The importance of carbon capture and storage technology in European refineries

This article describes the importance of carbon capture and storage (CCS) in meeting future emission targets. It presents an evaluation of the costs of retrofitting CCS technology in a range of existing refineries, and considers the reasons why these estimates are significantly larger than the estimated costs of CO_2 capture for other sources, e.g. power generation, cement and steel production, etc.

Background

For the first time in history, at the Conference of the Parties (COP 21) in December 2015, the world agreed to set an ambitious target. The headline emerging from the summit was the agreement to limit the increase of the global average temperature to well below 2°C, and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.[1]

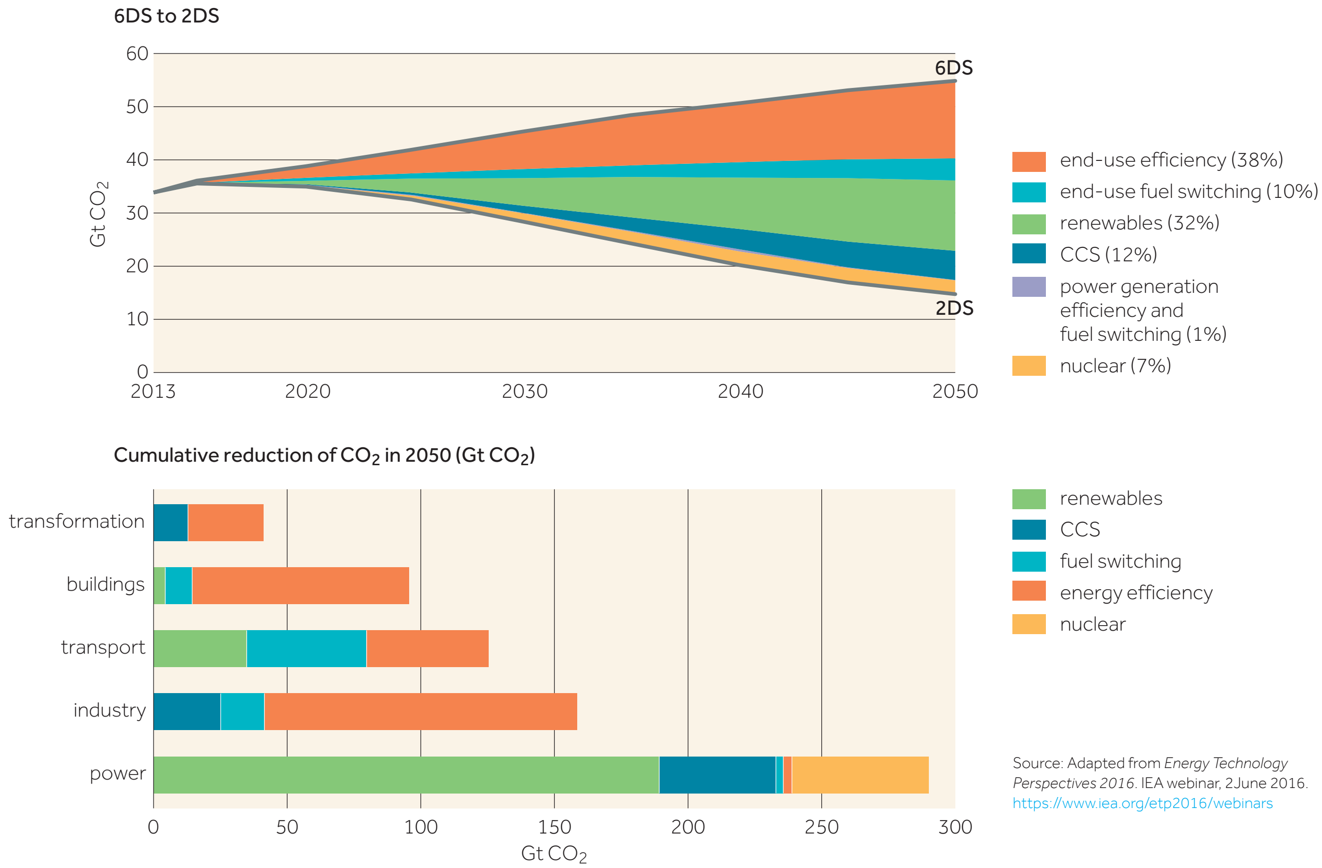
Carbon capture and storage (CCS) is an essential element of the portfolio of measures needed to reduce greenhouse gas (GHG) emissions. Without CCS, the cost of reaching the COP 21 targets will increase by about 40%[2] which is more costly than for any other low-carbon technology. CCS is a key technology to reduce CO_2 emissions across various sectors of the economy while providing other societal benefits (energy security and access, air pollution reduction, grid stability, and jobs preservation and creation). It is part of a broad range of measures aimed at reducing CO_2 emissions.

Until recently, CCS projects in Europe were mainly targeted at reducing GHG emission from the power sector, where some of the largest emissions points are found. The past few years have seen significant changes in the power sector in Europe, including increased penetration of renewable energy, a rapid phase-out of coal-fired power plants in several Member States, a fuel switch from coal to gas, and the emergence of nuclear power in Member State plans for medium-term reform of the energy system.

The International Energy Agency (IEA) describes three pathways for energy sector development to 2060. The Reference Technology Scenario (RTS) provides a baseline scenario that takes into account existing energy- and climate-related commitments by countries. The RTS—reflecting the world's current ambitions—is not consistent with achieving global climate mitigation objectives, but would still represent a significant shift from a historical 'business as usual' or 'current trajectory' approach (the '6°C Scenario'—6DS). More ambitious decarbonisation requires increased effort and sustained political commitment.

While COP 21 sets the 'must achieve' target at a maximum 2°C increase, a more ambitious 'stretch' target of 1.5°C was also agreed. This is reflected in the IEA's 'Beyond 2°C Scenario' (B2DS). Each scenario sets out a rapid decarbonisation pathway in line with international policy goals (see Figure 1 on page 35).

Figure 1: Contribution of technology area and sector to global cumulative CO_2 reductions



Source: Adapted from *Energy Technology Perspectives 2016*. IEA webinar, 2June 2016. https://www.iea.org/etp2016/webinars

To achieve the IEA 2DS, reductions of 740 Gt CO_2 (relative to RTS) would be required from the application of energy efficiency, renewables, nuclear, CCS and fuel switching. The technology scenarios would see the power sector decarbonised earliest, leaving industry and transport as the major emitters by 2050. In the 2DS, half of the captured CO_2 would come from industrial sectors, where there are currently limited or no alternatives for achieving deep emission reductions.

Such a transition will require an exceptional degree of effort. The share of fossil fuels in primary energy would have to reduce to 45% by 2050 in the 2DS (compared to 81% today). In this scenario, biomass becomes the largest energy source (for transport).

To achieve net zero emissions in the second half of the century, bioenergy with CCS (BECCS) has the potential to deliver negative emissions. The technology scenarios supported by IEA projections are illustrated in Figure 2 on page 36 which shows that:

- CCS will be required to achieve 12 to 15% of the reductions needed for 2DS.
- CCS will be required to achieve 32% of the additional reductions needed for B2DS.
- By 2060 the storage needed for industrial applications could equal that of power generation.

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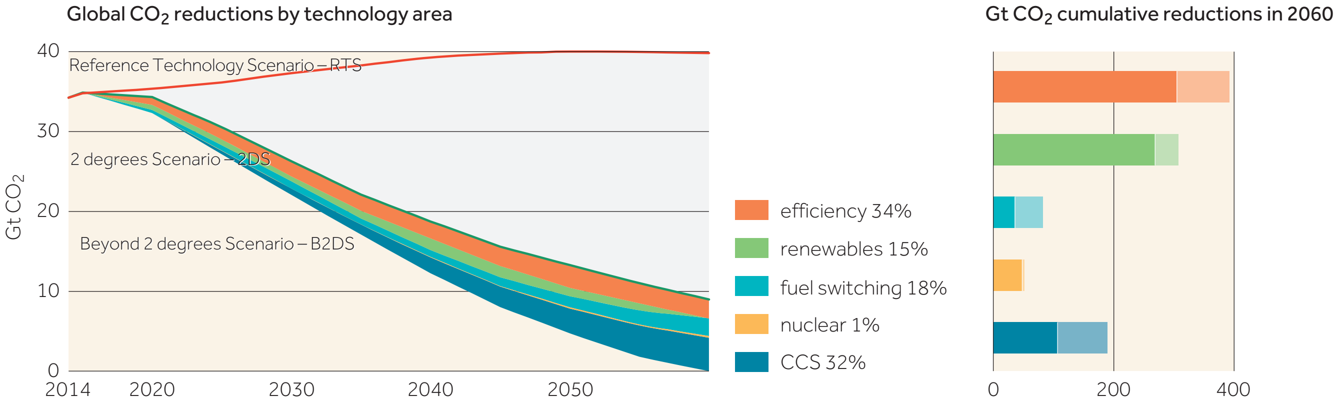
Figure 2: Technology area contribution to global cumulative CO_2 reductions

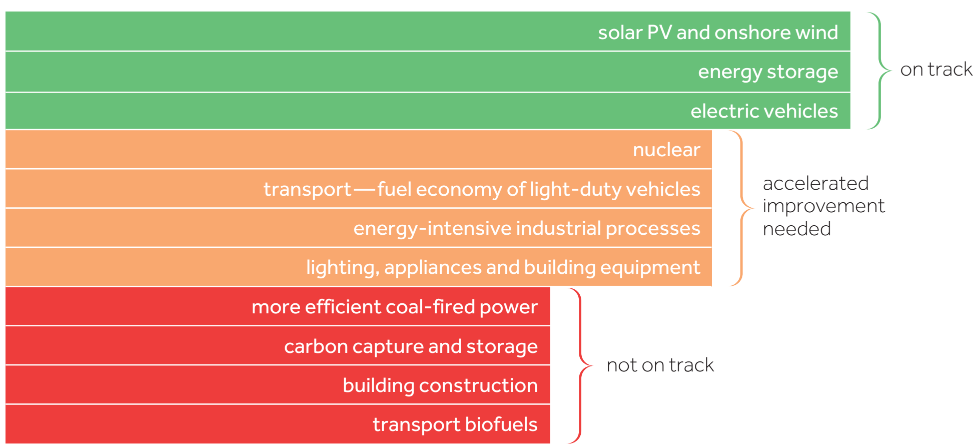


Source: *Adapted from Energy Technology Perspectives 2017*. IEA webinar, 2 July 2017. https://www.iea.org/etp2017/webinars

The agreement at COP 21 to pursue a more stringent target than the previous 2°C limit has strengthened the case for a need of deep-cut technologies such as CCS. Deep reductions are needed, not only in the power sector but also for the industry, where decarbonisation options are limited. GHG emission reductions from carbon-intensive industries will require carbon capture because fuel switching is often not an option, or process-related emissions cannot be avoided. Meeting the national emission reduction targets by 2030 will rely heavily on reducing emissions from carbon-intensive sectors such as steel and refining.

In the IEA's *Energy Technology Perspectives 2017*,[3] the organisation highlighted that the recent progress in some clean energy areas is promising, but many technologies still need a strong push to achieve their full potential and deliver a sustainable energy future. The potential of clean energy technology remains underutilised (see Figure 3).

Figure 3: Many technologies still need a strong push to achieve their full potential to deliver a sustainable energy future



Source: *Adapted from Energy Technology Perspectives 2017*. IEA webinar, 2 July 2017.
https://www.iea.org/etp2017/webinars

The importance of deploying CCS and the industry sector

In 2014 the global total energy-related direct emissions of CO_2 amounted to approximately 34,200 megatonnes (Mt), of which 8,300 Mt CO_2/year were direct emissions from industry and 13,600 Mt CO_2/year were direct emissions from the power sector.[3] To reach the Paris Agreement's 2°C target, the IEA estimated that global CO_2 emissions must be reduced to just below 9,000 Mt CO_2/year by 2060, a reduction of more than 60% compared to 2014, and must fall to net zero by no later than 2100.[3]

In the IEA's 2DS, CCS will account for 14% of the accumulated reduction of CO_2 emissions by 2060 and 32% of the reduction needed to go from 2DS to B2DS by 2060.[3] Major cuts will need to be made in all sectors in addition to the power sector. The industrial sector will have to capture and store 1,600 Mt CO_2/year in 2DS and 3,800 Mt CO_2/year in B2DS by 2060, yet this sector will still be the largest contributor to accumulated CO_2 emissions to 2060, and the major CO_2 source in 2060.

CCS is already being undertaken in industries such as natural gas processing, fertilizer production, bioethanol production, hydrogen production, coal gasification, and iron and steel production.[4] In addition, the demonstration of a CO_2 capture unit at a waste incineration plant has taken place in Japan,[5] and small-scale testing has taken place in Norway.[6] In 2060, CCS is expected to make up 38% of total emissions reductions in industry between RTS and B2DS, and somewhat less than half this amount between RTS and 2DS;[3] this shows that CCS will be a critical technology for many emissions-intensive industries.

There is a high likelihood that 2DS and, in particular B2DS, wil not be achievable without the deployment of 'negative emissions technologies' at scale.[7,3] There are several technologies that have the potential to contribute to the reduction of atmospheric CO_2 levels; each of these, however, brings its own uncertainties, challenges and opportunities. Included among them are reforestation, afforestation (photosynthesis), direct air capture, and bioenergy coupled with CCS (i.e. CCS applied to the conversion of biomass into final energy products or chemicals). In B2DS, almost 5,000 Mt CO_2 are captured from bioenergy, resulting in negative emissions in 2060.[3]

CO_2 capture technology

CO_2 capture is a process that involves the separation of CO_2 from gas streams. These gas streams could include, but are not limited to, combustion flue gases, process off-gases (i.e. by-product gases from blast furnaces and basic oxygen furnaces; tail gases from steam methane reforming and various refinery processes, etc.), syngas (i.e. synthesis gas produced from coal gasification, hydrocarbon reforming, coke oven, etc.) or natural gas (i.e. from natural gas processing). For many decades, CO_2 capture processes have been used in several industrial applications at a scale close to those required in CCS applications.

In general, CO_2 capture processes can be classified according to their gas separation principle, namely chemical absorption, physical absorption, adsorption, calcium and reversible chemical loops, membranes, and cryogenic separation.

In the ReCAP project (see below), the chosen technology was a chemical absorption process. It utilizes the reversible chemical reaction of CO_2 with an aqueous solvent, usually an amine or ammonia (MEA in this case). CO_2 is separated by passing the flue gas through a continuous scrubbing system. The absorbed CO_2 is stripped from the solution in a desorber, and a pure stream of CO_2 is sent for compression while the regenerated solvent is sent back to the absorber.

The oil refining industry

On a global level, the total CO_2 emitted by mainstream refineries in 2015 was estimated to be around 970 Mt per year.[8] The total processed crude oil was ~82 Mb/d (total capacity ~97.5 Mb/d) which results in a CO_2 intensity of around 200 kg CO_2/t crude oil. This intensity varies for each refinery and depends on the complexity, energy efficiency and ratio of feedstocks other than crude oil.

The global refining sector contributes around 4% of the total anthropogenic CO_2 emissions. CCS has been recognised as one of the technologies that could be deployed to achieve a deep reduction of greenhouse gas emissions in this and other industry sectors.

In the EU-28, the verified emissions from the 79 mainstream refineries were 138 Mt CO_2/y in 2015 (~14% of the world emissions from refineries). Today, the EU refining industry has reduced its environmental footprint by continually increasing its energy integration and investments in efficiency. Moreover, the widespread use of cogeneration and advanced catalyst technology has allowed for further energy reduction gains. As a result, the refining sector has improved its energy efficiency by nearly 1% per year since 1990.

The ReCAP project: understanding the cost of retrofitting CO_2 capture to refineries

In 2014, the ReCAP project was initiated by the IEA Greenhouse Gas R&D Programme (IEAGHG), in collaboration with GASSNOVA, SINTEF and Concawe, to evaluate the performance and cost of retrofitting CO_2 capture in an integrated oil refinery.

To enable the deployment of CCS in the oil refining sector, it is essential to have a good understanding of the direct impact on the financial performance and technical operations resulting from the retrofitting of CO_2 capture technology. In several OECD countries (especially in Europe), it is expected that no new refineries will be built in the coming decades. Furthermore, most of the existing refineries are at least 20 years old. Therefore, this study aims to evaluate and understand the cost of retrofitting CO_2 capture technologies to an existing integrated oil refinery. The project was supported under the Norwegian CLIMIT programme, with contributions from IEAGHG and Concawe and managed by SINTEF. The project consortium selected Amec Foster Wheeler as the engineering contractor to work with SINTEF in performing the basic engineering and cost estimation for the reference cases.

ReCAP project—scope of work

The main purpose of the study was to evaluate the cost of retrofitting CO_2 capture in a range of refinery types typical of those found in Europe. These included both simple and high-complexity refineries covering typical European refinery capacities from 100,000 to 350,000 bbl/d.

The refining industry is considered to be an energy-intensive industry, with direct emissions typically ranging from 100 to 200 kg CO_2/tonne crude oil. An oil refinery produces a broad range of highly valuable petroleum products using different and complex interconnected processes. While each plant is unique, the level of complexity is a common factor.

To ensure that the work could differentiate between the costs of CCS deployment for different types of refineries and those of varying capacities, four reference (model) oil refineries were evaluated:

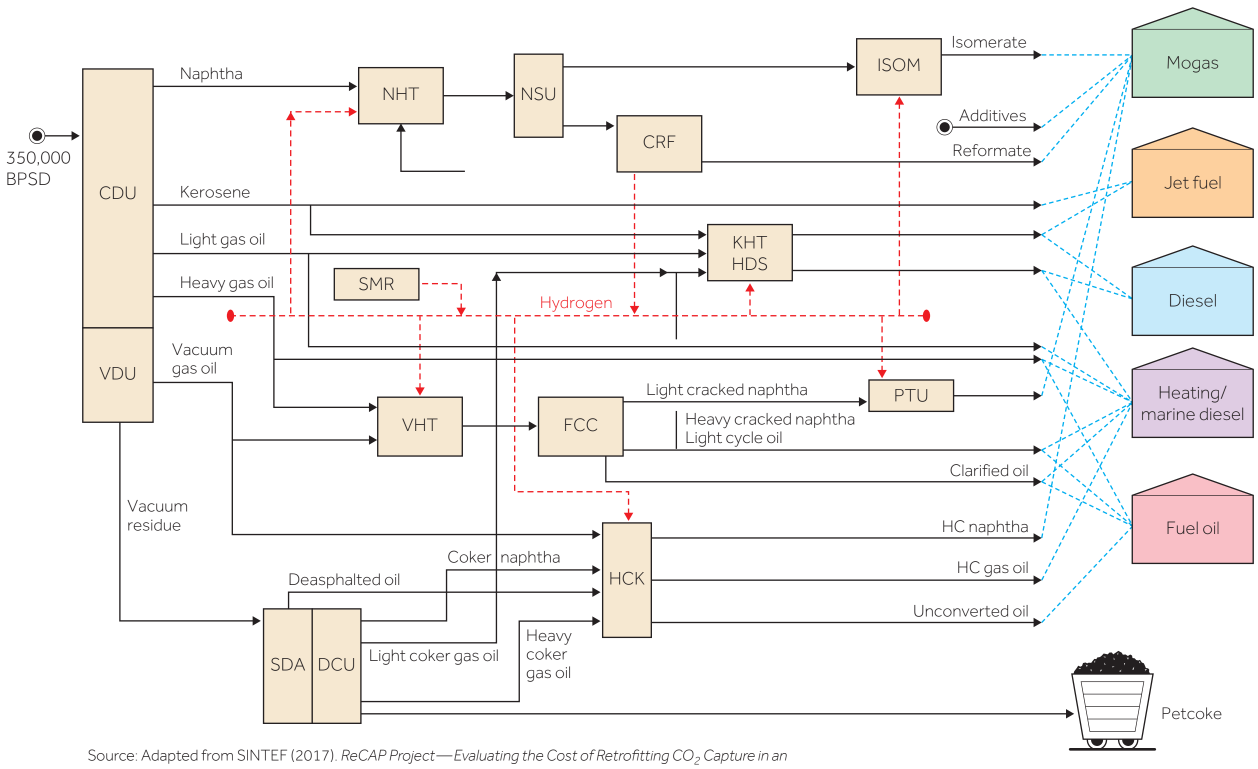
- Simple refinery with a nominal capacity of 100,000 bbl/d.
- Medium-complex refinery with a nominal capacity of 220,000 bbl/d.
- Highly-complex refinery with a nominal capacity of 220,000 bbl/d.
- Highly-complex refinery with a nominal capacity of 350,000 bbl/d.

Different scenarios presenting the cost of capturing CO_2 from the different processes within the refinery were evaluated. The priorities for which sources of CO_2 will be captured for each reference plant were defined based on the size of emissions and the plant layout, taking into account the practical considerations in deploying the CO_2 capture facilities on-site. The results established a wide range of overall refinery CO_2 capture ratios, and provide insights into their respective costs of CO_2 avoidance.

The analysis is based on a 'bottom up' approach to reflect the site-specific conditions and to identify what could likely be achieved in terms of CO_2 reduction potential and the related cost of retrofitting CCS technology. The assessments performed in this study focused on retrofit costs including modifications in the refineries, interconnections, and additional combined heat and power (CHP) and utility facilities.

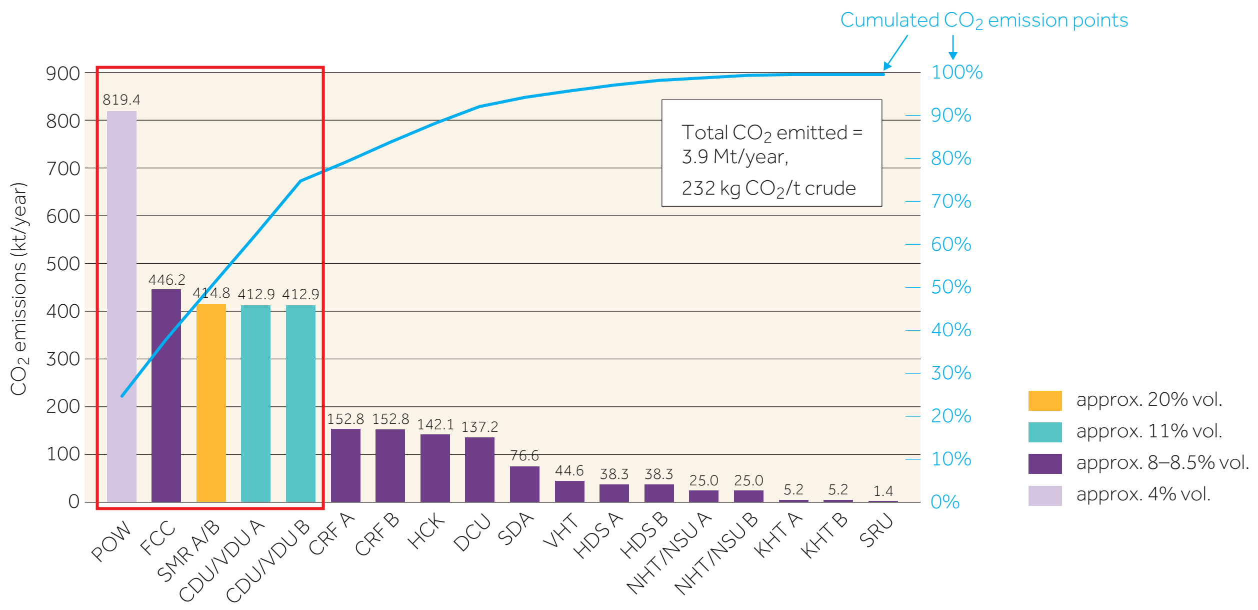
Figure 4 on page 40 presents a simplified flow diagram of a typical complex refinery with more than 10 emission sources. Figure 5 on page 40 shows that five of these sources represent 75% of the total CO_2 emitted. The CO_2 concentration fluctuates between 5% and 20% vol.

Figure 4: Simplified flow diagram for a typical complex refinery



Source: Adapted from SINTEF (2017). *ReCAP Project—Evaluating the Cost of Retrofitting CO_2 Capture in an Integrated Oil Refinery: Description of Reference Plants.* https://www.sintef.no/recap

Figure 5: The main CO_2 emission sources for a typical complex refinery with a nominal capacity of 350,000 bbl/day



Source: Adapted from SINTEF (2017). *ReCAP Project—Evaluating the Cost of Retrofitting CO_2 Capture in an Integrated Oil Refinery: Description of Reference Plants.* https://www.sintef.no/recap

Refinery base cases

Four refinery base cases were defined to represent the typical crude mix and product slate of similar-capacity European oil refineries:

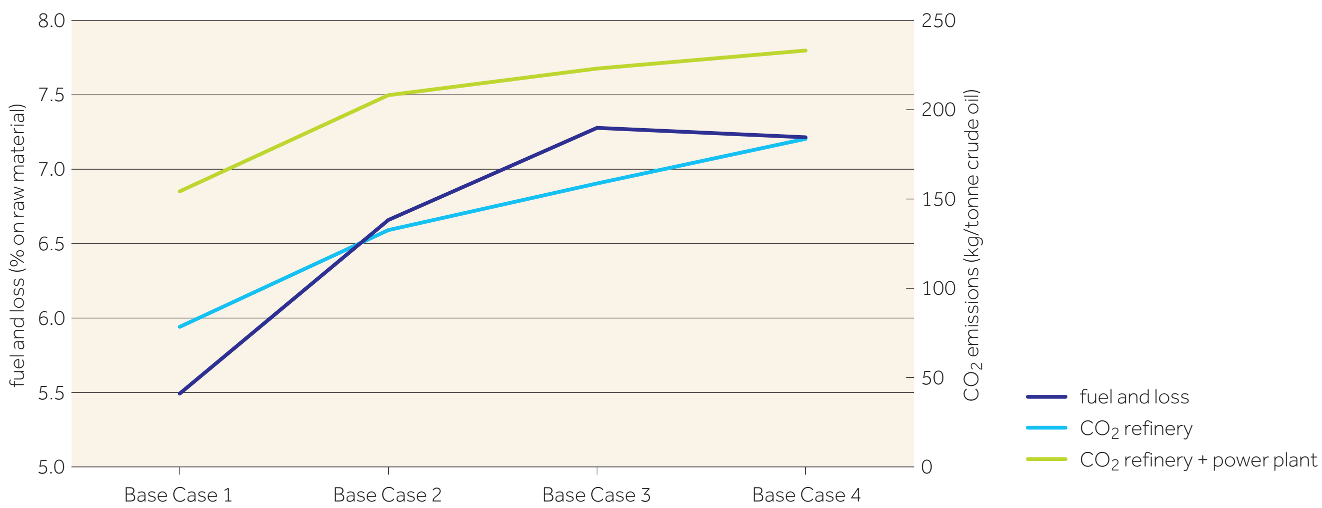
- Base Case 1 (BC1)—a simple hydroskimming refinery.
- Base Case 2 (BC2)—a medium complexity refinery that is a retrofit of BC1.
- Base Case 3 (BC3)—a complex refinery that is a retrofit of BC2.
- Base Case 4 (BC4)—a large complex oil refinery.

As the complexity of the refinery increases from BC1 to BC4, the yield of naphtha and gas oil fraction increases as the heavy cuts are converted into lighter and more valuable products in the more complex refineries.

The performance of the refinery base cases, in terms of mass and energy balances and CO_2 emissions, are the basis for comparison of the effectiveness and cost of oil refineries with CO_2 capture. The market conditions in the past decade have pushed the refineries to upgrade their configuration to process heavier crudes, cheaper than the lighter ones, and to reprocess heavy distillate products to obtain more valuable fractions. These energy-intensive units, however, demand a greater amount of fuel and, in turn, increase the amount of CO_2 emitted.

The four identified base cases are shown in Figure 6. These are good starting points for evaluating the effects of retrofitting CO_2 capture facilities in existing refineries, taking into account the different sizes and levels of complexity.

Figure 6: Fuel demand and CO_2 emissions in the four base case refineries



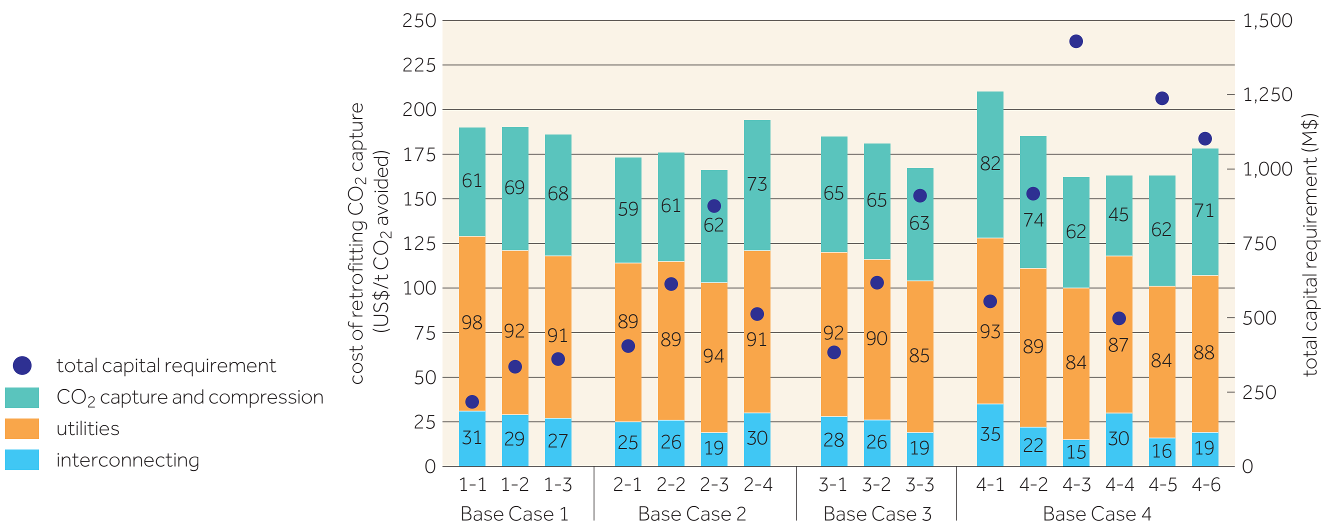
CO_2 capture integration

The focus of this study was on post-combustion capture. The primary emission sources in each base case refinery were identified, and CO_2 capture cases for the different refineries were established to explore CO_2 capture from a range of refinery CO_2 sources that vary in both capacity and CO_2 concentration. The capture cases were set up to include an absorber for each emission source and a common regenerator due to space constraints and to minimise expensive ducting in the refinery.

A total of 16 post-combustion capture cases using MEA as solvent were investigated. The MEA process for post-combustion capture has been simulated using Aspen HYSYS® (a process simulation software package) where a simple configuration with an intercooler in the absorber was modelled. The CO_2 capture process was not optimised for the different cases.

The assessments performed in the study focused on retrofit costs including modifications in the refineries, interconnections, and additional CHP and utility facilities. The main focus of the study was on CO_2 capture from refinery BC4, which was considered to be 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 was used to evaluate the cost of the different sections (CO_2 capture and compression, utilities and interconnecting) of the concept. In this approach, four of the 16 capture cases were selected to represent a wide range of CO_2 capture capacity and flue gas CO_2 content. In each case, detailed assessments were undertaken. These detailed cost assessments form the basis for the assessment of the other cases, based on subsequent scaling. The scaling equations have a larger purpose in that they can be used by refineries/policy experts to evaluate capital costs of retrofitting CO_2 capture to refineries of interest.

Figure 7: Costs of retrofitting CO_2 capture for all cases considered for the four refinery bases cases, by section



The results of the cost evaluation of the 16 CO_2 capture cases show that the cost of retrofitting CO_2 capture lies between 160 and 210 US$/t CO_2 avoided, as shown in Figure 7 on page 42. 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 as follows:

- The inclusion of the retrofit costs such as the costs of ducting, piping, moving tankages, etc.
- There is no synergy with the refinery. The utilities cost is based on the installation of an additional CHP plant, cooling water towers and waste water plant, which are 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 content below or equal to 11.3% vol).

The overall breakdown of the costs is as follows:

- 30–40% of costs are linked to CO_2 capture and conditioning;
- 45–55% are linked to utilities production; and
- 10–20% are linked to interconnecting costs.

In terms of investment cost, the estimations show that the total capital requirement lies between US$200 million and US$1,500 million for the different cases as shown in Figure 7 on page 42, depending primarily on the amount of CO_2 captured. It is worth noting that although a case may be cheaper in terms of normalised cost ($/t CO_2 avoided), the high total capital requirements could make retrofitting less attractive.

In general, the cost of retrofitting CO_2 capture reduces with increasing CO_2 avoided, showing the effect of economies of scale. However, this may not be the case where the effects of significant differences in flue gas CO_2 concentration, the number of flue gas desulphurisation units and the interconnecting distances outweigh the effects of economies of scale.

Future development and investigation

With this backdrop, an approach with a potential to significantly decrease the cost of capture is to reduce the cost of utilities—in particular the additional CHP plant required to supply steam and power for CO_2 capture and compression. It is also desirable to avoid additional CHP plant since it reduces the rate of CO_2 capture.

Three options that may be explored, individually or in concert, to avoid the need for additional CHP plant and thus reduce the cost of CO_2 capture include the following:

1. Reduce the steam (and if possible power) requirement for CO_2 capture and compression:
   - Evaluation of advanced solvents with lower specific heat requirements, such as piperazine: such solvents may require steam at different pressures/condensing temperatures, and the reboiler/stripper may also operate at a different pressure than in the present case.
   - Use of advanced process configurations for the post-combustion capture process, including process improvements for enhanced absorption, heat integration and heat pumping. Among these options, split flow arrangements are the most common where the general principle is to regenerate the solvent at two or more loading ratios.
   - Use of technologies, such as membranes, that do not require steam: power required for the capture process can be bought in over the fence from the electricity grid.
2. Lower utilities investment costs achieved through reduced design margins. The design of CHP plant has, in some cases, been undertaken to provide significant spare capacity (up to 30%). In practice, where this additional capacity has been included to provide the steam and power required for CO_2 capture, it may be reduced.
3. 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. This would most likely require performing a case study on an actual refinery, but could also be done for BC4 (the large complex refinery model).

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