CO₂ capture and storage (CCS) is seen as one of the most promising routes to a major reduction in CO₂ emissions to the atmosphere. Its deployment on a large scale would make it possible to continue using fossil energy resources while meeting the challenging emission reduction targets that are widely believed to be necessary to avoid serious climatic consequences. A 2009 McKinsey report¹ states that CCS is the largest single lever for abating oil and gas emissions, if enough resources—both in terms of capital and engineering capacity—are made available.

CCS does, however, raise a number of technological, economic and legal challenges. For example, it requires capture equipment, transport infrastructure, injection and monitoring facilities—bringing high complexity and cost. Beside the extra investment costs, there will also be additional operating costs because CCS will require additional resources, especially energy. The extra expenses can only be justified if CO₂ has a sufficiently high long-term price.

Technologies to collect, separate/capture, transport and inject CO₂ into geological structures are known and have all been applied in commercial ventures. Nonetheless, the scale required for widespread application of CCS and the need to combine all steps into a seamless chain raise significant technological, practical and regulatory challenges.

Underground storage of CO₂ over many centuries also raises specific legal issues regarding ownership and liabilities. Although governments and international institutions, particularly in Europe, are working on the development of appropriate legal frameworks, operators do not currently have a clear picture of their short- and long-term legal positions.

CONCAWE recently published a report (Report No. 7/11) which focuses on the specific challenges faced by oil refineries in Europe for the capture of the CO₂ they emit during normal operations, the availability of suitable storage sites within reasonable distances from refineries and the development of a CO₂ transport infra-

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Refinery CO₂ emissions are dominated by those from process furnaces and utilities, as shown in Figure 2. In practice, heat and power plants within refineries are the largest single sources, although a moderately complex refinery may have 20 to 30 separate process heaters often spread over a fairly large geographical area.

With the exception of some hydrogen plants, CO₂ is emitted in flue gases with fairly low CO₂ concentrations, typically in the order of 3–12% v/v CO₂.

**Refinery CO₂ capture and associated combustion technologies**

There are essentially three routes to CO₂ capture: post-combustion, pre-combustion and oxy-fuel combustion (Figure 3).

- **Post-combustion** capture does not change the combustor technology and captures CO₂ from large volumes of flue gases having low CO₂ concentrations. Existing chemical absorption technology can be used for the CO₂ capture but it would have to be implemented on an unprecedented scale. Impurities and contaminants commonly found in flue gases would also present new technical challenges. Post-combustion capture is costly from a capital perspective and requires a large amount of extra energy, mostly for desorbing CO₂ from the solvent, which in itself leads to extra CO₂ emissions. As a result, the total amount of CO₂ ‘avoided’, i.e. prevented from reaching the atmosphere, will be about 30% less than the total CO₂ captured.

- **Pre-combustion** consists of partially or completely decarbonising the refinery fuel to produce two separate streams: hydrogen for combustion as an energy source and concentrated CO₂ for removal ‘before combustion’. In practice, this approach consists of gasifying a heavy feedstock or converting fuel gas to a mixture of hydrogen and carbon monoxide (CO) known as syngas, followed by conversion of CO to hydrogen via the water-gas shift reaction in a reformer. Although the completely
decarbonised fuel chain is not used today, the process building blocks are already available as commercial technologies. These, however, can be complex and expensive installations. Retrofitting refinery heaters to burn pure hydrogen or hydrogen-enriched fuel gas could require extensive modifications, depending on the hydrogen concentration.

- **Oxy-fuel combustion** involves replacing the combustion air by pure oxygen, thereby eliminating nitrogen from the flue gases. This greatly increases the CO₂ concentration and reduces the flue gas volumes to be handled by the capture process. This approach has not been widely deployed in industry thus far and brings significant technological challenges. Retrofitting the large number of individual refinery process heaters to burn pure oxygen would also be complex and possibly expensive.

Whatever technology is selected, CO₂ capture would result in high cost and significant extra energy consumption and CO₂ production in a typical refinery. Adding large capture facilities with previously untested technology at the required scale could also affect the reliability of existing refinery installations. Although some of the developments in CCS for the power sector could be implemented in refineries, there is a need for demonstration projects using technology developed to address the specific challenges of refineries, such as specific impurities, lack of ground space, high reliability requirement, low retrofitting impact, energy consumption and energy integration.

Energy integration, in particular, is much easier in power plants, because they are steam and electricity producers and can easily be derated to provide the energy required for the CO₂ capture process. In refineries, which would need to install new utility plants for the additional energy demand, the need for improvement in energy consumption for CCS technology will be greater in refineries than in power plants. This will require special effort and support to be given to developing technologies that tackle this problem.

### CO₂ Transport

CO₂ can be transported in bulk either as a supercritical liquid in pipelines or as a refrigerated liquid in ships. There is already commercial experience with both approaches. For large quantities of CO₂ and short to medium transport distances, pipelines are the most cost-effective transport option.

Pipeline costs per tonne of CO₂ transported depend strongly on scale. The investment cost for a small-diameter pipeline dedicated to transporting about 2 Mt of CO₂ per year would be about 16 €/t CO₂. A larger diameter pipeline capable of transporting 5–10 Mt of CO₂ per year would cost about half this amount. Because of the cost and complexity of major pipeline projects, it will make economic and practical sense to build large pipelines serving several users, most probably around large single emitters such as power stations or in industrialised areas.

Quality specifications for the CO₂ streams will also need to be developed to address all potential impacts on pipeline performance including corrosion. Transport and handling of large quantities of CO₂ near populated areas could raise safety concerns and, therefore, public acceptance issues. The most significant safety risk is leakage of CO₂ from a pipeline into the atmosphere or the subsurface. High concentrations of CO₂ caused by a release to the atmosphere would pose health risks to humans and animals. Risk management techniques will be required to identify, mitigate and manage these risks in order to ensure the safety of CO₂ transport, handling and storage.

### CO₂ Storage

Large amounts of CO₂ can potentially be stored in various geological formations in Europe. Most of the potential CO₂ storage capacity in Europe is located offshore (68% of the total). Figure 4 shows the locations of refineries in Europe and potential onshore and offshore sedimentary basin storage sites.

Storage of CO₂ in deep saline aquifers is the most promising in terms of capacity. CO₂ can also be permanently stored in fully depleted oil and gas fields which are generally well known and documented, although storage capacity in these sites would be smaller than in aquifers. CO₂ injection into oil and gas fields for enhanced oil/gas recovery (EOR/EGR) is a fully developed technique...
through which some CO₂ can be retained. Compared to North America, where EOR and EGR are widely practiced, the use of CO₂ for EOR/EGR is not expected to be economic in Europe if the crude price is consistently lower than about 100 $/bbl.

After the CO₂ has been injected underground, the integrity of the storage sites will need to be continuously monitored using a range of techniques and protocols, many of which are already well known.

**Refinery CCS costs**

The cost of refinery CCS is expected to be significantly higher than the current estimates for CCS in coal-fired power plants, which range from 60–80 $ (43–57 €) per tonne of CO₂ avoided. The estimated cost of CO₂ capture, which is typically about 80% of the total, will vary widely, depending on each refinery’s size, complexity and location. The cost is also highly dependent on the fraction of the total emissions to be captured, because refineries usually have a small number of large emission sources and a large number of smaller, low concentration sources.

The capture cost for the first 50% of the total CO₂ emissions from a large, complex refinery has been estimated in a report by Shell[^3] at 90–120 € per tonne of CO₂ avoided (2007 basis). The cost will be considerably higher to capture the remaining 50% of CO₂ emissions. Smaller, less complex refineries would not benefit from the economy of scale and unique configuration of the refinery in the Shell study. Taking into account the costs of transport, storage and monitoring, the total CCS cost estimate for the Shell example refinery would be in the range of 132–178 € per tonne of CO₂ avoided (on a 2010 basis).

With the current lack of experience of large-scale CCS projects and therefore limited understanding of the cost implications, there are wide variations in published cost estimates. A detailed estimate of refinery CCS costs was beyond the scope of the current CONCAWE report, requiring rigorous analysis of a wide range of variables in order to place the costs in their proper context.