14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

21st -25th October 2018, Melbourne, Australia

Understanding the cost of retrofitting CO_2 capture to an integrated oil refinery

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Abstract

Understanding the cost of carbon capture and storage (CCS) is of paramount importance to depict a realistic pathway to decarbonise the industrial sector. This study provides an assessment on the cost of retrofitting CO_2 capture to the European refinery system. Four reference refineries were defined to encompass the current range of size and complexity of the continent. 16 post-combustion capture cases using a standard absorption process were investigated, including CO_2 emission sources of different size and CO_2 concentration. An additional combined heat and power plant was designed for each refinery to provide heat and power to the capture unit. Large demands of steam and electricity were estimated, and the associated specific utilities consumptions were calculated for each CO_2 capture case. This prepared the ground for the economic analysis. The cost of CO_2 avoided was found to be rather high. The scope of the analysis that considers retrofitting CO_2 capture to existing plants can explain the economic performance obtained, as retrofit costs constitute a large share of the overall cost.

Keywords: CO_2 capture; European refineries; brownfield retrofit; CO_2 avoided cost

1. Introduction

CO_2 Capture and Storage (CCS) is an indispensable technology to significantly reduce the carbon footprint of energy intensive industries [1], as many other decarbonization routes cannot be applied in this sector or can only be applied to a limited extent. The potential for reductions in the global CO_2 emissions is significant. The petroleum refining industry alone accounts for 4% of the total anthropogenic CO_2 emissions [2]. However, several issues have slowed down the deployment of CCS in the industrial sector. Key challenges are the presence of many emission

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point sources, often characterized by small CO_2 concentrations [3], and the costs associated with CCS [4], [5]. A number of studies dealt with concepts for the integration of CO_2 capture in an oil refinery [6] and in other energy intensive industries [7]–[10]. The novelty of this study consists in the evaluation of the retrofit costs related to the integration of a CO_2 capture unit to relevant refineries. Considering that the construction of new refineries in Europe is not foreseen in the near future, understanding the expected cost to retrofit existing refineries is of paramount importance. The paper summarizes the results obtained and provides guidelines to the European refinery industry to understand the actual impact of CCS. A more comprehensive insight with full reports and spreadsheets for cost calculations is available on the ReCAP project website [11].

Nomenclature

CCS	CO_2 Capture and Storage
CDU	Crude Distillation Unit
CHP	Combined Heat and Power
CRF	Catalytic Reformer
DCU	Delayed Coker Unit
FCC	Fluid Catalytic Cracking
GT	Gas Turbine
MEA	Mono-Ethanol Amine
NGCC	Natural Gas Combined Cycle
NSU	Naphtha Splitter Unit
POW	Power Plant
SMR	Steam Methane Reformer
SRD	Specific Reboiler Duty
VDU	Vacuum Distillation Unit

2. Analysis framework

2.1. Reference oil refineries

Four reference oil refineries were defined as base case plants for the analysis:

- Base Case 1 - Simple Hydro-skimming Refinery: simple refinery with a nominal capacity of 100,000 bbl/d.
- Base Case 2 - Medium Conversion Refinery: medium complex refineries with nominal capacity of 220,000 bbl/d
- Base Case 3 - High Conversion Refinery: highly complex refineries with nominal capacity of 220,000 bbl/d
- Base Case 4 - High Conversion Refinery: highly complex refinery with a nominal capacity of 350,000 bbl/d

The characteristics of the base cases were selected to provide a representative sample of the existing refineries in Europe. The refineries differ mainly in terms of capacity and complexity, with a gradual shift from black products (fuel oil, bitumen, coke and sulphur) to more valuable products (naphtha and gasoil). The energy requirements and CO_2 emissions increase in line with the refinery complexity.

2.2. Design basis

The following engineering and design basis applied to the study:

- Baskets of crude oils and of products were selected to represent, respectively, the typical feedstocks and production of European refineries.

- The reference refineries are energy-independent as they can autonomously produce the necessary electricity, steam and hydrogen. A connection to the grid is assumed to export the electricity surplus.
- An additional natural gas-fired Combined Heat and Power (CHP) plant was designed on the refinery site to meet the CO_2 capture related steam and power demands.
- The CO_2 capture technology considered is post-combustion absorption based on a standard 30 wt% Mono-Ethanol Amine (MEA) solvent (90% capture ratio). One absorber for each emission source was simulated, while the rich solvent was conveyed to a single common stripper.

2.3. CO_2 capture cases

CO_2 emission sources for the four base cases were identified. The different CO_2 emission sources were mainly characterized in terms of gas composition and magnitude of CO_2 emission. An analysis of those CO_2 emission sources led then to define 16 relevant CO_2 capture cases for the four base cases. The list of CO_2 capture cases defined is shown in Table 1. The 16 CO_2 capture cases were simulated in Aspen HYSYS v9.

Table 1. CO_2 capture cases

	Refinery	CO_2 emission sources	CO_2 emissions at operating point (t/h)	% of total CO_2 emissions	Avg CO_2 %vol
01-01	**Base Case 1**	POW	42.3	48.8%	8.2
01-02		POW+CDU	65.9	76.0%	9.2
01-03		POW+CDU+CRF	74.8	86.3%	9.1
02-01	**Base Case 2**	POW	92.3	35.9%	8.3
02-02		POW+FCC	136.5	53.1%	9.9
02-03		POW+FCC+CDU-B/VDU-B+CDU-A+SMR	212.7	82.7%	10.7
02-04		FCC+CDU-B/VDU-B+CDU-A	101.1	39.3%	13.1
03-01	**Base Case 3**	POW(NGCC)+POW(B)	79.3	28.6%	6.6
03-02		POW(NGCC)+POW(B)+FCC	132.4	47.7%	8.7
03-03		POW(NGCC)+POW(B)+FCC+CDU-B/VDU-B+CDU-A+SMR	221.7	79.8%	10.0
04-01	**Base Case 4**	POW(NGCC)+POW(B)	97.4	20.9%	4.7
04-02		POW(NGCC)+POW(B)+CDU-A/VDU-A+CDU-B/VDU-B	195.8	42.0%	6.7
04-03		POW(NGCC)+POW(B)+FCC+CDU-A/VDU-A+CDU-B/VDU-B+SMR	366.2	78.5%	9.4
04-04		SMR	117.3	25.1%	17.7
04-05		POW(NGCC)+POW(B)+CDU-A/VDU-A+CDU-B/VDU-B+SMR	313.1	67.1%	8.7
04-06		POW(NGCC)+POW(B)+FCC+CDU-A/VDU-A+CDU-B/VDU-B	248.9	53.3%	7.7

3. Results

A selection of the most important results is reported in this section of the paper. The complete set of results can be found on the project website [11].

3.1. Energy and CO_2 separation performance

The specific utilities consumption was calculated for the 16 CO_2 capture cases. The two main energy consumption terms are the specific reboiler duty (SRD) and the electric power demand. Steam has to be supplied to the reboiler section of the stripper, resulting in most of the cases in a SRD between 3.64 and 3.69 GJ/t_{CO2}. The electric power demand from compressors and fans adds up to over 90% of the total power demand, with pumps and the chiller being the main remaining consumers. The specific electric consumption ranges between a minimum of 139.8 kWh/t_{CO2} to a maximum of 182.7 kWh/t_{CO2}. The fraction of CO_2 emissions processed in the capture unit depends on the case selected but in no case includes the entire amount of CO_2 emissions from the refinery. Therefore, even though the absorption unit had a recovery ratio of 90%, the relative CO_2 avoided is below 50% in most cases. In absolute terms, the amount of CO_2 captured and avoided depends on the size and number of CO_2 emission sources considered. Table 2 summarizes the results obtained for the different cases.

Table 2. Specific utilities consumption for the different CO_2 capture cases

	Refinery	CO_2 captured (t/hr)	Net CO_2 avoided (t/hr)	Specific reboiler duty (GJ/tCO_2 captured)	Electricity demand (kWh/tCO_2 captured)
01-01	**Base Case 1**	37.5	24.9	3.66	148.0
01-02		59.3	39.3	3.67	146.1
01-03		67.3	44.7	3.67	146.8
02-01	**Base Case 2**	82.8	54.9	3.68	155.2
02-02		122.5	81.4	3.66	144.2
02-03		191.1	127.2	3.65	142.1
02-04		91.0	60.6	3.64	139.8
03-01	**Base Case 3**	71.5	47.1	3.74	159.1
03-02		119.6	79.0	3.69	149.0
03-03		199.6	132.9	3.67	144.7
04-01	**Base Case 4**	87.7	57.2	3.85	182.7
04-02		176.0	116.1	3.76	164.2
04-03		329.7	219.9	3.68	146.5
04-04		105.5	71.4	3.57	122.2
04-05		282.0	188.0	3.69	148.6
04-06		223.8	148.0	3.72	157.6

3.2. Retrofit cost

The cost of retrofitting CO_2 capture to an existing refinery was found to lie between 160 and 210 \$/$t_{CO2,avoided}$. Figure 1 shows the breakdown of this specific cost for each CO_2 capture case (30-40% CO_2 capture and conditioning, 45-55% utilities production, and 10-20% interconnecting costs). The level of total capital requirement necessary is also reported and, as expected, varies considerably with the different CO_2 capture capacities considered (from a minimum of 200 M\$, to maximum of 1500 M\$). It should be also pointed out that the results obtained are significantly larger than the estimates available in the literature. The higher values reported can be explained by the inclusion of the retrofit costs, the costs of the additional CHP plant and the assessment of small to medium CO_2 emission point sources with low to medium flue gas CO_2 content. It was also noted a tradeoff between the total capital requirement and the normalised costs of retrofitting CO_2 capture. This trend appears to favour large projects tackling large CO_2 capture capacities, provided that significant capitals are available.

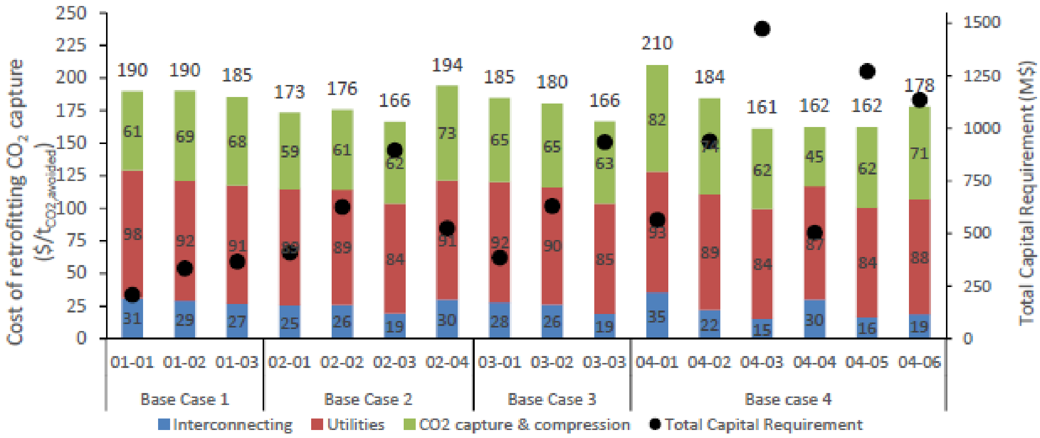

Figure 1. Cost of retrofitting CO_2 capture of all cases considered for the four refinery base cases with breakdown by section

Table 3 organizes and summarizes the outcome of the study. CO_2 avoidance costs intervals are reported as a function of certain refinery characteristics, making the table a useful tool to obtain a first estimation of the retrofit cost for a specific refinery.

Table 3. Classification of the CO_2 avoidance cost on the basis of the characteristics of the CO_2 capture cases

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

4. Conclusions

A study on the cost of retrofitting CO_2 capture to oil refineries was carried out. The assessment was based on four reference refineries, defined to encompass the typical configurations found in Europe. 16 CO_2 capture cases were defined by considering different emission point sources in each reference refinery. The analysis suggested that the two main energy consumption terms were the steam for the reboiler (3.64 to 3.69 GJ/t$_{CO2}$) and the electric power (139.8 kWh/t$_{CO2}$ to 182.7 kWh/t$_{CO2}$). The cost of retrofitting CO_2 capture was calculated to be in a range between 160 and 210 $/t$_{CO2,avoided}$. The total capital requirement necessary to retrofit CO_2 capture was largely affected by the size of the CO_2 emission sources considered (200 M$ to 1500 M$). It was noted that the cases characterized by the largest total capital requirements were also those returning the lowest normalised costs of retrofitting CO_2 capture, suggesting that, to some extent, the trend of economy of scale applies.

Acknowledgements

The work was mainly funded by the CLIMIT Demo program with support from CONCAWE and IEA Greenhouse Gas R&D program.

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