation rate) also have a very strong impact on the cost of retrofitting CO_2 capture to refinery.

Furthermore, the sensitivity analyses show that reducing the spare capacity of the CHP plant (33%) which was designed following common refinery practice could reduce the overall cost by around 5%. Finally, the sensitivity analyses show that advanced amine solvents with lower SRD requirement or waste heat integration could also significantly reduced to overall cost due to two effects. First, reducing the steam consumption for the CO_2 regeneration directly reduce the cost associated with the natural gas consumption of the power plant. Secondly, the lower associated natural gas consumption results in less emissions from the CHP plant and thus a higher amount of CO_2 avoided. It must be emphasized here that the sensitivity analysis of steam consumption assumes that the steam pressure (and therewith condensing temperature) remains unchanged, which is not necessarily the case for all advanced amine solvents. A more detailed techno-economic analysis would be required to estimate the impact on cost of considering additives such as piperazine or replacing MEA with advanced solvents.

Sensitivity analyses show that there are opportunities to reduce the cost of utilities that merit further investigation, for example:

- With the objective to *reduce the steam* (and if possible power) *requirement* for CO_2 capture and compression: Evaluation of advanced solvents with lower specific heat requirement as well as other CO_2 capture technologies[13].
- *Use of readily available waste heat* within the refinery plant as well as (when relevant) from nearby industries in combination with purchase of the necessary power for CO_2 capture and compression from the grid, preferably from renewable power or large efficient thermal power plants with CO_2 capture.
- *Lower utilities investment cost through reduced design margins:* The design of CHP plant has been performed considering significant overdesign in some cases (up to 30%). In practice, this over-design of the additional CHP, included to provide the steam and power required for CO_2 capture, might be reduced.
- *Operation at full load of existing CHP plants in a refinery*. This would mean to accept temporary shut-down of CO_2 capture when there is a CHP plant failure since refinery production has priority. This approach could be evaluated with the following steps:
    5. Determine maximum additional steam production in refinery if installed CHP capacity is fully used
    6. Knowing this additional steam production, and for selected solvent(s): Determine approximately how much CO_2 can be captured (i.e. what thermal power can be made available in the reboiler)
    7. Assess the different options in the refinery to capture this amount of CO_2 (i.e. the emission points that CO_2 could be captured from, where capture rate may be other than the 90% assumed in this work)
    8. Evaluate how practical different capture options are to implement, and how much they will cost.

[13] Such as membrane technologies, adsorption, hybrid technology concepts, etc.

3 CO_2 capture from SMR in refineries

IEAGHG has recently released a report[14] that evaluates steam methane reformer (SMR) for hydrogen production with CCS through a techno-economic analysis. The study evaluates the design, performance and cost of a "greenfield" state-of-the-art SMR plant producing 100,000 Nm^3/h of hydrogen using natural gas as feedstock and fuel. The work looked at different options for CO_2 capture within the H_2 plant with overall capture rate ranging between 50 and 90%. The different CO_2 capture cases considered are:

- Case 1A: SMR with CO_2 capture from shifted syngas using MDEA
- Case 1B: SMR with burners firing H_2 rich fuel and capture of CO_2 from the shifted syngas using MDEA
- Case 2A: SMR with CO_2 capture from PSA tail gas using MDEA
- Case 2B: SMR with CO_2 capture from PSA tail gas using cryogenic and membrane separation
- Case 03: SMR with capture of CO_2 from the flue has using MEA.

Cases 1A and Case 03 are the most relevant options for capturing CO_2 from SMR process for the purposes of this work. The economic performance parameters for these two cases compared with the base case SMR with no CO_2 capture are provided in Table 14. The CO_2 capture and compression CAPEX in Case 3 is signifanctly larger (more than 300%) than in Case 1A. This can be attributed to the larger CO_2 captured (72 010 kg/h versus 43856 kg/h) and larger volumetric flow rate of the gases to the capture unit due to lower operating pressure (1.03 bar versus 27 bar) thus resulting in larger equipment sizes.

From Table 14 it is clear that CO_2 capture from syngas using MDEA has significantly better economic performance that post-combustion CO_2 capture in an SMR. In fact, the post-combustion capture is around 60% more expensive than CO_2 capture from syngas when comparing the cost of CO_2 avoided. Note that the CO_2 avoided cost provided in Table 14 is only the CO_2 capture and compression cost while that presented in the IEAGHG report includes cost of CO_2 transport and storage.

Table 14. Economic performance of base case SMR with no CO_2 capture and two capture options[15]

	Base case	Case 1A	Case 3
CO_2 captured (kg/h)	**0**	**43 856**	**72 010**
Hydrogen plant (k€)	97 212	97 212	97 212
CO_2 capture and compression (k€)	-	39 072	123 198
Power island (k€)	20 124	11 064	14 608
Utilities & balance of plant (k€)	53 616	54 456	70 312
Others[a] (k€)	51 938	62 106	93 150
Total capital requirement (k€)	**222 890**	**263 910**	**398 480**
Direct labour (k€/y)	2 280	2 580	2 580
Adm/gen. overheads (k€/y)	992	1 137	1 324
Insurance & local taxes (k€/y)	1 710	2 018	3 053
Maintenance (k€/y)	2 564	3 037	4 580
Fixed operating cost (k€/y)	**7 546**	**8 772**	**11 537**
Feedstock & fuel (k€/y)	70 965	73 282	77 963
Raw water (k€/y)	99	102	70
Chemical and catalysts (k€/y)	420	420	420
Variable operating cost (k€/y)	**71 485**	**73 804**	**78 453**
Revenues from power (k€/y)	**-6 603**	**-993**	**-284**
CO_2 avoided cost (€/$t_{CO2,avoided}$)[b]	**-**	**36**	**57**

[a]Others includes interest during construction, spare parts cost, working capital, start-up costs and owner's costs.
[b]The CO_2 avoided cost does not include CO_2 transport and storage

[14] IEAGHG, Techno-Economic Evaluation of SMR Based Standalone (Merchant) Plant with CCS, 2017/02, February, 2017
[15] All data except CO_2 avoided cost extracted from the above IEAGHG report

Comparison of the results presented in the IEAGHG report with calculated values from this work could present insights on the effect of refinery integration. The economic data in the IEAGHG report is evaluated in Euros with Q42014 as the reporting period while in this work the economic data are reported in US Dollars with Q42015 as the reporting period. The IEAGHG economic performance data updated based on the CEPCI and a $/€ 2015 conversion rate of 1.11 is reported in Table 15.

Table 15. Economic performance of base case SMR with no CO_2 capture and two capture options corrected for 2015Q4 and converted currency to US Dollars

	Base case	Case 1A	Case 3
CO_2 captured (kg/h)	**0**	**43 856**	**72 010**
Hydrogen plant (k€)	99 707	99 707	99 707
CO_2 capture and compression (k€)	-	40 075	126 360
Power island (k€)	20 641	11 348	14 983
Utilities & balance of plant (k€)	54 992	55 854	72 117
Others (k€)	53 271	63 700	95 541
Total capital requirement (k€)	228 612	270 685	408 709
Direct labour (k€/y)	2 526	2 858	2 858
Adm/gen. overheads (k€/y)	1 099	1 260	1 466
Insurance & local taxes (k€/y)	1 753	2 070	3 132
Maintenance (k€/y)	2 630	3 115	4 697
Fixed operating cost (k€/y)	8 008	9 303	12 154
Feedstock & fuel (k€/y)	78 615	81 182	86 367
Raw water (k€/y)	111	113	78
Chemical and catalysts (k€/y)	468	468	468
Variable operating cost (k€/y)	79 195	81 763	86 913
Revenues from power (k€/y)	-6 603	-993	-284
CO_2 avoided cost (€/$t_{CO2,avoided}$)	**-**	**37.5**	**59.4**

A summary of the economic data for Case 04-04, which is similar to Case 3 of the IEAGHG report is presented below in Table 16. The details of the economic data for Capture Case 04-04 are presented in Appendix D4.4.

Table 16. Economic performance of Capture Case 04-04

	Case 04-04
CO_2 captured (kg/h)	105 485
CO_2 capture and compression (k€)	147 062
Power island & utilities(k€)	115 564
Interconnecting (k€)	137 770
Others (k€)	103 268
Total capital requirement (k€)	**503 664**
Direct labour (k€/y)	1 600
Maintenance (k€/y)	9 942
Other (k€/y)	1 795
Fixed operating cost (k€/y)	**13 337**
Feedstock & fuel (k€/y)	33 322
Raw water (k€/y)	261
Chemical and catalysts (k€/y)	3 684
Waste disposal (k€/y)	1 058
Variable operating cost (k€/y)	**38 325**
CO_2 avoided cost (€/$t_{CO2,avoided}$)	**151.4**

The results show that the capital cost of the CO_2 capture and compression plant are similar in this work and the IEAGHG report. Apart from that all other costs in this work are significantly higher. This is mainly because the capture case in this work involves building a new CHP plant for supplying the steam and power required for the CO_2 capture and compression plant while in the IEAGHG report, this is extracted from the stand-alone H_2 plant. This shows not only in the CAPEX of the power plant and utilities, but also in the variable operating cost attributed to the fuel. Additionally, the capture case in this work also required building a cooling tower for providing cooling water and there is a significant CAPEX associated with the interconnecting. These are not required in the IEAGHG case.

It is clear from the above discussion that the high cost of CO_2 avoided in Capture Case 04-04 is primarily due to its tight integration with the refinery and additional costs for building and operating a CHP plant to provide steam and power for the CO_2 capture and compression units. It is expected that CO_2 capture from syngas relevant to this work will also be 50% less expensive than the post-combustion capture case following a similar pattern to that presented in the IEAGHG report.

To summarize, CO_2 capture from the syngas stream in refineries leads to lower CO_2 avoidance cost compared to capture from the SMR furnace flue gas stream. However, only 55% of the SMR emissions are captured in the former compared to 90% capture in the latter. The choice of CO_2 capture from syngas or furnace flue gas will thus depend on how much CO_2 requires to be captured from the refinery. From the earlier discussion on post-combustion CO_2 capture, it is clear that CO_2 capture from SMR furnace flue gases result in one of the cheapest CO_2 avoidance cost. Thus when large amounts of CO_2 are required to be captured from refineries post-combustion CO_2 capture from SMR furnace flue gas is the most relevant option.

A Detailed equipment list of selected cases

A.1Base case 01-03

A.1.1 CO_2 capture and compression

Table 17. Equipment list for the CRF Absorber section for Base case 01-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	3 100	10 000	2,0	116	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	3 000	36 000	1,9	99	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	2 581	116	2,0	232	SS304L	
E-6002	DCC cooler	P&F	5 518	526	4,8	91	SS304L	
E-6003	Amine wash cooler	P&F	220	7	4,8	92	SS304L	
E-6008	Intercooler	P&F	632	50	4,8	74	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		64 538	492	2,00	232	SS304L	Pin/Poutrrrre 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	174	12	3,7	91	SS304L	Pin/Pout: 0.1/1.9
P-6002	Amine water wash pump	Centrifugal	17	1	3,5	92	SS304L	Pin/Pout: 0.1/1.7
P-6003	Rich amine pump	Centrifugal	138	24	7,1	70	SS304L	Pin/Pout: 0.1/5.2
P-6009	Intercooler pump	Centrifugal	135	7	3,4	74	SS304L	Pin/Pout: 0.1/1.5

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Stack for Absorber		101 291		0	212		H: 50m and same D as absorber

A.1.2 Utilities and interconnecting

Table 18. Equipment list for Utilities - Power plant for Base case 01-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Cooling towers							
CT-7001	Cooling towers	Forced draft	4 cells x 2500 m^3/h				By Vendor	Duty: 84 MW
	Inlcuding							
	Cooling water basin							
	Cooling Tower fans		4 fans					
	Chemical injection packages							
	Side stream filter							

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Head	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7003 A/B	CT circulation pump	Centrifugal Vertical Submerged	7250	62	12.0	70	Casing: Cast Iron Impeller: Bronze	2 x 100%, 1 operating 1 spare Motor rating: 1600 kW
P-7004 A/B	Raw water pump	Centrifugal	272	60	8.0	38	Casing: CS Impeller: Cast Iron	2 x 100%, 1 operating 1 spare Motor rating: 75 kW

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Packages							
PK-7007	Waste water treatment		Waste water to treatment: 56 t/h				By Vendor	
	Including							
	Equalization							
	Chemical conditioning							
	Chemical sludge settling							

	Sand filters and cartridge filters							
	Ultrafiltration							
	Reverse Osmosis							
	Chemical injection packages							

Table 19. Equipment list for Utilities – Other utilities for Base case 01-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Boilers							
SG-7001 A	Natural gas auxiliary boiler	Water tube, natural circulation	123 MWth 155 t/h, 420°C, 44 barg				By Vendor	Natural gas fired
	Including, per each boiler:							
	Combustion Air Fans							2 x 100%
	Natural gas Low NOx burners							
	HP desuperheater	Water spray						
	HP superheater	Coil						
	HP evaporator	Coil						
	HP steam drum	Horiziontal						1 Steam generation level
	HP economizer	Coil						
	Start-up system							
	Fuel gas skid							Including control valves and instrumentation
	Continuous blowdown drum	Vertical						
	Intermittent blowdown drum	Vertical						

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Steam Turbines							
ST-7001A	Steam Turbine and Generator Package		16 MW				By Vendor	
	Including, per each package:							
	Steam Turbine	Back pressure	HP inlet: 155 t/h, 420°C, 44 barg MP conrtolled extraction: 9 t/h, 293°C, 14 barg LP outlet: 146 t/h, 218°C, 6 barg					
G-7001 A	Steam Turbine Generator							
	Lubrication and control Oil system							

	Cooling system							
	Control Module							
	Drainage system							
	Seals system							
	Generator Cooling system							

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Desuperheaters		Inlet	Outlet				
DS-7001	MP steam export desuperheater	Water spray	9 t/h, 293°C, 14 barg	10 t/h, 270°C, 13 barg	16.30	350	By Vendor	
DS-7002	LP steam export desuperheater	Water spray	128 t/h, 218°C, 6 barg	130 t/h, 200°C, 5 barg	7.30	270	By Vendor	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)	Shell/Tube	Shell/Tube	Shell/Tube	
E-7001	BFW preheater	S&T	11,220	282	65/84	250/195	CS/CS	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	L	barg	°C		
	Tanks & Vessels		(mm)	(mm)				
D-7001	Deaerator	Horizontal, spray type	2,500	6,250	3.50	150	CS + 3mm Internals: SS304L	
TK-7001	Demi water tank	Cone roof	16,000	8,000 (T/T)	-0.01 / 0.025	38	CS +1.5 mm + epoxy lining	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Head	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7001 A/B	BFW pump	Centrifugal	165	670	84.0	150	12 Cr	2 x 100%, 1 operating 1 spare Motor rating: 375 kW
P-7002 A/B	Demi water pump	Centrifugal	62	85	11.5	38	SS304	2 x 100%, 1 operating 1 spare Motor rating: 18.5 kW

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Packages							
PK-7001	Demineralized water package		Demi water production: 62 t/h				By Vendor	
	Including							
	Cation beds							
	Degassing columns							
	Degassified Water Pumps							
	Anion beds							
	Mixed Bed Polishers							
	Regeneration and neutralization system							
	Neutralization basin							
	Neutralization Basin Drainoff Pumps							
PK-7002	Phosphates injection package						By Vendor	Including storage drum and dosing pumps
PK-7003	Amines injection package						By Vendor	Including storage drum and dosing pumps
PK-7004	Oxygen scavenger injection package						By Vendor	Including storage drum and dosing pumps
PK-7005	Sampling package						By Vendor	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Other		(m)	(m)				
PK-7006	Continuous emission monitoring system						By Vendor	Actual flow: 222,340 m^3/h
S-7001	Natural gas boiler Stack		2.4	50	0	160	Reinforced concrete	Actual flow: 222,340 m^3/h

Table 20. Equipment list for Interconnecting Equipment - Lines for Base case 01-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	Length	barg	°C		
	Interconnecting lines		(inch)	(m)				
Cooling water lines	Main header		36	240	12.0	70	CS+3mm	Total length includes supply and return

	Subheader to CO_2 Stripper/Compression		28	240	12.0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Absorber (PP+CDU+CRF)		28	720	12.0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Absorber (PP)		24	1200	12.0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Absorber (CDU+CRF)		18	720	12.0	70	CS+3mm	Total length includes supply and return
Amine lines	Lean Amine main header from CO_2 Stripper		16	240	12.0	150	KCS+3mm+ PWHT	
	Lean Amine from main header to Absorbers CDU + CRF		10	360	12.0	150	KCS+3mm+ PWHT	
	Lean Amine from main header to Absorber PP		12	600	12.0	150	KCS+3mm+ PWHT	
	Rich Amine from Absorbers CDU + CRF to main header		16	360	8.0	100	KCS+3mm+ PWHT	
	Rich Amine from Absorber PP to main header		20	600	8.0	100	KCS+3mm+ PWHT	
	Rich Amine main header to CO_2 Stripper		24	240	8.0	100	KCS+3mm+ PWHT	Rich Amine main header to CO_2 Stripper
CO2 line	From CO_2 Compressor to refinery fence		6	960	140	80	CS+3mm	
Steam lines	LP Steam from New Power Plant to CO_2 Stripper		28	840	7.3	270	CS+3mm	
	MP Steam from New Power Plant to CO_2 Stripper		8	840	15.0	350	CS+3mm	
Condensate line	Condensate return line from CO_2 Stripper to new Power Plant		8	840	15.0	120	CS+3mm	
Condensate line	Condensate return line from CO_2 Stripper to new Power Plant		4	2000	10.0	120	CS+3mm	
Other lines	- say - other 12 interconnecting lines		4	12X1300	15.0	150	CS+3mm	
	Pipe-rack extensions/new pipe supports			1300 total length				

Table 21. Equipment list for Interconnecting Equipment – Other items for Base case 01-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	Length	barg	°C		
	Other items		(inch)	(m)				
DCS expansion	Additional cards for new plants							
Electrical grid expansion	Power supply cables from new Power Plant to CO_2 capture plants and CO_2 compression	2 x 3 x 300 mm^2		1300 total length				
Flue gas ducting	From PP to CO_2 Absorber	Square section duct	2.7 X 2.7 m	100 m total length	0.2	300	SS	Supports for duct to be included
	From CDU to FGD/ CO_2 Absorber	Square section duct	1.9 X 1.9 m	200 m total length	0.2	300	SS	Supports for duct to be included
	From CRF to CO_2 Absorber	Square section duct	1.3 X 1.3 m	150 m total length	0.2	300	SS	Supports for duct to be included

A.2Base case 02-02

A.2.1 CO_2 capture and compression

Table 22. Equipment list for the Absorber POW section for Base case 02-02

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	6 500	20 000	2,0	91,00	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	9 250	47 000	1,9	99,00	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	15 510	798	2,0	180,00	SS304L	
E-6002	DCC cooler	P&F	52 476	5 324	5,0	91	SS304L	
E-6003	Amine wash cooler	P&F	2 143	64	5,0	92	SS304L	
E-6008	Intercooler	P&F	6 061	181	5,0	74	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		622 531	4 224	2,00	180,00	SS304L	Pin/Pout: 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	1 660	234	5,8	91	SS304L	Pin/Pout: 0.1/3.8
P-6002	Amine water wash pump	Centrifugal	158	17	4,7	92	SS304L	Pin/Pout: 0.0/3.0
P-6003	Rich amine pump	Centrifugal	1 315	232	7,1	70	SS304L	Pin/Pout: 0.1/5.3
P-6009	Intercooler pump	Centrifugal	1 303	62	3,3	74	SS304L	Pin/Pout: 0.1/1.5

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Stack for Absorber		863 490		0	160		H: 50m and same D as absorber

Table 3-23. Equipment list for the Absorber FCC section for Base case 02-02

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	5 000	15 000	2,0	93,00	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	5 500	36 000	1,9	108,00	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	13 706	543	2,0	345,00	SS304L	
E-6002	DCC cooler	P&F	18 009	1 713	5,0	93	SS304L	
E-6003	Amine wash cooler	P&F	1 343	34	5,0	100	SS304L	
E-6008	Intercooler	P&F	3 591	272	5,0	75	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		149 166	442	1,90	345,00	SS304L	Pin/Pout: 0.0/0.1
C-6002	Fan after FGD		182 902	1 020	2,00	104,00	SS304L	Pin/Pout: 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	523	46	4,3	93	SS304L	Pin/Pout: 0.1/2.5
P-6002	Amine water wash pump	Centrifugal	74	6	3,9	100	SS304L	Pin/Pout: 0.0/2.0
P-6003	Rich amine pump	Centrifugal	616	108	7,1	71	SS304L	Pin/Pout: 0.1/5.3
P-6009	Intercooler pump	Centrifugal	613	30	3,3	75	SS304L	Pin/Pout: 0.1/1.5

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Flue Gas Desulfurization Unit		320 000		1,9			Limestone based wet scrubbing system
	Stack for Absorber		341 942		0	304		H: 50m and same D as absorber

Table 3-24. Equipment list for the desorption section for Base case 02-02

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Tanks & Vessels		(mm)	(mm)				
TK-6001	Amine storage tank	Vertical	23 000	18 500	1,8	58	CS	
TK-6002	CO_2 reflux accumulator	Vertical	6 200	14 500	2,8	70	SS316L	Tank with demister
TK-6003	IP condensate separator	Horizontal	1 300	7 500	5,1	175	CS	
TK-6004	LP condensate separator	Horizontal	3 200	13 300	2,7	150	CS	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6003	Regenerator (stripper)	Vertical	6 200	24 000	7,1	148	SS316L	Packed column (Mellapak 250X). Designed to operate at full vacuum.

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6004	Lean/Rich Heat exchanger	P&F	120 761	5 474	7,1	148	SS316L	
E-6005	Lean amine cooler	P&F	4 912	143	7,1	81	SS316L	
E-6006	Reflux condenser	S&T	44 297	1 034	7,1	125	SS316L	
E-6007	Stripper reboiler	Kettle	137 053	4 908	5,3	176	SS316L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6004	Lean Amine makeup pump	Centrifugal	0	0	7,1	59	SS304L	Pin/Pout: 0.0/5.3
P-6005	Lean Amine pump	Centrifugal	1 763	414	9,0	148	SS316L	Pin/Pout: 0.8/7.2
P-6006	Stripper Reflux pump	Centrifugal	61	6	4,8	69	SS304L	Pin/Pout: 0.3/3.0
P-6007	Condensate return pump (reboiler)	Centrifugal	233	28	8,3	176	SS316L	Pin/Pout: 3.5/6.5

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other Equipment		(Actual m^3/h)					
F-6001	Amine filter	Basket	445		2,6	82	SS304L	
F-6002	Amine Filter	Charcoal	445		2,6	82	SS304L	
F-6003	Amine Filter	Catridge	445		2,6	82	SS304L	
A-6001	Thermal reclaimer unit						SS316L	Design flow of 175500 kg/h

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	CO_2 processing section		(Actual m^3/h)	(kW)				
C-7001	CO_2 Compression package		64 760	11 847		120,00	SS304L	7 stage compression train with intercoolers. Pin/Pout: 0.2/84
P-7001	CO_2 product pump		172	187		58	SS304L	Pin/Pout: 84/111
PK-7001	Molecular sieve package for conditioning (dehydration)						CS	Adsorbent 3A. 3 columns of 1200 mm ID and 3800 mm length.
PK-7002	Chiller package for CO_2 product cooling							Duty: 4500 kW with temperature range 40 to 25°C, pressure: 84barg

A.2.2 Utilities and interconnecting

Table 25. Equipment list for Utilities Equipment – Power plant for Base case 02-02

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Boilers							
SG-7001 A/B	Natural gas auxiliary boiler	Water tube, natural circulation	111 MWth 140 t/h, 420°C, 44 barg				By Vendor	2 boilers, natural gas fired
	Including, for each boiler:							
	Combustion Air Fans							2 x 100%
	Natural gas Low NOx burners							
		Water spray						
	HP superheater	Coil						
	HP evaporator	Coil						

	HP steam drum	Horiziontal						1 Steam generation level
	HP economizer	Coil						
	Start-up system							
								Including control valves and instrumentation
	Continuous blowdown drum	Vertical						
	Intermittent blowdown drum	Vertical						

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Steam Turbines							
ST-7001A/B	Steam Turbine and Generator Package		14 MW				By Vendor	2 steam turbines
	Including, for each package:							
	Steam Turbine	Back pressure	HP inlet: 140 t/h, 420°C, 44 barg MP conrtolled extraction: 9 t/h, 293°C, 14 barg LP outlet: 131 t/h, 218°C, 6 barg					
G-7001A/B	Steam Turbine Generator							
	Lubrication and control Oil system							
	Cooling system							
	Control Module							
	Drainage system							
	Seals system							
	Generator Cooling system							

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Desuperheaters		Inlet	Outlet				
DS-7001	MP steam export desuperheater	Water spray	17 t/h, 293°C, 14 barg	17 t/h, 270°C, 13 barg	16.30	350	By Vendor	
DS-7002	LP steam export desuperheater	Water spray	230 t/h, 218°C, 6 barg	233 t/h, 200°C, 5 barg	7.30	270	By Vendor	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	**Area**	barg	°C		
	Heat Exchangers		(kW)	(m^2)	Shell/Tube	Shell/Tube	Shell/Tube	
E-7001A/B	BFW preheater	S&T	9,136	230	65/84	250/195	CS/CS	2 heat exchangers

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	L	barg	°C		
	Tanks & Vessels		(mm)	(mm)				
D-7001	Deaerator	Horizontal, spray type	3,000	7,500	3.50	150	CS + 3mm Internals: SS304L	
TK-7001	Demi water tank	Cone roof	20,000	9,000 (T/T)	-0.01 / 0.025	38	CS +1.5 mm + epoxy lining	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Head	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7001 A/B/C	BFW pump	Centrifugal	148	670	84.0	150	12 Cr	3 x 100%, 2 operating 1 spare Motor rating: 335 kW
P-7002 A/B	Demi water pump	Centrifugal	109	95	12.5	38	SS304	2 x 100%, 1 operating 1 spare Motor rating: 37 kW

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Packages							
PK-7001	Demineralized water package		Demi water production: 108 t/h				By Vendor	
	Including							
	Cation beds							
	Degassing columns							
	Degassified Water Pumps							
	Anion beds							
	Mixed Bed Polishers							
	Regeneration and neutralization system							
	Neutralization basin							
	Neutralization Basin Drainoff Pumps							
PK-7002	Phosphates injection package						By Vendor	Including storage drum and dosing pumps
PK-7003	Amines injection package						By Vendor	Including storage drum and dosing pumps
PK-7004	Oxygen scavenger injection package						By Vendor	Including storage drum and dosing pumps
PK-7005	Sampling package						By Vendor	

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ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Other		(m)	(m)				
PK-7006A/B	Continuous emission monitoring system						By Vendor	2 packages, 1 for each boiler Actual flow: 199,400 m^3/h
S-7001A/B	Natural gas boiler Stack		2.2	50	0	160	Reinforced concrete	2 packages, 1 for each boiler Actual flow: 199,400 m^3/h

Table 26. Equipment list for Utilities Equipment – Other utilities for Base case 02-02

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Cooling towers							
CT-7001	Cooling towers	Forced draft	8 cells x 2500 m3/h				By Vendor	Duty: 154 MW
	Inlcuding							
	Cooling water basin							
	Cooling Tower fans		8 fans					
	Chemical injection packages							
	Side stream filter							

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Head	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7003 A/B/C	CT circulation pump	Centrifugal Vertical Submerged	6605	62	12.0	70	Casing: Cast Iron Impeller: Bronze	3 x 100%, 2 operating 1 spare Motor rating: 1600 kW
P-7004 A/B	Raw water pump	Centrifugal	500	60	8.0	38	Casing: CS Impeller: Cast Iron	2 x 100%, 1 operating 1 spare Motor rating: 110 kW

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Packages							
PK-7007	Waste water treatment		Waste water to treatment: 106 t/h				By Vendor	
	Including							
	Equalization							
	Chemical conditioning							

	Chemical sludge settling							
	Sand filters and cartridge filters							
	Ultrafiltration							
	Reverse Osmosis							
	Chemical injection packages							

Table 27: Equipment list for Interconnecting Equipment – Lines for Base case 02-02

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	Length	barg	°C		
	Interconnecting lines		(inch)	(m)				
Cooling water lines	Main header		42	360	12.0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Absorber (FCC)		20	720	12.0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Stripper/Compression and Absorber (PP)		36	1320	12.0	70	CS+3mm	Total length includes supply and return
	Subheader to Absorber (PP)		36	2160	12.0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Stripper/Compression		20	120	12.0	70	CS+3mm	Total length includes supply and return
Amine lines	Lean Amine main header from CO_2 Stripper		20	60	12.0	150	KCS+3mm + PWHT	
	Lean Amine from main header to Absorber FCC		14	960	12.0	150	KCS+3mm + PWHT	
	Lean Amine from main header to Absorber PP		18	1080	12.0	150	KCS+3mm + PWHT	
	Rich Amine from Absorbers PP to main header		28	1080	8.0	100	KCS+3mm + PWHT	
	Rich Amine from Absorbers FCC to main header		18	960	8.0	100	KCS+3mm + PWHT	
	Rich Amine main header to CO_2 Stripper		32	60	8.0	100	KCS+3mm + PWHT	

CO2 line	From CO_2 Compressor to refinery fence		6	360	140	80	CS+3mm	
Steam lines	LP Steam from New Power Plant to CO_2 Stripper		32	1080	7.3	270	CS+3mm	
	MP Steam from New Power Plant to CO_2 Stripper		10	1080	15.0	350	CS+3mm	
Condensate line	Condensate return line from CO_2 Stripper to new Power Plant		10	1080	15.0	120	CS+3mm	
Waste water line	From CO_2 Capture Plants and Power Plant to WWT		6	3120	10.0	120	CS+3mm	
Other lines	- say - other 12 interconnecting lines		4	12x2000	15.0	150	CS+3mm	
	Pipe-rack extensions/new pipe supports			2000 total length				

Table 28. Equipment list for Interconnecting Equipment – Other items for Base case 02-02

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	**Height**	barg	°C		
	Other items		(m)	(m)				
New Storage tanks	5 new storage tanks in place of the ones dismantled	Cone roof	30	15	atm	200	CS	
	new tank basin to be built							
	new pipeway (say 20 lines) to be built, approx. length 800 m							
	5 existing storage tanks to be dismantled							
DCS expansion	Additional cards for new plants							

Electrical grid expansion	Power supply cables from new Power Plant to CO_2 capture plants and CO_2 compression	3 x 3 x 300 mm^2		2000 total length				
Flue gas ducting	From FCC to CO_2 Absorber	Square section duct	2.3 X 2.3 m	200 m total length	0.2	300	SS	Supports for duct to be included
	From PP to CO_2 Absorber	Square section duct	4 X 4 m	100 m total length	0.2	300	SS	Supports for duct to be included

A.3Base case 04-03

A.3.1 CO_2 capture and compression

Table 29. Equipment list for the Absorber NGCC section for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	12 100	36 500	2,0	100	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	10 200	48 000	1,9	85	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	27 300	1 575	2,0	173,00	SS304L	
E-6002	DCC cooler	P&F	20 150	3 875	2,0	76	SS304L	
E-6003	Amine wash cooler	P&F	910	40	5,80	82	SS304L	
E-6008	Intercooler	P&F	7 600	550	3,40	76	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		1 010 000	6 709	2,00	173,00	SS304L	Pin/Pout: 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	**Power**	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	1 425	221	6,2	76	SS304L	Pin/Pout: 0.1/4.4
P-6002	Amine water wash pump	Centrifugal	135	19	5,8	82	SS304L	Pin/Pout: 0.0/3.9
P-6003	Rich amine pump	Centrifugal	1 175	163	6,0	70	SS304L	Pin/Pout: 0.1/4.2
P-6009	Intercooler pump	Centrifugal	1 150	60	3,4	76	SS304L	Pin/Pout: 0.1/1.6

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Stack for Absorber		1 476 041		0	152		H: 50m and same D as absorber

Table 3-30. Equipment list for the Absorber POW_CDU_VDU section for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	**H**	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	10 250	31 000	2,0	114	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	10 600	48 000	1,9	68	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	**Area**	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	25 500	852	2,0	173,00	SS304L	
E-6002	DCC cooler	P&F	55 100	5 793	2,0	76	SS304L	
E-6003	Amine wash cooler	P&F	2 800	81	4,90	82	SS304L	
E-6008	Intercooler	P&F	8 650	697	3,40	76	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		490 750	1 255	1,90	245,00	SS304L	Pin/Pout: 0.0/0.1
C-6002	Fan after FGD		715 200	4 102	2,00	114,00	SS304L	Pin/Pout: 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	1 900	251	5,6	89	SS304L	Pin/Pout: 0.1/3.8
P-6002	Amine water wash pump	Centrifugal	210	23	4,9	93	SS304L	Pin/Pout: 0.0/3.0
P-6003	Rich amine pump	Centrifugal	1 750	236	6,0	70	SS304L	Pin/Pout: 0.1/4.2
P-6009	Intercooler pump	Centrifugal	1 700	87	3,4	74	SS304L	Pin/Pout: 0.1/1.6

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Flue Gas Desulfurization unit		491 000		1,9			Limestone based wet scrubbing system
	Stack for Absorber		1 084 589		0	189		H: 50m and same D as absorber

Table 3-31. Equipment list for the Absorber SMR section for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	8000	24000	2,0	121	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	8850	44000	1,9	101	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	11 750	600	2,0	114,00	SS304L	
E-6002	DCC cooler	P&F	35 745	3315	2,0	91	SS304L	
E-6003	Amine wash cooler	P&F	3 500	85	4,00	99	SS304L	
E-6008	Intercooler	P&F	14 550	1050	3,40	75	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		421 100	2945	2,00	193,00	SS304L	Pin/Pout: 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	1135	125	4,4	91	SS304L	Pin/Pout: 0.1/2.6
P-6002	Amine water wash pump	Centrifugal	195	18	4,0	99	SS304L	Pin/Pout: 0.0/2.2
P-6003	Rich amine pump	Centrifugal	1840	240	6,0	71	SS304L	Pin/Pout: 0.1/4.2
P-6009	Intercooler pump	Centrifugal	1830	93	3,4	75	SS304L	Pin/Pout: 0.1/1.6

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Stack for Absorber		743 000		0	173		

Table 3-32. Equipment list for the Absorber FCC section for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	6 000	18 000	2,0	104	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	5 850	36 000	1,9	68	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	16 468	653	2,0	193,00	SS304L	
E-6002	DCC cooler	P&F	21 608	2 056	2,0	91	SS304L	
E-6003	Amine wash cooler	P&F	1 490	38	4,00	100	SS304L	
E-6008	Intercooler	P&F	4 305	326	3,40	75	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		179 009	553	1,90	346,00	SS304L	Pin/Pout: 0.0/0.1
C-6002	Fan after FGD		219 483	1 255	2,00	104,00	SS304L	Pin/Pout: 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	627	57	4,4	93	SS304L	Pin/Pout: 0.1/2.6
P-6002	Amine water wash pump	Centrifugal	90	7,1	4,0	100	SS304L	Pin/Pout: 0.0/2.2
P-6003	Rich amine pump	Centrifugal	740	102	6,0	71	SS304L	Pin/Pout: 0.1/4.2
P-6009	Intercooler pump	Centrifugal	731	38	3,4	75	SS304L	Pin/Pout: 0.1/1.6

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Flue Gas Desulfurization unit		179 009		1,9			Limestone based wet scrubbing system
	Stack for Absorber		410 511		0	304		

Table 3-33. Equipment list for the desorption section for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H/L	barg	°C		
	Tanks & Vessels		(mm)	(mm)				
TK-6001	Amine storage tank	Vertical	32 000	25 700	1,8	58	CS	
TK-6002	CO_2 reflux accumulator	Vertical	10 200	18 000	2,8	70	SS316L	Tank with demister
TK-6003	IP condensate separator	Horizontal	1 800	9 000	5,1	175	CS	
TK-6004	LP condensate separator	Horizontal	4 500	17 000	2,7	150	CS	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6003	Regenerator (stripper)	Vertical	10 200	38 000	6,0	148	SS316L	Packed column (Mellapak 250X). Designed to operate at full vacuum.

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6004	Lean/Rich Heat exchanger	P&F	328 000	14 500	6,0	148	SS316L	4 parallel units
E-6005	Lean amine cooler	P&F	14 128	405	6,0	81	SS316L	
E-6006	Reflux condenser	S&T	121 000	2 765	6,0	124	SS316L	
E-6007	Stripper reboiler	Kettle	370 350	13 025	5,3	176	SS316L	7 parallel units

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6004	Lean Amine makeup pump	Centrifugal	1	0	8,6	148	SS304L	Pin/Pout: 0.0/4,2
P-6005	Lean Amine pump	Centrifugal	4 775	1 035	4,8	148	SS316L	Pin/Pout: 0.8/6.8
P-6006	Stripper Reflux pump	Centrifugal	167	17	8,3	69	SS304L	Pin/Pout: 0.3/3.0
P-6007	Condensate return pump (reboiler)	Centrifugal	715	193	10,0	148	SS316L	Pin/Pout: 1/8.3

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other Equipment		(Actual m^3/h)					
F-6001	Amine filter	Basket	1 200		2,6		SS304L	
F-6002	Amine Filter	Charcoal	1 200		2,6		SS304L	
F-6003	Amine Filter	Catridge	1 200		2,6		SS304L	
A-6001	Thermal reclaimer unit						SS316L	Design for flow of 475500 kg/h

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	CO_2 processing section		(Actual m^3/h)	(kW)				
C-7001	CO_2 Compression package		196 700	31 950		120,00	SS304L	7 stage compression train with intercoolers. Pin/Pout: 0.2/84
P-7001	CO_2 product pump		440	505		58	SS304L	Pin/Pout: 84/111
PK-7001	Molecular sieve package for conditioning (dehydration)						CS	Adsorbent 3A. 3 columns of 2050 mm ID and 5850 mm length.
PK-7002	Chiller package for CO_2 product cooling							Duty: 12000 kW with temperature range 40 to 25C, pressure: 84barg

A.3.2 Utilities and interconnecting

Table 34. Equipment list for Utilities - Power plant for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Boilers							
SG-7001 A/B/C/D	Natural gas auxiliary boiler	Water tube, natural circulation	140 MWth 200 t/h, 420°C, 44 barg				By Vendor	4 boilers, natural gas fired
	Including, per each boiler:							
	Combustion Air Fans							2 x 100%
	Natural gas Low NO_x burners							
	HP desuperheater	Water spray						
	HP superheater	Coil						
	HP evaporator	Coil						
	HP steam drum	Horiziontal						1 Steam generation level
	HP economizer	Coil						
	Start-up system							
	Fuel gas skid							Including control valves and instrumentation
	Continuous blowdown drum	Vertical						
	Intermittent blowdown drum	Vertical						

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Steam Turbines							
ST-7001A/B/C/D	Steam Turbine and Generator Package		20 MW				By Vendor	4 steam turbines
	Including, per each package:							
	Steam Turbine	Backpressure	HP inlet: 200 t/h, 420°C, 44 barg MP conrtolled extraction: 15 t/h, 293°C, 14 barg LP outlet: 185 t/h, 218°C, 6 barg					
G-7001 A/B/C/D	Steam Turbine Generator							
	Lubrication and control Oil system							
	Cooling system							
	Control Module							
	Drainage system							

	Seals system							
	Generator Cooling system							

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Desuperheaters		Inlet	Outlet				
DS-7001	MP steam export desuperheater	Water spray	50 t/h, 293°C, 14 barg	50 t/h, 270°C, 13 barg	16,30	350	By Vendor	
DS-7002	LP steam export desuperheater	Water spray	650 t/h, 218°C, 6 barg	660 t/h, 200°C, 5 barg	7,30	270	By Vendor	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	**Area**	barg	°C		
	Heat Exchangers		(kW)	(m^2)	Shell/Tube	Shell/Tube	Shell/Tube	
E-7001A/B/C/D	BFW preheater	S&T	14 174	356	65/84	250/195	CS/CS	4 heat exchangers

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	**L**	barg	°C		
	Tanks & Vessels		(mm)	(mm)				
D-7001A/B	Deaerator	Horizontal, spray type	3 400	8 500	3,50	150	CS + 3mm Internals: SS304L	2 deaerators
TK-7001	Demi water tank	Cone roof	28 000	13,000 (T/T)	-0.01 / 0.025	38	CS +1.5 mm + epoxy lining	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	**Head**	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7001 A/B/C/D/E/F	BFW pump	Centrifugal	210	670	84,0	150	12 Cr	6 x 100%, 4 operating 2 spare Motor rating: 475 kW
P-7002 A/B	Demi water pump	Centrifugal	295	95	12,5	38	SS304	2 x 100%, 1 operating 1 spare Motor rating: 110 kW

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Packages							
PK-7001	Demineralized water package		Demi water production: 295 t/h				By Vendor	
	Including							
	Cation beds							
	Degassing columns							
	Degassified Water Pumps							
	Anion beds							
	Mixed Bed Polishers							
	Regeneration and neutralization system							
	Neutralization basin							
	Neutralization Basin Drainoff Pumps							
PK-7002	Phosphates injection package						By Vendor	Including storage drum and dosing pumps
PK-7003	Amines injection package						By Vendor	Including storage drum and dosing pumps
PK-7004	Oxygen scavenger injection package						By Vendor	Including storage drum and dosing pumps
PK-7005	Sampling package						By Vendor	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	**H**	barg	°C		
	Other		(m)	(m)				
PK-7006A/B/C/D	Continuous emission monitoring system						By Vendor	4 packages, 1 for each boiler Actual flow: 281,000 m3/h
S-7001A/B/C/D	Natural gas boiler Stack		3,0	50	0	160	Reinforced concrete	4 packages, 1 for each boiler Actual flow: 281,000 m3/h

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Table 35. Equipment list for Utilities – Other utilities for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Cooling towers							
CT-7001	Cooling towers	Forced draft	15 cells x 2500 m^3/h				By Vendor	Duty: 376 MW
	Inlcuding							
	Cooling water basin							
	Cooling Tower fans		15 fans					
	Chemical injection packages							
	Side stream filter							

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	**Head**	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7003 A/B/C/D/E	CT circulation pump	Centrifugal Vertical Submerged	10830	62	12,0	70	Casing: Cast Iron Impeller: Bronze	5 x 100%, 3 operating 2 spare Motor rating: 2600 kW
P-7004 A/B	Raw water pump	Centrifugal	1273	60	8,0	38	Casing: CS Impeller: Cast Iron	2 x 100%, 1 operating 1 spare Motor rating: 280 kW

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Packages							
PK-7007	Waste water treatment		Waste water to treatment: 205 t/h				By Vendor	
	Including							
	Equalization							
	Chemical conditioning							
	Chemical sludge settling							
	Sand filters and cartridge filters							
	Ultrafiltration							
	Reverse Osmosis							
	Chemical injection packages							

Table 36. Equipment list for Interconnecting Equipment - Lines for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	Length	barg	°C		
	Interconnecting lines		(inch)	(m)				
Cooling water lines	Main headers (2 headers in parallel)		2X54	1 440	12,0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Absorber (FCC + SMR)		36	480	12,0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Absorber (CDU/VDU + PP)		42	1 680	12,0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Stripper/Compression		54	720	12,0	70	CS+3mm	Total length includes supply and return
Amine lines	Lean Amine main header from CO_2 Stripper		32	360	12,0	150	KCS+3mm+ PWHT	
	Lean Amine from main header to Absorbers FCC + SMR		24	240	12,0	150	KCS+3mm+ PWHT	
	Lean Amine from main header to Absorbers CDU/VDU + PP		24	840	12,0	150	KCS+3mm+ PWHT	
	Lean Amine from Absorbers CDU/VDU + PP to main header		36	840	8,0	100	KCS+3mm+ PWHT	
	Lean Amine from Absorbers FCC + SMR to main header		36	240	8,0	100	KCS+3mm+ PWHT	
	Rich Amine main header to CO_2 Stripper		48	360	8,0	100	KCS+3mm+ PWHT	
CO_2 line	From CO_2 Compressor to refinery fence		12	1 500	140	80	CS+3mm	
Steam lines	LP Steam from New Power Plant to CO_2 Stripper		24	1 200	7,3	270	CS+3mm	
	MP Steam from New Power Plant to CO_2 Stripper		14	1 200	15,0	350	CS+3mm	
Condensate line	Condensate return line fro CO_2 Stripper to new Power Plant		16	1 200	15,0	120	CS+3mm	
Waste water line	From CO_2 Capture Plants and Power Plant to WWT		8	3 000	10,0	120	CS+3mm	

Other lines	- say - other 12 interconnecting lines		8	12x2500	15,0	150	CS+3mm	
	Pipe-rack extensions/new pipe supports			2 500 total length				

Table 37. Equipment list for Interconnecting Equipment – Other items for Base case 04-03

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	Height	barg	°C		
	Other items		(m)	(m)				
New Storage tanks	8 new storage tanks in place of the ones dismantled	Cone roof	30	15	atm	200	CS	
	2 new tank basins to be built							
	new pipeway (say 30 lines) to be built, approx. length 800 m							
	8 existing storage tanks to be dismantled							
DCS expansion	Additional cards for new plants							
Electrical grid expansion	Power supply cables from new Power Plant to CO_2 capture plants and CO_2 compression	3 x 3 x 630 mm^2		2500 total length				30 kV assumed
Flue gas ducting	From Steam Reformer to CO_2 Absorber	Square section duct	3.3 X 3.3 m	350 m total length	0,2	300	SS	Supports for duct to be included
	From FCC to FGD/CO_2 Absorber	Square section duct	2.6 X 2.6 m	200 m total length	0,2	400	SS	Supports for duct to be included
	From CDU/VDU to FGD/CO_2 Absorber	Square section duct	2.0 X 2.0 m	350 m total length	0,2	400	SS	Supports for duct to be included
	From Steam Boiler to CO_2 Absorber	Square section duct	3.4 X 3.4 m	150 m total length	0,2	300	SS	Supports for duct to be included
	From GT/HRSG to CO_2 Absorber (3 ducts in parallel)	Square section duct	3 X (2.8 x 2.8 m)	150 m total length	0,2	300	SS	Supports for duct to be included

A.4Base case 04-04

A.4.1 CO_2 capture and compression

Table 38. Equipment list for the Absorber section for Base case 04-04

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6001	Direct Contact Cooler	Vertical	8 000	24 000	2,0	121	SS304L	Packed column (Mellapak 250X)
T-6002	Absorber	Vertical	8 850	44 000	1,9	108	SS304L	Packed column (Mellapak 250X). Water wash section included

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6001	Flue gas reheater	P&F	11 750	600	2,0	193	SS304L	
E-6002	DCC cooler	P&F	35 745	3 315	2,0	91	SS304L	
E-6003	Amine wash cooler	P&F	3 500	85	4,00	99	SS304L	
E-6008	Intercooler	P&F	14 550	1 050	3,30	69	SS304L	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Fans and Compressors		(N m^3/h)	(kW)				
C-6001	Exhaust fan		421 100	2 945	2,00	193	SS304L	Pin/Pout: 0.0/0.1

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6001	DCC Circulating pump	Centrifugal	1 135	125	4,6	91	SS304L	Pin/Pout: 0.1/2.8
P-6002	Amine water wash pump	Centrifugal	195	18	4,0	99	SS304L	Pin/Pout: 0.0/2.2
P-6003	Rich amine pump	Centrifugal	1 840	240	5,9	71	SS304L	Pin/Pout: 0.1/4.07
P-6009	Intercooler pump	Centrifugal	1 830	93	3,3	69	SS304L	Pin/Pout: 0.1/1.5

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other		(Actual m^3/h)					
	Stack for Absorber		743 000		0	173		H: 50m D:6.1

Table 3-39. Equipment list for desorption section for Base case 04-04

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Tanks & Vessels		(mm)	(mm)				
TK-6001	Amine storage tank	Vertical	22 250	17 800	1,8	58	CS	Cone roof tank
TK-6002	CO2 reflux accumalator	Vertical	6 150	18 000	2,8	70	SS316L	Tank with demister
TK-6003	IP condensate separator	Horizontal	1 300	7 700	5,1	175	CS	
TK-6004	LP condensate separator	Horizontal	3 000	12 000	2,7	150	CS	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Columns		(mm)	(mm)				
T-6003	Regenerator (stripper)	Vertical	6 150	24	2,8	148	SS316L	Packed column (Mellapak 250X). Designed to operate at full vacuum.

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	Area	barg	°C		
	Heat Exchangers		(kW)	(m^2)				
E-6004	Lean/Rich Heat exchanger	P&F	49 000	6 150	2,8	148	SS316L	2 parallel units
E-6005	Lean amine cooler	P&F	4 050	110	2,8	81	SS316L	
E-6006	Reflux condenser	S&T	42 500	910	2,8	124	SS316L	
E-6007	Stripper reboiler	Kettle	130 700	4 300	5,3	176	SS316L	2 parallel units

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	Pumps		(Actual m^3/h)	(kW)				
P-6004	Lean Amine makeup pump	Centrifugal	0	0	5,9	59	SS304L	Pin/Pout: 0.0/4,07
P-6005	Lean Amine pump	Centrifugal	1 680	400	9,3	148	SS316L	Pin/Pout: 0.8/7.5
P-6006	Stripper Reflux pump	Centrifugal	59	6	4,8	69	SS304L	Pin/Pout: 0.3/3.0
P-6007	Condensate return pump (reboiler)	Centrifugal	252	68	8,3	176	SS316L	Pin/Pout: 1.0/8.3

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow		barg	°C		
	Other Equipment		(Actual m^3/h)					
F-6001	Amine filter	Basket	425		2,6		SS304L	
F-6002	Amine Filter	Charcoal	425		2,6		SS304L	
F-6003	Amine Filter	Catridge	425		2,6		SS304L	
A-6001	Thermal reclaimer unit						SS316L	Designed for flow of 167,000 kg/h

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	Power	barg	°C		
	CO_2 processing section		(Actual m^3/h)	(kW)				
C-7001	CO_2 Compression package		63 250	11 575		120	SS304L	7 stage compression train with intercoolers. Pin/Pout: 0.2/84
P-7001	CO_2 product pump		84	77		58	SS304L	Pin/Pout: 84/111
PK-7001	Molecular sieve package for conditioning (dehydration)						CS	Adsorbent 3A. 3 columns of 1225 mm ID and 3450 mm length.
PK-7002	Chiller package for CO_2 product cooling							Duty: 4330 kW with temperature range 40 to 25°C, pressure: 84barg

A.4.2 Utilities and interconnecting

Table 40. Equipment list for Utilities – Power plant for Base case 04-04

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Boilers							
SG-7001 A/B	Natural gas auxiliary boiler	Water tube, natural circulation	106 MWth 135 t/h, 420°C, 44 barg				By Vendor	2 boilers, natural gas fired
	Including, for each boiler:							
	Combustion Air Fans							2 x 100%
	Natural gas Low NOx burners							
	HP desuperheater	Water spray						
	HP superheater	Coil						
	HP evaporator	Coil						
	HP steam drum	Horiziontal						1 Steam generation level
	HP economizer	Coil						
	Start-up system							
	Fuel gas skid							Including control valves and instrumentation
	Continuous blowdown drum	Vertical						
	Intermittent blowdown drum	Vertical						

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Steam Turbines							
ST-7001A/B	Steam Turbine and Generator Package		13 MW				By Vendor	2 steam turbines
	Including, for each package:							
	Steam Turbine	Backpressure	HP inlet: 133 t/h, 420°C, 44 barg					
G-7001A/B	Steam Turbine Generator		MP conrtolled extraction: 8 t/h, 293°C, 14 barg LP outlet: 125 t/h, 218°C, 6 barg					
	Lubrication and control Oil system							
	Cooling system							
	Control Module							
	Drainage system							
	Seals system							
	Generator Cooling system							

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ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Desuperheaters		Inlet	Outlet				
DS-7001	MP steam export desuperheater	Water spray	16 t/h, 293°C, 14 barg	17 t/h, 270°C, 13 barg	16,30	350	By Vendor	
DS-7002	LP steam export desuperheater	Water spray	220 t/h, 218°C, 6 barg	225 t/h, 200°C, 5 barg	7,30	270	By Vendor	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Duty	**Area**	barg	°C		
	Heat Exchangers		(kW)	(m^2)	Shell/Tube	Shell/Tube	Shell/Tube	
E-7001A/B	BFW preheater	S&T	9 613	242	65/84	250/195	CS/CS	2 heat exchangers

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	**L**	barg	°C		
	Tanks & Vessels		(mm)	(mm)				
D-7001	Deaerator	Horizontal, spray type	3 000	7 500	3,50	150	CS + 3mm Internals: SS304L	
TK-7001	Demi water tank	Cone roof	18 000	10,000 (T/T)	-0.01 / 0.025	38	CS +1.5 mm + epoxy lining	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	**Head**	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7001 A/B/C	BFW pump	Centrifugal	142	670	84,0	150	12 Cr	3 x 100%, 2 operating 1 spare Motor rating: 335 kW
P-7002 A/B	Demi water pump	Centrifugal	98	92	12,0	38	SS304	2 x 100%, 1 operating 1 spare Motor rating: 37 kW

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ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE barg	DESIGN TEMPERATURE °C	MATERIAL	REMARKS
	Packages							
PK-7001	Demineralized water package		Demi water production: 98 t/h				By Vendor	
	Including							
	Cation beds							
	Degassing columns							
	Degassified Water Pumps							
	Anion beds							
	Mixed Bed Polishers							
	Regeneration and neutralization system							
	Neutralization basin							
	Neutralization Basin Drainoff Pumps							
PK-7002	Phosphates injection package						By Vendor	Including storage drum and dosing pumps
PK-7003	Amines injection package						By Vendor	Including storage drum and dosing pumps
PK-7004	Oxygen scavenger injection package						By Vendor	Including storage drum and dosing pumps
PK-7005	Sampling package						By Vendor	

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	H	barg	°C		
	Other		(m)	(m)				
PK-7006A/B	Continuous emission monitoring system						By Vendor	2 packages, 1 for each boiler Actual flow: 190,500 m^3/h
S-7001A/B	Natural gas boiler Stack		2,2	50	0	160	Reinforced concrete	2 packages, 1 for each boiler Actual flow: 190,500 m3/h

Table 41. Equipment list for Utilities – Other utilities for Base case 04-04

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Cooling towers							
CT-7001	Cooling towers	Forced draft	6 cells x 2 500 m^3/h				By Vendor	Duty: 120 MW
	Including							
	Cooling water basin							
	Cooling Tower fans		6 fans					
	Chemical injection packages							
	Side stream filter							

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			Flow	**Head**	barg	°C		
	Pumps		(Actual m^3/h)	(m)				
P-7003 A/B/C	CT circulation pump	Centrifugal Vertical Submerged	5 170	55	12,0	70	Casing: Cast Iron Impeller: Bronze	3 x 100%, 2 operating 1 spare Motor rating: 1000 kW
P-7004 A/B	Raw water pump	Centrifugal	390	60	8,0	38	Casing: CS Impeller: Cast Iron	2 x 100%, 1 operating 1 spare Motor rating: 90 kW

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
					barg	°C		
	Packages							
PK-7007	Waste water treatment		Waste water to treatment: 56 t/h				By Vendor	
	Including							
	Equalization							
	Chemical conditioning							
	Chemical sludge settling							
	Sand filters and cartridge filters							
	Ultrafiltration							
	Reverse Osmosis							
	Chemical injection packages							

Table 3-42. Equipment list for Interconnecting Equipment – lines for Base case 04-04

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	Length	barg	°C		
	Interconnecting lines		(inch)	(m)				
Cooling water lines	Main header		54	240	12,0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Absorber		36	240	12,0	70	CS+3mm	Total length includes supply and return
	Subheader to CO_2 Stripper/Compression		36	1 680	12,0	70	CS+3mm	Total length includes supply and return
Amine lines	Lean Amine from CO_2 Stripper to Absorber		18	960	12,0	150	KCS+3mm+ PWHT	
	Rich Amine from Absorber		28	960	8,0	100	KCS+3mm+ PWHT	
CO2 line	From CO_2 Compressor to refinery fence		8	1 500	140	80	CS+3mm	
Steam lines	LP Steam from New Power Plant to CO_2 Stripper		28	1 200	7,3	270	CS+3mm	
	MP Steam from New Power Plant to CO_2 Stripper		8	1 200	15,0	350	CS+3mm	
Condensate line	Condensate return line from CO_2 Stripper to new Power Plant		8	1 200	15,0	120	CS+3mm	
Waste water line	From CO_2 Capture Plants and Power Plant to WWT		4	3 000	10,0	120	CS+3mm	
Other lines	- say - other 12 interconnecting lines		4	12x2500	15,0	150	CS+3mm	
	Pipe-rack extensions/new pipe supports			2 500 total length				

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Table 43. Equipment list for Interconnecting Equipment – Other items for Base case 04-04

ITEM No.	DESCRIPTION	TYPE	SIZE		DESIGN PRESSURE	DESIGN TEMPERATURE	MATERIAL	REMARKS
			ID	Height	barg	°C		
	Other items		(m)	(m)				
New Storage tanks	5 new storage tanks in place of the ones dismantled	Cone roof	30	15	atm	200	CS	
	new tank basin to be built							
	new pipeway (say 20 lines) to be built, approx. length 800 m							
	5 existing storage tanks to be dismantled							
DCS expansion	Additional cards for new plants							
Electrical grid expansion	Power supply cables from new Power Plant to CO_2 capture plants and CO_2 compression	3 x 3 x 300 mm^2		2500 total length				
Flue gas ducting	From Steam Reformer to CO_2 Absorber	Square section duct	3.3 X 3.3 m	350 m total length	0,2	300	SS	Supports for duct to be included

B Equipment cost functions developed

As previously explained, equipment cost functions for simplified assessment of some of the CO_2 capture cases. These functions can be used in order to assess the 12 cases considered for simplified assessment as well as to help others to assess their own CO_2 capture cases. These cost functions are based on the four cases assessed in details and experience on system characteristics important for equipment cost scaling. In order to ensure a good trade-off between level of detail and accuracy, cost functions are developed for the eight system subsections considered:

- CO_2 capture and compression
    - Flue gas desulphurisation unit
    - Absorber section
    - Regeneration section
    - CO_2 compression
- Utilities
    - CHP plant
    - Cooling towers
    - Waste water treatment
- Interconnecting (no subsection)

Once the both the equipment and total plant cost for the reference cases 01-03, 02-02, 04-03 and 04-04 was developed, the cost for all the other capture cases was calculated based on a factored estimating methodology, which is described hereinafter.

With the capacity factored estimate methodology, the cost of the plant under evaluation is derived from the known cost of a similar plant of known capacity (power cost law). Cost and capacity are related by means of a non-linear equation, which can be expressed as:

$$\mathrm{Cost}_{actual} = \left(\frac{\mathrm{Capacity}_{actual}}{\mathrm{Capacity}_{ref}}\right)^{\mathrm{exp}} \times \mathrm{Cost}_{ref}$$

In this function:

- $Cost_{actual}$ is the cost of the plant under evaluation
- $Cost_{ref}$ is the cost of the reference plant
- $Capacity_{actual}$ and $Capacity_{ref}$ are the respective capacities of the plants
- *exp* is the exponent, which typically varies between 0.5 and 0.85, depending on plant type and size. The exponent is usually lower than 1, when scale economies are given evidence in scaling up or down the reference cost, while it approaches the value of 1 for modularized systems.

The above described methodology was used to calculate the investment cost of the main plant units, including the most significant capacity parameters of each process section.

B.1 CO_2 capture and compression cost estimate

B.1.1 Absorption section estimate

For the four selected cases, the absorption section cost was estimated based on the developed equipment lists:

- Case 01-03: CRF absorber
- Case 02-02: Power Plant and FCC absorbers
- Case 04-03: NGCC, Boiler + CDU/VDU, SMR, FCC absorbers
- Case 04-04: SMR absorber

Using these equipment-based estimates as references, the absorption section costs for all the other cases were estimated as a factored cost estimate. The absorption section cost calculations were performed considering the cost of the absorber column separately from all the other section items:

$$\text{Cost of absorption}_{new}^{total} = \text{Cost of absorber}_{new} + \text{ Cost of other items}_{new}$$

In order to ensure a higher accuracy of the cost function for the absorber, the cost function is based on scaling from the absorber diameter and height as shown below. This allow to better take into account the indirect influence of flowrate and CO_2 concentration on the absorber cost. An exponent of 1.8 for the dependence on the diameter was identified as most suitable, which is consistent with an exponent of 0.9 applied to the cross sectional area, which in turns depends on the flue gas rate.

$$\text{Cost of absorber}_{new} = \left(\frac{\text{Absorber Diameter}_{\text{new}}}{\text{Absorber Diameter}_{\text{ref}}}\right)^{1.8} \times \left(\text{Absorber cost}_{\text{ref}} \cdot \frac{\text{Absorber height}_{\text{new}}}{\text{Absorber height}_{\text{ref}}}\right)$$

The cost of the other items, instead, is mostly dependent on the flue gas mass flowrate (as per equipment-based estimates developed). This cost was prorated according to the exponential cost function shown previously, with the flue gas mass flowrate being the most relevant capacity parameter, and with an exponent equal to 1.

$$\text{Cost of other items}_{new} = \left(\frac{\text{Flue Gas mass rate}_{new}}{\text{Flue Gas mass rate}_{ref}}\right)^{1} \times \text{Cost of other items}_{ref}$$

In Table 3-31, the total equipment cost of the absorber sections, calculated with the above cost laws (starting from Case 04-03 SMR Absorber, as reference case), is compared with the cost evaluated on the basis of the detailed equipment lists developed for the cases 01-03, 02-02, 04-03 and 04-04. It can be noted that the difference is comprised in the range -11% to +15%, so demonstrating the sufficient accuracy of the cost law.

Table 3-31: Validation of Absorber cost law (vs. detailed equipment cost calculations)

Absorber cost regression	Case 04-03	Case 04-03	Case 02-02	Case 04-03	Case 04-03	Case 02-02	Case 01-03
	NGCC T-6002	POW/CDU /VDU T-6002	POW T-6002	SMR T-6002	FCC T-6002	FCC T-6002	CRF T-6002
Flow rate flue gas [tonne/h]	1149.81	749.06	642.2	407.17	225.41	187.8	61.3
Molar fraction CO_2 in flue gas [-]	0.04	0.11	0.09	0.20	0.16	0.16	0.10
Amount CO_2 removed from the flue gas [tonne/h]	68.58	107.67	82.73	105.80	47.71	39.83	7.99
Absorber Diameter (m)	10.2	10.6	9.25	8.85	5.85	5.50	3.00
Absorber Height (m)	48	48	47	44	36	36	36
Absorber weight [tons]	471.8	501.1	394	335.2	125	110	40
Absorber cost [k$]	13739	14705	11308	9735	3688	3304	1259
Cost of rest of abs section [k$]	16740	13895	10806	7546	3952	2917	1296
Total equipment cost [k$]	30479	28600	22114	17281	7640	6221	2555
Calculations							
Absorber cost [k$]	13721	14705	11267	9741	3783	3386	1137
deviation	*0%*	*0%*	*0%*	*0%*	*3%*	*2%*	*-10%*
Cost of rest of abs section [k$]	21329	13895	11914	7553	4181	3485	1136
deviation	*27%*	*0%*	*10%*	*0%*	*6%*	*19%*	*-12%*
Total equipment cost [k$]	35050	28600	23181	17294	7964	6870	2273
deviation	*15%*	*0%*	*5%*	*0%*	*4%*	*10%*	*-11%*

B.1.2 Regeneration section estimate

As far as the regeneration section is concerned, the rich amine coming from different absorbers is conveyed to a common stripper. For Cases 02-02, 04-03 and 04-04, the stripper section cost was estimated based on detailed equipment lists.

For the other cases, the regeneration section cost estimate was performed as factored estimate using Case 04-04 as reference, with an exponent equal to 0.9. However, the striper height is also a factor to scale the cost of the stripper. Hence, the cost function was corrected by introducing also a linear dependency on the column height as follow:

$$\text{Cost of Regeneration}_{new} = \left(\frac{\text{CO}_2\text{ Flowrate to compression}_{\text{new}}}{\text{CO}_2\text{ Flowrate to compression}_{\text{ref}}}\right)^{0.9} \times \left(\text{Stripper cost}_{\text{ref}} \cdot \frac{\text{Stripper height}_{\text{new}}}{\text{Stripper height}_{\text{ref}}} + \text{Other items cost}_{\text{ref}}\right)$$

In Table 3-32, the cost of Regeneration sections calculated with the above cost law (starting from Case 04-04, as reference case) is compared with the cost evaluated based on the detailed equipment lists developed for the cases 04-03 and 02-02. It can be noted that the difference is comprised in the range -0.3% to +12%, so demonstrating the sufficient accuracy of the cost law.

Table 3-32. Validation of Regeneration cost law (vs. detailed equipment cost calculations)

Regeneration cost regression	**Case 04-03**	**Case 04-04**	**Case 02-02**
Flow rate to compression (wet) [tonne/h]	338.9	108.1	125.7
Stripper height (m)	38	24	24.0
Stripper cost [k$]	15 155	3 278	2 737
Other cost [k$]	18 284	6 732	7 475
Total estimated cost [k$]	33 439	10 010	10 212
Calculations			
Stripper cost [k$]	14 517	3 278	3 756
Other cost [k$]	18 830	6 732	7 714
Total estimated cost [k$]	33 348	10 010	11 470
deviation	*-0.27%*	*0.0%*	*12.3%*

B.1.3 CO_2 compression section estimate

As far as the CO_2 compression section is concerned, equipment-based cost estimates were assessed based on the equipment list for cases 02-02, 04-03 and 04-04.For the other cases, the cost of the CO_2 compression section was evaluated as a factored estimate (using Case 04-03 as reference).

CO_2 compression cost calculations were performed considering that not all the relevant costs depend directly on the amount of CO_2 captured and delivered at refinery fence. The total cost results from the sum of two contributions (one capacity dependent, one capacity independent):

$$\text{Cost of compression}_{new}^{total} = \text{Cost of compression}_{new}^{capacity\ dependent} + \text{Cost of compression}_{new}^{capacity\ independent}$$

In this analysis, the following costs were considered depending on the amount of CO_2 captured: equipment and piping. These costs were prorated according to the exponential cost function, with the amount of CO_2 captured being the most relevant capacity parameter, and with an exponent equal to 0.75.

The CO_2 compression unit costs that are not depending on the amount of $_{CO2}$ captured are: steel structures, iInstrumentation, electrical connections. The cost relevant to these items is approximately estimated at 600k$ US$ for all cases.

In summary, the total cost of compression section has been calculated as follows, while a validation of this equation on case 04-04 is presented in Table 3-33.

$$\text{Cost of compression}_{new} = \left(\frac{\text{CO}_2\ \text{Flowrate to compression}_{\text{new}}}{\text{CO}_2\ \text{Flowrate to compression}_{\text{ref}}}\right)^{0.75} \times \left(\text{Cost of compression}_{ref}^{equipment+piping}\right) + 600\,000\ US\$$$

Table 3-33. Example of validation of cost law for the compression section (vs. detailed cost calculation)

Compression cost regression	**Case 04-03**	**Case 04-04**
Flow rate to compression (wet) [tonne/h]	338.9	108.1
Total equipment cost [k$]	19 000	8 000
Piping cost [k$]	500	300
Other cost [k$]	600	600
Total equipment cost [k$]	20 100	8 900
Calculations		
Total calculated equipment cost [k$]	20 100	8 875
deviation	*0.0%*	*-0.28%*

B.2 Utilities cost estimate

The utilities cost estimate was calculated based on the exponential cost function shown previously. The reference case for all the evaluations was Case 04-03. The exponential cost function was applied to each of the following utility sections:

Utility unit	Capacity parameter	Exponent
Power plant: natural gas boilers	Boiler steam production	0.7
Power plant: steam turbines	Turbine power output	0.7
Power plant: demineralized water plant	DMW production capacity	0.7
Cooling towers	Number of cells (2,500 m^3/h each)	1
Waste water treatment	WWT water inlet	0.87

The power plant cost calculation was split into three main sections: natural gas boilers, steam turbines and demineralized water plant. For each of these sections, the reference cost was prorated by scaling the single equipment capacity and considering the different number of parallel trains. The exponent of 0.7, which is the typical value for these types of units, was also validated on utility costs of cases 02-02 and 04-04.
In Figure 3-1, the specific direct cost (materials plus construction, in k$ per t_{CO2}/h) estimated for the power plant in all cases is plotted, for ease of reference. The trend of the curve with some peaks is attributable to the different concentration of CO_2 in the various sources, as well as to the number of parallel trains (minimum 2) foreseen in the power plant.

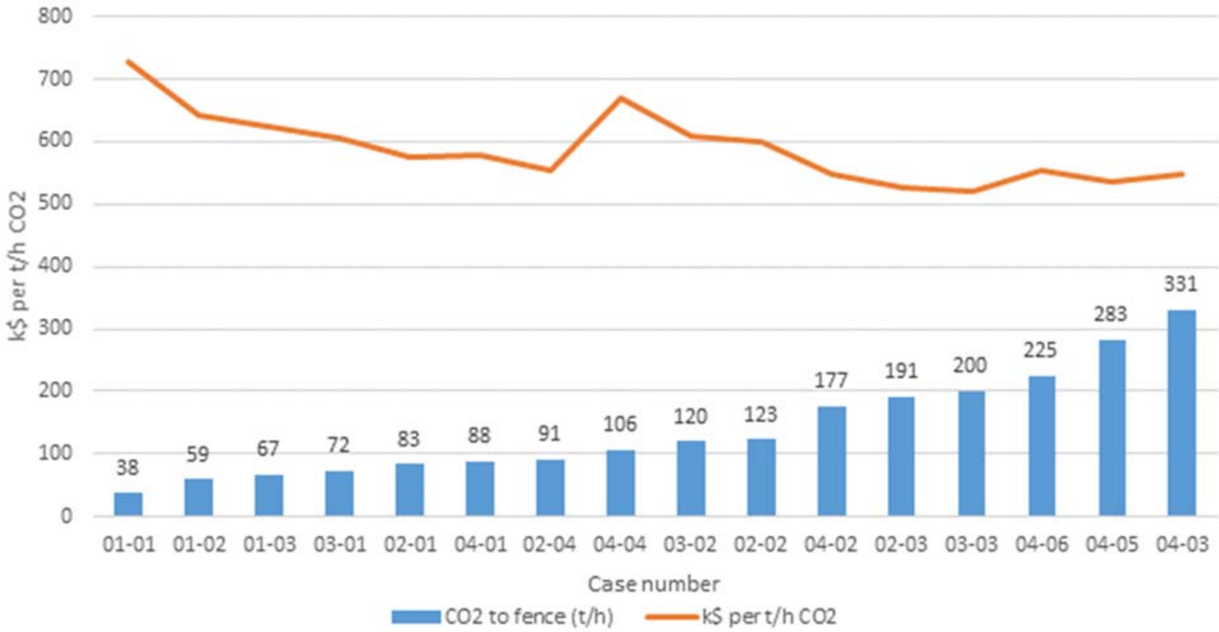

Figure 3-1. Specific power plant cost (per t_{CO2}/h) - per each case

The cooling tower cost was calculated based on the number of cells to be installed in each case. Cooling towers are a modularized system and the size of the cells is equal in all cases (2,500 m^3/h). Therefore, an exponent 1 was considered (negligible scale economies). The specific direct cost (material plus construction) for cooling towers has been evaluated in the range 60-90 k$ per t_{CO2}/h, for all cases.
For the waste water treatment, the reference cost was prorated by scaling the waste water treatment capacity with an exponent equal to 0.87. The exponent value was validated by the detailed cost estimate of Cases 02-02 and 04-04. The specific direct cost (material plus construction) for waste water treatment expansion/revamping has been evaluated in the range 20-30 k$ per t_{CO2}/h for all cases.

B.3 Interconnecting cost estimate

For three selected cases (representative of the four refinery Base Cases), the interconnecting cost was estimated based on preliminary sized equipment lists:

- Case 01-03 (representative of Base Case 01)
- Case 02-02 (representative of Base Case 02 and 03): Cases 02 and 03 are based on very similar layouts. The only difference between these configurations is the DCU (which is foreseen only in Base Case 03). However, since no CO_2 capture is considered in any case for the DCU, Case 02-02 is representative for both Base Cases 02 and 03.
- Case 04-03 (representative of Base Case 04)

Using these three equipment-based estimates as references, the interconnecting costs for all the other cases were estimated as a factored cost estimate, considering:

- Case 01-03 as reference for the costs of Cases 01-01, 01-02
- Case 02-02 as reference for the costs of Cases 02-01, 02-03, 02-04, 03-01, 03-02, 03-03
- Case 04-03 as reference for the costs of Cases 04-01, 04-02, 04-04

Interconnecting cost calculations were performed considering that not all the relevant costs depend directly on the amount of CO_2 captured and delivered at refinery fence. The total interconnecting cost results from the sum of two contributions (one capacity dependent, one capacity independent):

$$\text{Cost of interconnecting}_{new}^{total} = \text{Cost of interconnecting}_{new}^{capacity\ dependent} + \text{Cost of interconnecting}_{new}^{capacity\ independent}$$

In this analysis, the following costs were considered to be dependent of the amount of CO_2 captured: flue gas ducting, cooling water lines, amine lines, CO_2 line to refinery fence, steam lines, condensate line, waste water line, DCS expansion, electrical grid expansion. These costs were prorated according to the exponential cost function previously presented, with the amount of CO_2 captured being the most relevant capacity parameter, and with an exponent equal to 0.75.

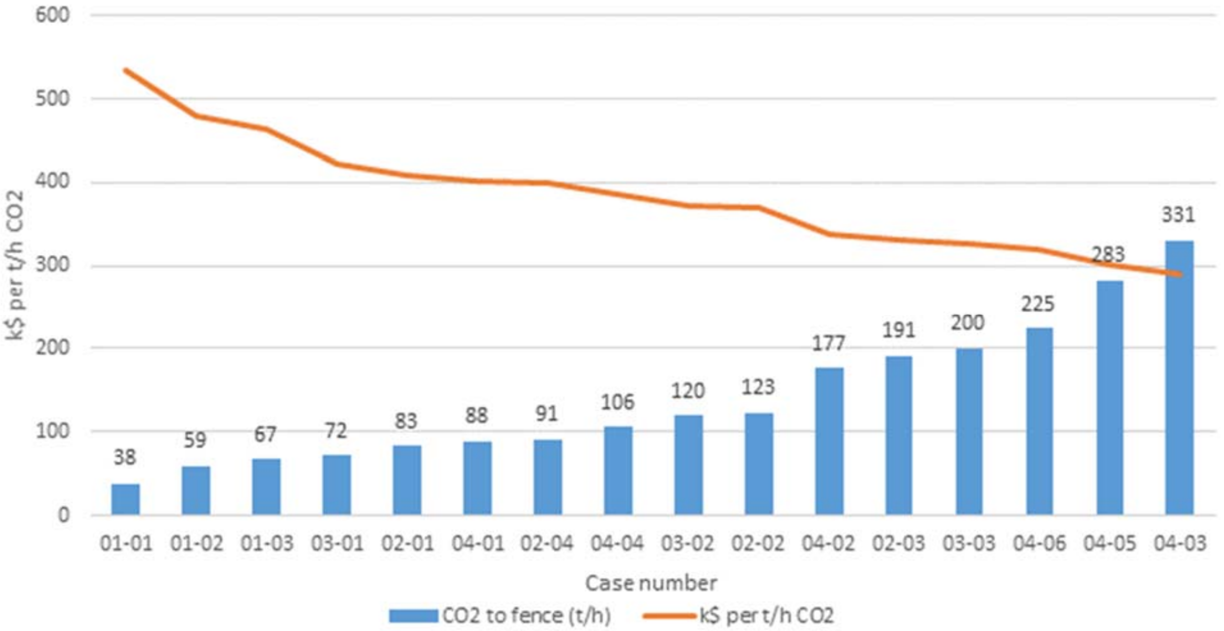

Figure 3-2. Specific interconnecting cost (per t_{CO2}/h) - capacity dependent portion - per each case

The interconnecting costs that do not depend on the amount of CO_2 captured, but only on the refinery layout, are: storage tanks relocation (calculated based on the number of relocated tanks) and pipe-rack extensions/new pipe supports (calculated on the basis of the length of new pipe supports). A total direct cost (materials + construction) of 2500 k$ has been estimated per each tank to be relocated, while a total direct cost of new piperack has been estimated equal to approx. 1900 k$/100m.

It has to be noticed that the economic outcomes of the above described interconnecting cost methodology are strongly dependent on the specificity of each site. Therefore, it is recommended that a careful evaluation of site characteristics is performed when developing interconnecting cost estimates for other refiner

C Excel model for evaluating the cost of retrofitting CO_2 capture from refineries

The following elements present and describe how to use the excel model developed by SINTEF Energy Research for evaluation of the cost of retrofitting CO_2 capture from refineries and available at http://www.sintef.no/RECAP.

Presentations:

This spreadsheet aims at providing help for potential users to evaluate and understand the cost of retrofitting CO_2 capture on a refinery.

This spreadsheet is divided into five sheets:

- Sheet "Presentation - instructions": which includes the presentation of the spreadsheet and instructions to perform an evaluation
- Sheet "Input data": in which all data required (case, technical, cost, and sensitivity analyses) to evaluate the cost of retrofitting CO_2 capture shall be filled in.
- Sheet "Discount factor": in which the discount factors (used to evaluate the annualized CAPEX) are assessed for the base case and the sensitivity analyses (when varying project duration, discount rate and utilisation rate)
- Sheet "Detailed cost results": which includes the detailed cost evaluation results of retrofitting CO_2 capture (values)
- Sheet "Summarised cost results": which includes the breakdown of the cost of retrofitting CO_2 capture ($\$/t_{CO2,avoided}$) results - (values and graphical representation)
- Sheet "Sensitivity analyses": which includes the results of the sensitivity analyses - (values and graphical representation)

Instructions:

To evaluate a case with the present spreadsheet, the user needs to fill out, with the data corresponding to the case which needs to be evaluated, all the orange cells in the sheet "Input data":

1. Project valuation data (discount rate, reference year, number of years of operations, average annual utilisation rate)
2. CO_2 captured and avoided streams (amount of CO_2 captured, amount of CO_2 emitted by the power plant)
3. Data for calculation of CAPEX (costs for each of the cost sections of the system, contingencies, data for evaluation of the Total Capital requirement, planned allocation of construction costs)
4. Data for calculation of the annual fixed OPEX (number of employees, average fully burdened salary, annual material maintenance percentages, overall maintenance cost percentage, other cost percentages)
5. Data for calculation of the annual variable OPEX (utilities consumptions and sludge disposal quantities and cost, material replacement and cost, share of natural gas consumption linked to steam production for CO_2 stripping)
6. Data for valorisation of excess power if relevant (Choice to consider excess power valorisation, amount and economic value of excess power)
7. Variation ranges considered for sensitivity analyses

Remark: It is strongly recommended that the user always checks carefully the units used.

The user is free to use their own estimates, however help to evaluate CAPEX through cost functions can be found in Appendix B while help to evaluate utilities consumption and material replacement can be found in the document *Performance analysis of CO_2 capture options*.

Once these data are filled out, the results generated (presented above) can directly be found in the three sheets "Detailed cost results", "Summarised cost results", and "Sensitivity analyses".

To provide support for user based evaluations, the spreadsheets of the 16 CO_2 capture cases evaluated in the ReCap project can be found at http://www.sintef.no/RECAP.

It is worth noting that the cost of retrofitting CO_2 capture is calculated based on the additional costs of implementing CO_2 capture (including utilities generation and interconnecting) using the following equation:

$$CO_2 \text{ avoided cost} = \frac{\text{Annualized } CO_2 \text{ capture CAPEX} + \text{Annual } CO_2 \text{ capture OPEX}}{\text{Annual amount of } CO_2 \text{ avoided}}$$

Finally, note that, apart from the cells marked in orange, all the cells of the spreadsheet are locked for editing and may not be modified.

Contact:

For further question(s) on this spreadsheet, please contact Simon Roussanaly at SINTEF Energy Research at simon.roussanaly@sintef.no with the following e-mail subject "**Spreadsheet for evaluation of cost of retrofitting CO_2 capture from refineries**".

Acknowledgement:

This Spreadsheet was developed by SINTEF Energy Research in the ReCap project with funding from Gassnova (contract 232308), IEAGHG and Concawe.

Disclaimer:

SINTEF Energy Research has developed this spreadsheet for calculations of the costs presented in the report "Understanding the cost of retrofitting CO_2 capture to integrated oil refineries"

The spreadsheet is provided as is for enabling user-specific assessments of CO_2 capture retrofit to integrated oil refineries. SINTEF assumes no responsibility for the results generated with this spreadsheet.

SINTEF

D Cost evaluation results for all the cases considered

D.1 Base case 1

D.1.1 Base case 01-01

Overall CAPEX (k$)	CO_2 capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Direct materials	**0**	**17,500**	**7,500**	**4,420**	**17,620**	**2,220**	**820**	**15,500**	**65,580**
Construction	0	10,300	4,400	3,000	10,000	1,600	500	19,600	49,400
Direct Field Cost	**0**	**27,800**	**11,900**	**7,420**	**27,620**	**3,820**	**1,320**	**35,100**	**114,980**
Other costs	0	1,600	700	500	1,500	200	100	1,000	5,600
EPC services	0	5,600	2,400	1,500	5,500	800	300	7,000	23,100
Total installed cost	**0**	**35,000**	**15,000**	**9,420**	**34,620**	**4,820**	**1,720**	**43,100**	**143,680**
Project contingencies	0	5,250	2,250	1,413	5,193	723	258	6,465	21,552
Total plant cost	**68,333**				**47,334**			**49,565**	**165,232**
Spare parts	342				237			248	826
Inventory of fuel and chemicals	152				268			0	420
Start-up cost	1,567				1,147			991	3,705
Owner cost	4,783				3,313			3,470	11,566
Interest during construction	10,875				7,533			7,888	26,295
Total capital requirement	**86,051**				**59,832**			**62,162**	**208,045**

Annual OPEX (k$/y)	CO_2 capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. Unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Labour cost	800				800			0	1,600
Annual maintenance	2,278				1,784			826	4,888
Other	342				237			248	826
Annual fixed operating cost	**3,419**				**2,821**			**1,074**	**7,314**
Natural gas consumption	0				12,412			0	12,412
Chemical and catalyst	1,444				0			0	1,444
Raw process water (make-up)	0				118			0	118
Waste disposal	378				0			0	378
Annual variable operating cost	**1,822**				**12,530**			**0**	**14,351**
Total annual operating cost	**5,241**				**15,351**			**1,074**	**21,666**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	189.8

D.1.2 Base case 01-02

Overall CAPEX (k$)	**CO_2 capture and compression**					**Utilities**		**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Power plant	Cooling towers	Waste water treatment		
Direct materials	**11,300**	**26,200**	**11,200**	**5,980**	**24,240**	**2,960**	**1,080**	**23,000**	**105,960**
Construction	7,400	15,400	6,600	4,200	13,700	2,100	600	29,300	79,300
Direct Field Cost	**18,700**	**41,600**	**17,800**	**10,180**	**37,940**	**5,060**	**1,680**	**52,300**	**185,260**
Other costs	1,100	2,400	1,000	600	2,100	300	100	1,000	8,600
EPC services	3,700	8,400	3,600	2,000	7,600	1,000	300	10,500	37,100
Total installed cost	**23,500**	**52,400**	**22,400**	**12,780**	**47,640**	**6,360**	**2,080**	**63,800**	**230,960**
Project contingencies	3,525	7,860	3,360	1,917	7,146	954	312	9,570	34,644
Total plant cost	**127,742**				**64,492**			**73,370**	**265,604**
Spare parts	639				322			367	1,328
Inventory of fuel and chemicals	228				424			0	652
Start-up cost	2,855				1,490			1,467	5,812
Owner cost	8,942				4,514			5,136	18,592
Interest during construction	20,329				10,263			11,676	42,269
Total capital requirement	**160,734**				**81,506**			**92,016**	**334,257**

Annual OPEX (k$/y)	**CO_2 capture and compression**					**Utilities**		**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Power plant	Cooling towers	Waste water treatment		
Labour cost	1,200				800			0	2,000
Annual maintenance	4,258				2,445			1,223	7,925
Other	639				322			367	1,328
Annual fixed operating cost	**6,097**				**3,567**			**1,590**	**11,253**
Natural gas consumption	0				19,633			0	19,633
Chemical and catalyst	2,128				0			0	2,128
Raw process water (make-up)	0				181			0	181
Waste disposal	605				0			0	605
Annual variable operating cost	**2,732**				**19,814**			**0**	**22,546**
Total annual operating cost	**8,829**				**23,381**			**1,590**	**33,800**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	**190.1**

D.1.3 Base case 01-03

Overall CAPEX (k$)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Direct materials	**11 300**	**30 500**	**13 100**	**6 520**	**26 660**	**2 960**	**1 210**	**24 300**	**116 550**
Construction	7 400	17 900	7 700	4 700	15 200	2 100	700	30 800	86 500
Direct Field Cost	**18 700**	**48 400**	**20 800**	**11 220**	**41 860**	**5 060**	**1 910**	**55 100**	**203 050**
Other costs	1 100	2 800	1 200	700	2 300	300	100	1 000	9 500
EPC services	3 700	9 700	4 200	2 200	8 300	1 000	400	11 000	40 500
Total installed cost	**23 500**	**60 900**	**26 200**	**14 120**	**52 460**	**6 360**	**2 410**	**67 100**	**253 050**
Project contingencies	3 525	9 135	3 930	2 118	7 869	954	362	10 065	37 958
Total plant cost	**143 428**				**70 415**			**77 165**	**291 008**
Spare parts	717				352			386	1 455
Inventory of fuel and chemicals	259				480			0	740
Start-up cost	3 169				1 608			1 543	6 320
Owner cost	10 040				4 929			5 402	20 371
Interest during construction	22 825				11 206			12 280	46 312
Total capital requirement	**180 439**				**88 990**			**96 776**	**366 205**

Annual OPEX (k$/y)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Labour cost	1 200				800			0	2 000
Annual maintenance	4 781				2 682			1 286	8 749
Other	717				352			386	1 455
Annual fixed operating cost	**6 698**				**3 834**			**1 672**	**12 204**
Natural gas consumption	0				22 240			0	22 240
Chemical and catalyst	2 432				0			0	2 432
Raw process water (make-up)	0				205			0	205
Waste disposal	680				0			0	680
Annual variable operating cost	**3 113**				**22 446**			**0**	**25 558**
Total annual operating cost	**9 811**				**26 279**			**1 672**	**37 762**

Cost of retrofitting CO_2 capture ($/t$_{CO2,avoided}$)	185,3

D.2.1 Base case 02-01

Overall CAPEX (k$)

	CO₂ capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Direct materials	**0**	**43 400**	**15 000**	**7 510**	**30 460**	**4 440**	**1 540**	**27 500**	**129 850**
Construction	0	25 500	8 800	5 400	17 200	3 200	900	36 600	97 600
Direct Field Cost	**0**	**68 900**	**23 800**	**12 910**	**47 660**	**7 640**	**2 440**	**64 100**	**227 450**
Other costs	0	3 800	1 300	800	2 600	500	100	1 000	10 100
EPC services	0	13 700	4 800	2 600	9 500	1 500	500	12 800	45 400
Total installed cost	**0**	**86 400**	**29 900**	**16 310**	**59 760**	**9 640**	**3 040**	**77 900**	**282 950**
Project contingencies	0	12 960	4 485	2 447	8 964	1 446	456	11 685	42 443
Total plant cost	**152 502**				**83 306**			**89 585**	**325 393**
Spare parts	763				417			448	1 627
Inventory of fuel and chemicals	312				594			0	905
Start-up cost	3 250				1 866			1 792	6 908
Owner cost	10 675				5 831			6 271	22 777
Interest during construction	24 269				13 258			14 257	51 784
Total capital requirement	**191 770**				**105 271**			**112 352**	**409 394**

Annual OPEX (k$/y)

	CO₂ capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Labour cost	800				800			0	1 600
Annual maintenance	5 083				3 107			1 493	9 683
Other	763				417			448	1 627
Annual fixed operating cost	**6 646**				**4 323**			**1 941**	**12 910**
Natural gas consumption	0				27 468			0	27 468
Chemical and catalyst	2 910				0			0	2 910
Raw process water (make-up)	0				256			0	256
Waste disposal	832				0			0	832
Annual variable operating cost	**3 741**				**27 724**			**0**	**31 465**
Total annual operating cost	**10 387**				**32 047**			**1 941**	**44 375**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	**173,3**

D.2.2 Base case 02-02

Overall CAPEX (k$)	**CO_2 capture and compression**				**Utilities**			**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Power plant	Cooling towers	Waste water treatment		
Direct materials	**13 600**	**56 200**	**22 400**	**9 870**	**46 860**	**5 920**	**2 110**	**41 200**	**198 160**
Construction	8 900	33 000	13 200	7 300	26 600	4 300	1 200	54 700	149 200
Direct Field Cost	**22 500**	**89 200**	**35 600**	**17 170**	**73 460**	**10 220**	**3 310**	**95 900**	**347 360**
Other costs	1 400	4 900	2 000	1 100	3 900	600	200	2 000	16 100
EPC services	4 500	17 800	7 100	3 400	14 700	2 000	700	19 200	69 400
Total installed cost	**28 400**	**111 900**	**44 700**	**21 670**	**92 060**	**12 820**	**4 210**	**117 100**	**432 860**
Project contingencies	4 260	16 785	6 705	3 251	13 809	1 923	632	17 565	64 929
Total plant cost	**237 671**				**125 454**			**134 665**	**497 789**
Spare parts	1 188				627			673	2 489
Inventory of fuel and chemicals	466				873			0	1 339
Start-up cost	5 053				2 709			2 693	10 456
Owner cost	16 637				8 782			9 427	34 845
Interest during construction	37 823				19 965			21 431	79 219
Total capital requirement	**298 839**				**158 409**			**168 889**	**626 137**

Annual OPEX (k$/y)	**CO_2 capture and compression**				**Utilities**			**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Power plant	Cooling towers	Waste water treatment		
Labour cost	1 200				800			0	2 000
Annual maintenance	7 922				4 738			2 244	14 904
Other	1 188				627			673	2 489
Annual fixed operating cost	**10 311**				**6 165**			**2 918**	**19 393**
Natural gas consumption	0				40 370			0	40 370
Chemical and catalyst	4 365				0			0	4 365
Raw process water (make-up)	0				381			0	381
Waste disposal	1 229				0			0	1 229
Annual variable operating cost	**5 594**				**40 751**			**0**	**46 345**
Total annual operating cost	**15 905**				**46 916**			**2 918**	**65 738**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	**175,6**

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D.2.3 Base case 02-03

Overall CAPEX (k$)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Direct materials	**32 100**	**82 600**	**35 500**	**13 530**	**64 310**	**7 400**	**2 870**	**48 800**	**287 110**
Construction	21 100	48 500	20 900	10 200	36 500	5 300	1 700	65 100	209 300
Direct Field Cost	**53 200**	**131 100**	**56 400**	**23 730**	**100 810**	**12 700**	**4 570**	**113 900**	**496 410**
Other costs	3 300	7 300	3 100	1 500	5 500	800	200	2 000	23 700
EPC services	10 600	26 200	11 300	4 800	20 200	2 500	900	22 800	99 300
Total installed cost	**67 100**	**164 600**	**70 800**	**30 030**	**126 510**	**16 000**	**5 670**	**138 700**	**619 410**
Project contingencies	10 065	24 690	10 620	4 505	18 977	2 400	851	20 805	92 912
Total plant cost		**382 410**				**170 407**		**159 505**	**712 322**
Spare parts		1 912				852		798	3 562
Inventory of fuel and chemicals		735				1 354		0	2 089
Start-up cost		8 048				3 608		3 190	14 846
Owner cost		26 769				11 928		11 165	49 863
Interest during construction		60 858				27 119		25 384	113 361
Total capital requirement		**480 731**				**215 268**		**200 042**	**896 041**

Annual OPEX (k$/y)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Labour cost		1 600				800		0	2 400
Annual maintenance		12 747				6 477		2 658	21 883
Other		1 912				852		798	3 562
Annual fixed operating cost		**16 259**				**8 129**		**3 456**	**27 844**
Natural gas consumption		0				62 675		0	62 675
Chemical and catalyst		6 892				0		0	6 892
Raw process water (make-up)		0				577		0	577
Waste disposal		1 928				0		0	1 928
Annual variable operating cost		**8 820**				**63 252**		**0**	**72 072**
Total annual operating cost		**25 079**				**71 381**		**3 456**	**99 916**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	166,2

D.2.4 Base case 02-04

Overall CAPEX (k$)	CO_2 capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Direct materials	**32 100**	**33 900**	**16 800**	**8 010**	**32 280**	**3 700**	**1 450**	**36 200**	**164 440**
Construction	21 100	19 900	9 900	5 800	18 300	2 700	900	48 200	126 800
Direct Field Cost	**53 200**	**53 800**	**26 700**	**13 810**	**50 580**	**6 400**	**2 350**	**84 400**	**291 240**
Other costs	3 300	3 000	1 500	900	2 800	400	100	1 000	13 000
EPC services	10 600	10 800	5 300	2 800	10 200	1 300	500	16 900	58 400
Total installed cost	**67 100**	**67 600**	**33 500**	**17 510**	**63 580**	**8 100**	**2 950**	**102 300**	**362 640**
Project contingencies	10 065	10 140	5 025	2 627	9 537	1 215	443	15 345	54 396
Total plant cost		**213 567**				**85 825**		**117 645**	**417 036**
Spare parts		1 068				429		588	2 085
Inventory of fuel and chemicals		355				696		0	1 051
Start-up cost		4 571				1 916		2 353	8 841
Owner cost		14 950				6 008		8 235	29 193
Interest during construction		33 987				13 658		18 722	66 368
Total capital requirement		**268 498**				**108 532**		**147 544**	**524 574**

Annual OPEX (k$/y)	CO_2 capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Labour cost		1 200				800		0	2 000
Annual maintenance		7 119				3 258		1 961	12 338
Other		1 068				429		588	2 085
Annual fixed operating cost		**9 387**				**4 487**		**2 549**	**16 423**
Natural gas consumption		0				32 290		0	32 290
Chemical and catalyst		3 354				0		0	3 354
Raw process water (make-up)		0				280		0	280
Waste disposal		907				0		0	907
Annual variable operating cost		**4 261**				**32 570**		**0**	**36 831**
Total annual operating cost		**13 648**				**37 057**		**2 549**	**53 254**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	**194,1**

D.3.1 Base case 03-01

Overall CAPEX (k$)	**CO_2 capture and compression**				**Utilities**			**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Direct materials	**0**	**43 500**	**13 100**	**6 800**	**27 760**	**3 700**	**1 170**	**26 000**	**122 030**
Construction	0	25 500	7 700	4 900	15 700	2 700	700	34 600	91 800
Direct Field Cost	**0**	**69 000**	**20 800**	**11 700**	**43 460**	**6 400**	**1 870**	**60 600**	**213 830**
Other costs	0	3 800	1 200	700	2 300	400	100	1 000	9 500
EPC services	0	13 800	4 200	2 300	8 700	1 300	400	12 100	42 800
Total installed cost	**0**	**86 600**	**26 200**	**14 700**	**54 460**	**8 100**	**2 370**	**73 700**	**266 130**
Project contingencies	0	12 990	3 930	2 205	8 169	1 215	356	11 055	39 920
Total plant cost	**146 625**				**74 670**			**84 755**	**306 050**
Spare parts	733				373			424	1 530
Inventory of fuel and chemicals	269				519			0	788
Start-up cost	3 133				1 693			1 695	6 521
Owner cost	10 264				5 227			5 933	21 423
Interest during construction	23 334				11 883			13 488	48 705
Total capital requirement	**184 357**				**94 365**			**106 295**	**385 018**

Annual OPEX (k$/y)	**CO_2 capture and compression**				**Utilities**			**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Labour cost	800				800			0	1 600
Annual maintenance	4 888				2 810			1 413	9 110
Other	733				373			424	1 530
Annual fixed operating cost	**6 421**				**3 984**			**1 836**	**12 241**
Natural gas consumption	0				24 073			0	24 073
Chemical and catalyst	2 506				0			0	2 506
Raw process water (make-up)	0				212			0	212
Waste disposal	718				0			0	718
Annual variable operating cost	**3 224**				**24 285**			**0**	**27 509**
Total annual operating cost	**9 645**				**28 268**			**1 836**	**39 749**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	**184,9**

D.3.2 Base case 03-02

Overall CAPEX (k$)	CO_2 capture and compression Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Direct materials	**15 400**	**58 100**	**22 400**	**9 690**	**46 450**	**5 180**	**1 860**	**40 800**	**199 880**
Construction	10 100	34 000	13 200	7 100	26 400	3 700	1 100	54 200	149 800
Direct Field Cost	**25 500**	**92 100**	**35 600**	**16 790**	**72 850**	**8 880**	**2 960**	**95 000**	**349 680**
Other costs	1 500	5 100	2 000	1 100	3 900	600	100	2 000	16 300
EPC services	5 100	18 500	7 100	3 400	14 700	1 800	600	19 000	70 200
Total installed cost	**32 100**	**115 700**	**44 700**	**21 290**	**91 450**	**11 280**	**3 660**	**116 000**	**436 180**
Project contingencies	4 815	17 355	6 705	3 194	13 718	1 692	549	17 400	65 427
Total plant cost	**245 859**				**122 349**			**133 400**	**501 607**
Spare parts	1 229				612			667	2 508
Inventory of fuel and chemicals	453				855			0	1 308
Start-up cost	5 217				2 647			2 668	10 532
Owner cost	17 210				8 564			9 338	35 112
Interest during construction	39 127				19 471			21 230	79 827
Total capital requirement	**309 095**				**154 498**			**167 303**	**630 895**

Annual OPEX (k$/y)	CO_2 capture and compression Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Labour cost	1 200				800			0	2 000
Annual maintenance	8 195				4 668			2 223	15 087
Other	1 229				612			667	2 508
Annual fixed operating cost	**10 625**				**6 080**			**2 890**	**19 595**
Natural gas consumption	0				39 591			0	39 591
Chemical and catalyst	4 249				0			0	4 249
Raw process water (make-up)	0				363			0	363
Waste disposal	1 191				0			0	1 191
Annual variable operating cost	**5 439**				**39 954**			**0**	**45 394**
Total annual operating cost	**16 064**				**46 034**			**2 890**	**64 989**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	**180,3**

D.3.3 Base case 03-03

Overall CAPEX (k$)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Direct materials	**34 100**	**87 400**	**37 400**	**13 970**	**66 460**	**8 140**	**2 750**	**49 700**	**299 920**
Construction	22 400	51 200	22 000	10 500	37 800	5 900	1 600	66 300	217 700
Direct Field Cost	**56 500**	**138 600**	**59 400**	**24 470**	**104 260**	**14 040**	**4 350**	**116 000**	**517 620**
Other costs	3 400	7 700	3 300	1 600	5 600	900	200	2 000	24 700
EPC services	11 300	27 800	11 900	4 900	20 900	2 800	900	23 200	103 700
Total installed cost	**71 200**	**174 100**	**74 600**	**30 970**	**130 760**	**17 740**	**5 450**	**141 200**	**646 020**
Project contingencies	10 680	26 115	11 190	4 646	19 614	2 661	818	21 180	96 903
Total plant cost	**403 501**				**177 043**			**162 380**	**742 923**
Spare parts	2 018				885			812	3 715
Inventory of fuel and chemicals	766				1 426			0	2 192
Start-up cost	8 470				3 741			3 248	15 458
Owner cost	28 245				12 393			11 367	52 005
Interest during construction	64 214				28 175			25 842	118 231
Total capital requirement	**507 213**				**223 663**			**203 648**	**934 524**

Annual OPEX (k$/y)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: Power plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Labour cost	1 600				800			0	2 400
Annual maintenance	13 450				6 710			2 706	22 866
Other	2 018				885			812	3 715
Annual fixed operating cost	**17 068**				**8 395**			**3 518**	**28 981**
Natural gas consumption	0				66 039			0	66 039
Chemical and catalyst	7 189				0			0	7 189
Raw process water (make-up)	0				607			0	607
Waste disposal	2 003				0			0	2 003
Annual variable operating cost	**9 192**				**66 646**			**0**	**75 838**
Total annual operating cost	**26 260**				**75 041**			**3 518**	**104 819**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	166,5

D.4 Base case 4

D.4.1 Base case 04-01

Overall CAPEX (k$)	COCO_2 capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Direct materials	**0**	**76 800**	**16 800**	**7 830**	**32 430**	**3 700**	**920**	**42 000**	**180 480**
Construction	0	45 100	9 900	5 700	18 400	2 700	500	50 900	133 200
Direct Field Cost	**0**	**121 900**	**26 700**	**13 530**	**50 830**	**6 400**	**1 420**	**92 900**	**313 680**
Other costs	0	6 800	1 500	900	2 800	400	100	2 000	14 500
EPC services	0	24 300	5 300	2 700	10 200	1 300	300	18 600	62 700
Total installed cost	**0**	**153 000**	**33 500**	**17 130**	**63 830**	**8 100**	**1 820**	**113 500**	**390 880**
Project contingencies	0	22 950	5 025	2 570	9 575	1 215	273	17 025	58 632
Total plant cost	**234 175**				**84 813**			**130 525**	**449 512**
Spare parts	1 171				424			653	2 248
Inventory of fuel and chemicals	330				650			0	981
Start-up cost	4 883				1 896			2 611	9 390
Owner cost	16 392				5 937			9 137	31 466
Interest during construction	37 267				13 497			20 772	71 536
Total capital requirement	**294 219**				**107 217**			**163 697**	**565 133**

Annual OPEX (k$/y)	CO_2 capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Labour cost	800				800			0	1 600
Annual maintenance	7 806				3 249			2 175	13 230
Other	1 171				424			653	2 248
Annual fixed operating cost	**9 777**				**4 473**			**2 828**	**17 077**
Natural gas consumption	0				30 530			0	30 530
Chemical and catalyst	3 076				0			0	3 076
Raw process water (make-up)	0				237			0	237
Waste disposal	888				0			0	888
Annual variable operating cost	**3 965**				**30 768**			**0**	**34 732**
Total annual operating cost	**13 741**				**35 241**			**2 828**	**51 810**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	209,8

D.4.2 Base case 04-02

Overall CAPEX (k$)	CO₂ capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Direct materials	**25 000**	**112 400**	**31 800**	**12 790**	**61 630**	**5 920**	**2 110**	**53 900**	**305 550**
Construction	16 500	66 000	18 700	9 600	35 000	4 300	1 200	63 400	214 700
Direct Field Cost	**41 500**	**178 400**	**50 500**	**22 390**	**96 630**	**10 220**	**3 310**	**117 300**	**520 250**
Other costs	2 500	9 900	2 800	1 400	5 300	600	200	2 000	24 700
EPC services	8 300	35 600	10 100	4 500	19 300	2 000	700	23 500	104 000
Total installed cost	**52 300**	**223 900**	**63 400**	**28 290**	**121 230**	**12 820**	**4 210**	**142 800**	**648 950**
Project contingencies	7 845	33 585	9 510	4 244	18 185	1 923	632	21 420	97 343
Total plant cost	**423 074**				**158 999**			**164 220**	**746 293**
Spare parts	2 115				795			821	3 731
Inventory of fuel and chemicals	678				1 280			0	1 958
Start-up cost	8 761				3 380			3 284	15 426
Owner cost	29 615				11 130			11 495	52 240
Interest during construction	67 329				25 303			26 134	118 767
Total capital requirement	**531 573**				**200 887**			**205 955**	**938 415**

Annual OPEX (k$/y)	CO₂ capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Labour cost	1 200				800			0	2 000
Annual maintenance	14 102				6 135			2 737	22 975
Other	2 115				795			821	3 731
Annual fixed operating cost	**17 418**				**7 730**			**3 558**	**28 706**
Natural gas consumption	0				60 824			0	60 824
Chemical and catalyst	6 362				0			0	6 362
Raw process water (make-up)	0				513			0	513
Waste disposal	1 777				0			0	1 777
Annual variable operating cost	**8 139**				**61 338**			**0**	**69 477**
Total annual operating cost	**25 557**				**69 068**			**3 558**	**98 183**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	184,2

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D.4.3 Base case 04-03

Overall CAPEX (k$)	CO_2 capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Direct materials	**39 000**	**161 100**	**63 600**	**20 080**	**115 400**	**11 100**	**3 740**	**71 300**	**485 320**
Construction	25 700	94 600	37 400	15 300	65 600	8 000	2 200	81 800	330 600
Direct Field Cost	**64 700**	**255 700**	**101 000**	**35 380**	**181 000**	**19 100**	**5 940**	**153 100**	**815 920**
Other costs	3 900	14 200	5 600	2 300	9 800	1 200	300	2 000	39 300
EPC services	12 900	51 100	20 200	7 100	36 200	3 800	1 200	30 600	163 100
Total installed cost	**81 500**	**321 000**	**126 800**	**44 780**	**227 000**	**24 100**	**7 440**	**185 700**	**1 018 320**
Project contingencies	12 225	48 150	19 020	6 717	34 050	3 615	1 116	27 855	152 748
Total plant cost	**660 192**				**297 321**			**213 555**	**1 171 068**
Spare parts	3 301				1 487			1 068	5 855
Inventory of fuel and chemicals	1 283				2 334			0	3 617
Start-up cost	13 604				6 146			4 271	24 021
Owner cost	46 213				20 812			14 949	81 975
Interest during construction	105 065				47 316			33 986	186 367
Total capital requirement	**829 658**				**375 417**			**267 828**	**1 472 903**

Annual OPEX (k$/y)	CO_2 capture and compression				Utilities			Interconnecting	Total cost
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Labour cost	1 600				800			0	2 400
Annual maintenance	22 006				11 482			3 559	37 047
Other	3 301				1 487			1 068	5 855
Annual fixed operating cost	**26 907**				**13 768**			**4 627**	**45 303**
Natural gas consumption	0				108 301			0	108 301
Chemical and catalyst	12 069				0			0	12 069
Raw process water (make-up)	0				930			0	930
Waste disposal	3 326				0			0	3 326
Annual variable operating cost	**15 396**				**109 231**			**0**	**124 627**
Total annual operating cost	**42 303**				**122 999**			**4 627**	**169 929**

Cost of retrofitting CO_2 capture ($/t$_{CO2,avoided}$)	**161,2**

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D.4.4 Base case 04-04

Overall CAPEX (k$)	**CO₂ capture and compression** Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	**Utilities** CHP plant	Cooling towers	Waste water treatment	**Interconnecting**	**Total cost**
Direct materials	**0**	**33 700**	**20 700**	**8 880**	**44,940**	**4 440**	**1 210**	**44 200**	**158,070**
Construction	0	19 800	12 200	6 400	25,600	3 200	700	54 000	121,900
Direct Field Cost	**0**	**53 500**	**32 900**	**15 280**	**70,540**	**7 640**	**1 910**	**98 200**	**279,970**
Other costs	0	3 000	1 800	1 000	3,800	500	100	2 000	12,200
EPC services	0	10 700	6 600	3 100	14,100	1 500	400	19 600	56,000
Total installed cost	**0**	**67 200**	**41 300**	**19 380**	**88,440**	**9 640**	**2 410**	**119 800**	**348,170**
Project contingencies	0	10 080	6 195	2 907	13,266	1 446	362	17 970	52,226
Total plant cost		**147 062**				**115,564**		**137 770**	**400,396**
Spare parts		735				578		689	2,002
Inventory of fuel and chemicals		395				716		0	1,111
Start-up cost		3 141				2,511		2 755	8,408
Owner cost		10 294				8,089		9 644	28,028
Interest during construction		23 404				18,391		21 925	63,720
Total capital requirement		**185 032**				**145,849**		**172 783**	**503,664**

Annual OPEX (k$/y)	**CO₂ capture and compression** Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	**Utilities** CHP plant	Cooling towers	Waste water treatment	**Interconnecting**	**Total cost**
Labour cost		800				800		0	1,600
Annual maintenance		4 902				4,469		2 296	11,667
Other		735				578		689	2,002
Annual fixed operating cost		**6 437**				**5,847**		**2 985**	**15,269**
Natural gas consumption		0				33,322		0	33,322
Chemical and catalyst		3 684				0		0	3,684
Raw process water (make-up)		0				261		0	261
Waste disposal		1 058				0		0	1,058
Annual variable operating cost		**4 742**				**33,583**		**0**	**38,325**
Total annual operating cost		**11 179**				**39,430**		**2 985**	**53,594**

Cost of retrofitting CO_2 capture ($/t$_{CO2,avoided}$)	**162.1**

D.4.5 Base case 04-05

Overall CAPEX (k$)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: CHP plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Direct materials	**25 000**	**146 100**	**52 400**	**17 930**	**96 480**	**10 360**	**3 110**	**66 200**	**417 580**
Construction	16 500	85 800	30 800	13 600	54 900	7 500	1 800	76 400	287 300
Direct Field Cost	**41 500**	**231 900**	**83 200**	**31 530**	**151 380**	**17 860**	**4 910**	**142 600**	**704 880**
Other costs	2 500	12 900	4 600	2 000	8 200	1 100	200	2 000	33 500
EPC services	8 300	46 300	16 600	6 300	30 200	3 500	1 000	28 500	140 700
Total installed cost	**52 300**	**291 100**	**104 400**	**39 830**	**189 780**	**22 460**	**6 110**	**173 100**	**879 080**
Project contingencies	7 845	43 665	15 660	5 975	28 467	3 369	917	25 965	131 862
Total plant cost	**560 775**				**251 103**			**199 065**	**1 010 942**
Spare parts	2 804				1 256			995	5 055
Inventory of fuel and chemicals	1 096				1 998			0	3 095
Start-up cost	11 615				5 222			3 981	20 819
Owner cost	39 254				17 577			13 935	70 766
Interest during construction	89 243				39 961			31 680	160 884
Total capital requirement	**704 787**				**317 117**			**249 656**	**1 271 560**

Annual OPEX (k$/y)	CO₂ capture and compression: Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	Utilities: CHP plant	Cooling towers	Waste water treatment	Interconnecting	Total cost
Labour cost	1 600				800			0	2 400
Annual maintenance	18 692				9 641			3 318	31 651
Other	2 804				1 256			995	5 055
Annual fixed operating cost	**23 096**				**11 697**			**4 313**	**39 106**
Natural gas consumption	0				92 804			0	92 804
Chemical and catalyst	10 320				0			0	10 320
Raw process water (make-up)	0				778			0	778
Waste disposal	2 835				0			0	2 835
Annual variable operating cost	**13 155**				**93 582**			**0**	**106 737**
Total annual operating cost	**36 251**				**105 279**			**4 313**	**145 843**

Cost of retrofitting CO_2 capture ($/$t_{CO2,avoided}$)	162,2

D.4.6 Base case 04-06

Overall CAPEX (k$)	**CO_2 capture and compression**				**Utilities**			**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Direct materials	**39 000**	**127 400**	**41 100**	**15 180**	**79 400**	**7 400**	**2 730**	**59 600**	**371 810**
Construction	25 700	74 800	24 200	11 500	45 100	5 300	1 600	69 400	257 600
Direct Field Cost	**64 700**	**202 200**	**65 300**	**26 680**	**124 500**	**12 700**	**4 330**	**129 000**	**629 410**
Other costs	3 900	11 200	3 600	1 700	6 700	800	200	2 000	30 100
EPC services	12 900	40 400	13 100	5 300	24 900	2 500	900	25 800	125 800
Total installed cost	**81 500**	**253 800**	**82 000**	**33 680**	**156 100**	**16 000**	**5 430**	**156 800**	**785 310**
Project contingencies	12 225	38 070	12 300	5 052	23 415	2 400	815	23 520	117 797
Total plant cost	**518 627**				**204 160**			**180 320**	**903 107**
Spare parts	2 593				1 021			902	4 516
Inventory of fuel and chemicals	863				1 647			0	2 510
Start-up cost	10 773				4 283			3 606	18 662
Owner cost	36 304				14 291			12 622	63 217
Interest during construction	82 536				32 490			28 697	143 723
Total capital requirement	**651 695**				**257 892**			**226 147**	**1 135 734**

Annual OPEX (k$/y)	**CO_2 capture and compression**				**Utilities**			**Interconnecting**	**Total cost**
	Flue gas desulph. unit	Absorber section	Regeneration section	CO_2 compression	CHP plant	Cooling towers	Waste water treatment		
Labour cost	1 600				800			0	2 400
Annual maintenance	17 288				7 891			3 005	28 183
Other	2 593				1 021			902	4 516
Annual fixed operating cost	**21 481**				**9 711**			**3 907**	**35 099**
Natural gas consumption	0				76 392			0	76 392
Chemical and catalyst	8 107				0			0	8 107
Raw process water (make-up)	0				666			0	666
Waste disposal	2 249				0			0	2 249
Annual variable operating cost	**10 356**				**77 058**			**0**	**87 414**
Total annual operating cost	**31 837**				**86 770**			**3 907**	**122 513**

Cost of retrofitting CO_2 capture ($\$/t_{CO2,avoided}$)	**177,8**