MITIGATION OF CO₂ EMISSIONS USING LOW AND NEAR ZERO CO₂ EMISSION POWER PLANTS

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In this paper, CO₂ control technologies like decarbonization either of the flue gas or of the fuel, as well as the use of oxyfuels in near zero emission cycles are investigated. Among four existing technologies of CO₂ removal from flue gas- namely, chemical absorption using amines, membranes, cryogenic distillation and selective adsorption on solids-chemical absorption is the most mature and the best suited to power plants and is analyzed from the point of view of its penalties on performance and costs of fossil fuel-fired power plants. The overcost of its generated kWh is around 60%. Decarbonization of the fuel is also considered; it is much less penalizing than chemical absorption and produces hydrogen. A new concept of near zero CO₂ emission power plants is presented, the so-called MATIANT cycle, using an oxyfuel with total CO₂ recycling. The cost of its kWh is 50% to 100% higher than that of a Combined Cycle.

In conclusion, when the external costs are internalized, the resulting social cost (generation + external costs) of the generated kWh in fossil fuel-fired plants with capture and sequestration of CO₂, as well as in MATIANT cycles, is in the range of the social costs of windmills and, for a MATIANT cycle, is comparable to that of a Combined Cycle with capture and storage of CO₂.

INTRODUCTION

One of the main sources of CO₂ emissions is the combustion of fossil fuels (coal, oil, and gas) in power plants, in industry, in the transport sector, and in domestic and tertiary sectors. Under the Kyoto Protocol, the target of Europe is to reduce its emissions by 8% below the 1990 levels by 2008–2012. But in order to stabilize CO₂ concentrations at the 1990 level, the emissions are likely to be reduced drastically, by more than 50% in the long run (30 years). Such deep cuts would require a combination of maximal increase in the efficiency of energy conversion processes and fuel use, a greatly reduced energy demand and consumption, a massive switching from high-carbon fuels to low-carbon fuels (e.g., coal to natural gas), a widespread use of renewable energy and nuclear energy, and enhancement of natural "sinks" for CO₂, such as new forest growth (thus lowering CO₂ emissions in the atmosphere).

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Nevertheless, if reliable, affordable methods can be developed for capturing and sequestering (storage on a permanent basis) CO\textsubscript{2} from fossil fuels, it would allow fossil fuels, whose reserves are still very large (especially coal), to burn cleanly and efficiently. This would avoid social and economic disruptions and/or move less rapidly to nonfossil energy sources, provided a strategy is pursued based on very large and relatively rapid reduction in CO\textsubscript{2} emissions, such as:

- capturing technologies downstream of the combustion in the flue gas and upstream in the fuel (Low Emission Power Plants or LEPP)
- using oxyfuel in CO\textsubscript{2}/O\textsubscript{2} power cycles (like the MATIANT cycle designed and developed in Liege, Belgium); they are near Zero Emission Power Plants or ZEPP.

Consequently, beyond 2010 substantial reductions in emissions of CO\textsubscript{2} from fossil fuel combustion for power generation could be achieved by use of technologies of capture and sequestration of CO\textsubscript{2}. Strategies for achieving deep reductions in CO\textsubscript{2} emissions will be most robust if they involve all types of mitigation options. The potential for generation of electricity with capture and storage of CO\textsubscript{2} is determined by the availability of resources of fossil fuels, as well as of the capacity for storage of CO\textsubscript{2}. Published estimates of CO\textsubscript{2} storage capacity show that capacity is not likely to be a major constraint on the application of this technology. The technology is currently available for CO\textsubscript{2} separation, for piping CO\textsubscript{2} over large distances, and for underground storage.

In order to set the scene, let us assess the CO\textsubscript{2} emissions reduction by improvement of the process efficiency. The equation:

\[
\left[\text{CO}_2\right] \text{ g/kWh} = \left[\text{C}\right] \text{ kg/kg fuel} \times \frac{44}{12} \times \frac{3.6}{\text{kJ/kWh}} \frac{1}{\text{LHV(kJ/kg fuel)}} \frac{1}{\eta(\%)}
\]
and Figure 1 show how the CO₂ emissions are dependent on this efficiency and on the fuel composition (carbon content, LHV) for centralized electricity production based on coal (PC, SC, USC, IGCC) and natural gas-fired plants (GT, CC). An increase of the efficiency by 1 percentage point leads to an average CO₂ emissions reduction of 2.5 %, depending on the absolute efficiency. For a 500 MWₑ CC with an 85% load factor and a specific emission of 400 gCO₂/kWhₑ at 55% efficiency, the annual avoided CO₂ emission is 500 × 0.85 × 8760 × 400 × 0025 = 37.23 kton/y.

Mathieu et al. (1998; 1999; 2000) have modeled the so-called E-MATIANT cycle. This latter belongs to the family of near zero emission power cycles among them, CO₂/O₂ cycles that use CO₂ as the working fluid and O₂ as the fuel oxidizer. Their main asset is the removal of nearly 100% of the CO₂ coming from the combustion process through a simple purge, in liquid or supercritical state at high pressure. The cycle efficiencies range from 40 to 50%. This gives to the system the ability, for example, to provide CO₂ for enhancing the oil recovery from oil wells or for methane recovery from coal beds (see Figure 3). After its reuse, the CO₂ can then be sequestered in the exhausted stable geological sites in the long term.

**CO₂ CAPTURE IN POWER GENERATION (LEPP AND ZEPP)**

The three options considered here are: CO₂ removal after the combustion or flue gas decarbonization, CO₂ removal before the combustion or fuel decarbonization, and the use of oxyfuels with CO₂ recycling. The four main currently available
capture technologies in the flue gas are chemical absorption using amines (MEA scrubber), membranes, cryogenic distillation, and selective adsorption on a solid surface. Capture and storage technologies are best suited to large-scale point sources of CO₂ such as power stations, which account for about one third of global CO₂ emissions, and energy-intensive industry, rather than small, dispersed sources such as transport and heating. The two main technologies for power generation are natural gas combined cycles (NGCC), and pulverized coal-fired (PC) steam cycles. Other large fossil power plant configurations, such as integrated coal gasification combined cycles (IGCC), are also considered as serious candidates for CO₂ capture.

**Postcombustion CO₂ Capture or Downstream CO₂ Removal**

Concentrations of CO₂ in power station flue gases are rather low and range from around 3–4% by volume for NGCC plants to 9–10% for coal-fired IGCC plants and 10–14% for PC plants. This means that a large volume of flue gas has to be treated. Equipment is correspondingly large and capital costs are high. If CO₂ is captured using amine solvents to scrub the flue gases, large amounts of energy are required for solvent regeneration (around 4 MJ/kg CO₂ extracted). This leads to severe performance penalties (10–13% points for the efficiency and around 20% for the power output) as well as to additional costs (an average over-cost of the generated kWh of about 60%). This technology is mature and already in use for removing CO₂ from natural gas (Sleipner in Norway) and for separating CO₂ from flue gases for use in the food industry.

Another option, used in NGCC notably, is a partial recirculation of the flue gas towards the compressor inlet (Bolland *et al.*, 1997). The performance of existing CO₂ capture technologies, for a new 500 MWₑ gas- or coal-fired plant incorporating CO₂ capture, with CO₂ compression to a supercritical state at 110bar and at ambient temperature, is as follows:

- an 80% to 90% reduction in CO₂ emissions to the atmosphere
- a reduction in electrical generation efficiency of 8 to 13 percentage points respectively for gas- and coal-fired plants
- an increase in capital costs of 50% to 100%
- an increase in the cost of electricity generation of about 50% in gas-fired plants with postcombustion capture and IGCC plants with precombustion capture, and about 70% in PC plants with postcombustion capture.

**Precombustion CO₂ Capture or Upstream CO₂ Removal**

A precombustion capture technology, producing a CO₂ concentration of 35 to 40%, can avoid many of these problems. Precombustion CO₂ capture involves
reacting the fuel with oxygen or air and, in some cases, steam, to produce a syn-gas consisting mainly of CO and H₂. A catalytic "shift" reaction with steam in a catalytic reactor (shift converter of CO into CO₂ and H₂) gives CO₂ and more hydrogen. The CO₂ is removed and the hydrogen is used as an energy carrier either to a gas turbine or to a fuel cell or to any other process. This technique needs more gas purification stages when applied to coal or oil compared to applications using gas as the fuel. This can be considered as a way to produce H₂ cheaper and due to higher pressure and CO₂ concentration leads to less severe performance penalties (around 7 to 8 percentage points for the efficiency and around 15% for the power output in an IGCC plant) and less additional costs than MEA scrubbers. Most of the technology required is well proven in ammonia production and other industrial processes. Nevertheless, the use of hydrogen as a turbine fuel is novel. Some turbine manufacturers are seeking to adapt their machines for the combustion of hydrogen-rich fuels. The integrated operation of these technologies for generating electricity while capturing CO₂ has no major technical barriers but does need to be demonstrated (Audus, 2000).

**NEAR ZERO EMISSION POWER PLANTS (ZEPP)**

The concentration of CO₂ in a power station flue gas stream can be increased substantially (to more than 90%) by using pure oxygen for combustion instead of air. Then postcombustion capture of CO₂ is a very easy step but the temperature of combustion must be moderated by recycling CO₂ from the exhaust, something that has been demonstrated for use with boilers but would require major development for use with gas turbines. Currently, the normal method of oxygen production is by cryogenic air separation, which requires expensive equipment and high levels of energy consumption (typically 0.25 kWh/kg O₂ at 1 bar and 99.5% purity with 0.5% Argon). Development of lower energy-consuming oxygen separation processes (using membranes, chemical looping) are awaited in the near future and would require much less energy to separate O₂ and N₂ to a high degree; consequently, the performance penalties would be much smaller.

The idea (Mathieu, 1998) of near zero emission cycles (ZEPP) is based on a quite simple new concept of power cycle: the use of an oxyfuel (mixture of a fossil fuel and O₂ produced in an air separation unit) and of a complete recycling of CO₂. The so-called MATIANT cycle is of this type. Now the nitrogen of air is simply replaced by CO₂ itself, which becomes the working fluid and the thermal ballast for the control of the flame temperature, and nearly pure O₂ is the fuel oxidizer. The combustion products are mainly CO₂ and H₂O. The water is removed from the CO₂ flow in a cooler/separator whereas the excess CO₂, gener-
ated in the combustion, is extracted from the main CO₂ flow using a simple valve at the outlet of the compressor. This is done without any costly and energy-consuming systems like scrubbers and subsequent compression of CO₂, avoiding the associated high penalties on efficiency (typically 10 to 13 percentage points) and on capital and operation and maintenance costs.

The so-called E-MATIANT cycle (Houyou et al., 2000 and Mathieu et al., 2000) is a regenerative Ericsson-like gas cycle (see Figure 2) with two near-isothermal processes: on the one hand, a staged compressor with intercoolers (1–2) and a staged expansion with one reheat (4–5–6–7) and, on the other hand, two quasi-isobaric processes, namely, in a regenerator (7–1 and 2–3), in the two combustion chambers (3–4 and 5–6) and in the cooling of the flue gas down to the compressor inlet temperature (9–1). The cycle is situated outside the CO₂ saturation line on the T-s diagram so that no condenser is needed in the system. The upper cycle pressure (P₁) is the pressure of the combustion chamber (40 to 80 bars); the fuel and the oxygen are compressed from 1 bar up to the pressure of the combustion chamber, the pressure losses being taken into account. A water cooler/separater is used for the water removal (9–1) before the compressor. The
nonextracted water there is removed at the intercoolers’ outlets in the staged compressor. The excess CO₂ generated in the combustion process is removed at the compressor’s exhaust (point 2) in liquid or supercritical state at high pressure, ready to be reused and/or sequestered. If required, an additional compressor takes the removed excess CO₂ flow from the combustion chamber pressure up to the pressure required for a possible use of CO₂ (like Enhanced Oil Recovery and Enhanced Recovery of coal bed methane) or for its long term sequestration. The extracted excess CO₂ and H₂O flows amount to 8% and 6% respectively of the recycled CO₂ flow. A small fraction of CO₂ (namely, 1.5% of the extracted CO₂ flow) leaves the cycle with the extracted water flow (9–1). Figure 3 shows the layout of a power plant based on this power cycle, using an oxyfuel and using CO₂ as the working fluid and thermal moderator.

Table I gives the design values of the cycle parameters used for the calculation of the performances. When the fuel is natural gas and for the set of data mentioned in Table I, calculations show that the best upper cycle pressure is 60 bar (Mathieu, 1998, 1999). The efficiency lies in the range of 40 to 47% depending on the reheat pressure and when the TIT is 1300⁰C, the upper and lower cycle pressures being 60 and 1 bar respectively. Its optimal value is 40% when the reheat pressure is optimal, namely at 12 bar (corresponding to the maximal specific work). One of the main features is the CO₂ expander exhaust temperature, which is much higher (900 to 1000⁰C) than in a typical current gas turbine.
operating on air (550°C). This provides a lot of heat at high temperature recuperated in a regenerator for the preheating of the recycled CO₂.

Figure 4 shows that the efficiency increases in the range 40 to 47% when the reheat pressure increases from its optimal value (12 bar) up to 54 bar (lower curve). Due to its electricity consumption (0.25 kWh/kg O₂), the cryogenic ASU makes the efficiency fall by some 11 percentage points for the considered range of reheat pressures. Taking account of the penalty due to the cooling of the hot parts (about 2.5%), the net efficiency declines to about 40% and the specific work to 560 kJ/kg CO₂ recycled at the optimal reheat pressure (at 12 bar on the lower curve). That is the price to pay in order to avoid the use of CO₂ chemical

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**TABLE I** Operating parameters of the E-MATIANT cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper cycle pressure (2–4)</td>
<td>60 bar</td>
</tr>
<tr>
<td>Pinch-point at the recuperator outlet</td>
<td></td>
</tr>
<tr>
<td>Lower cycle pressure (7–1)</td>
<td>1 bar</td>
</tr>
<tr>
<td>Pinch-point at the recuperator outlet</td>
<td></td>
</tr>
<tr>
<td>Pressure drop in the combustion chamber (3–4)</td>
<td>3% pₚₐ</td>
</tr>
<tr>
<td>Expansors inlet temperature TIT (points 4, 6)</td>
<td>130°C</td>
</tr>
<tr>
<td>Isentropic effectiveness of the 3 expanders (4–5;6–7)</td>
<td>0.87</td>
</tr>
<tr>
<td>Cycle low temperature (point 1)</td>
<td>30°C</td>
</tr>
<tr>
<td>Isentropic effectiveness of the O₂ compressors</td>
<td>0.75</td>
</tr>
<tr>
<td>Isentropic effectiveness of the fuel compressor</td>
<td>0.75</td>
</tr>
<tr>
<td>Isentropic effectiveness of the intercooled CO₂ compressor: 0.85 for the 3 first stages — 0.8 for the last one</td>
<td></td>
</tr>
</tbody>
</table>
scrubbers and of a CO\(_2\) compressor aimed at bringing up the CO\(_2\) to be extracted in supercritical state (80 to 110 bar). Small amounts of Argon (0.5% of the O\(_2\) throughput from the ASU) are introduced in the cycle with O\(_2\). At equilibrium, the concentration of this accumulated Argon remains under 1% of the CO\(_2\) mass flow rate.

In the CO\(_2\) mass balance, for a utilization of 7000 h/y of a 1 MW plant, 442 gCO\(_2\)/kWh\(_e\) at a purity of 99.5% are removed, and 6 gCO\(_2\)/kWh\(_e\) escapes out of the cycle by dissolution in the extracted water at the cooler/sePARATOR and at the compressor’s intercoolers’ outlets. This amounts to 0.12% of the recycled CO\(_2\) mass flow rate or 1.5% of the removed CO\(_2\) flow. This is eight times less than the emissions of a Combined Cycle (400 gCO\(_2\)/kWh\(_e\) at 55% efficiency) equipped with a CO\(_2\) scrubber in the flue gas (50g CO\(_2\)/kWh\(_e\)).

Another option is the Combined Cycle (Houyou, 2000), consisting of an O\(_2\)/CO\(_2\) Brayton-like cycle (see Figure 5) without (1–2–4–5–8–1) and with reheat (1–2–4–5–6–7–1) and a Rankine cycle, comprising a heat-recovery steam generator (8–9) with two pressure levels and operating at subcritical pressures (under 221 bar). Here the compression (1–2) is adiabatic instead of nearly isothermal.
The mixture CO$_2$/water is compressed without any further water extraction along the compressor. The composition of the mixture CO$_2$/H$_2$O moves towards equilibrium, and some water flows out together with the CO$_2$ flow extracted at the compressor outlet (point 2).

Due to the high temperature at the GT expander’s exhaust (point 7), two options are possible: either the use of a recuperator (7–8) to cool the gas down to the acceptable temperature at the HRSG inlet (700°C) and to preheat the recirculated CO$_2$ flow at the compressor outlet (2–3), or a quench of the hot exhaust gas carried out by a partial recycling of the cold CO$_2$ from point 1 to point 7. From 700°C, the sensible heat of the exhaust gas is transferred to the steam cycle (8–9). When a reheat is incorporated in the expander of the CO$_2$/O$_2$ Brayton cycle, both net efficiency and specific work increase by 3.5 percentage points (49% instead of 45.5% for the non-reheated cycle) and by 20% respectively, when the upper cycle pressure ($P_1$ opt = 60 bar) and the reheat pressure (about 10 bar) are optimized. This is the efficiency of a typical CC composed of two gas turbines, two HRSG and one steam turbine when the HRSG contains one optimized pressure level and when the GTs operate on air and natural gas. In order to further increase the efficiency, the performance of the steam cycle can be boosted, for instance using an HRSG with 2 and 3 pressure levels and reheat and supercritical steam conditions (Dechamps and Mathieu, 1993). This case is presently theoretical, as the temperatures in the cycle are too high for the existing materials of the recuperator. In conclusion, only the configuration without reheat is technically feasible. Nevertheless, it does not show a marked advantage on the E-MATIANT gas cycle, which is much easier to build and consequently less expensive.

**TECHNICAL ISSUES**

Regarding MEA scrubbers, most of the technology is well proven, in particular, in ammonia production. As for CO$_2$ sequestration, the technology is not yet proven even though the storage in saline aquifers is already being practiced, namely the storage of CO$_2$ in a saline aquifer in the North Sea (operated by Statoil, Norway). The storage of natural gas in onshore aquifers is practiced as well (e.g., in Belgium). Regarding the MATIANT cycle, some components require a new design; e.g., the high temperature cooled expanders, the combustion with pure O$_2$ in a CO$_2$ atmosphere under pressure. Also components like intercooled compressors, pumps, heat exchangers, and cooler/separators have to be adapted to CO$_2$ as the working fluid. The biggest technical issue is the design of the hot parts of the system that require an internal cooling.
**CO₂ CAPTURE AND STORAGE COSTS**

The overall cost of CO₂ capture and storage is estimated at about 40 to 70 €/ton CO₂ (150 to 260 €/ton C) emissions avoided or not released in the atmosphere for a range of coal- and gas-fired power plants, using pre and postcombustion capture techniques. This cost has four main components (IEA Greenhouse Gas R&D Program, 2000–2001):

- CO₂ capture: 30–60 €/ton CO₂ for a 500MWₑ gas- or coal-fired plant at current fuel prices (2.5 and US$1.5/GJ respectively)
- compression to 110 bar: 6-8 €/ton;
- transportation by pipeline (this is feasible and technically proven): 3–7 €/ton CO₂ per 100 km.
- storage: 3–10 €/ton CO₂.

The costs of transportation and storage are much lower than the capture costs. As with most new technologies, there is scope to reduce these costs in future through technical developments and wider application.

**COMPARISON OF CO₂ CAPTURE TECHNOLOGIES**

Table II is taken from reports of the IEA Greenhouse Gas R&D Program and shows the cost of capture and the extra cost of the generated electricity for various technologies of conversion of coal and natural gas. Regarding coal (PC), the use of membranes for CO₂ capture is currently twice as costly as the chemical absorption. The best technology to burn coal efficiently (currently 43% with a potential to 50–52%) and cleanly is clearly IGCC, the cost of CO₂ capture by

<table>
<thead>
<tr>
<th>plant</th>
<th>net efficiency</th>
<th>Technology of capture</th>
<th>Cost of capture (€/2000/ton CO₂)</th>
<th>∆CE (€/kWh)</th>
<th>∆CE/CE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC Coal</td>
<td>40%</td>
<td>Chem.Abs. MEA</td>
<td>35.4–40.6</td>
<td>2.6–3</td>
<td>50–60</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>Membranes</td>
<td>67.7–83.3</td>
<td>4.9–6.1</td>
<td>95–120</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>cryog.distillation</td>
<td>31.2–46.8</td>
<td>2.3–3.4</td>
<td>45–65</td>
</tr>
<tr>
<td>IGCC</td>
<td>33%</td>
<td>Chem.Abs. MEA</td>
<td>62.5–72.9</td>
<td>4.6–5.3</td>
<td>90–100</td>
</tr>
<tr>
<td></td>
<td>35–43%</td>
<td>Physical Absorption (upstream)</td>
<td>18.7–33.3</td>
<td>1.46–2.6</td>
<td>18–33</td>
</tr>
<tr>
<td>NGCC</td>
<td>55%</td>
<td>Chem.Abs. MEA</td>
<td>38.5</td>
<td>1.15–1.9</td>
<td>50</td>
</tr>
<tr>
<td>MATIAN Tcycle (natural gas)</td>
<td>45–50%</td>
<td>O₂/CO₂</td>
<td>–</td>
<td>0.73–1.46</td>
<td>50–100</td>
</tr>
</tbody>
</table>
physical absorptions being half of the chemical absorption cost. Regarding natural gas in CC, the additional generating cost of CO₂ capture by chemical absorption is a little lower but in the same range (50 to 60%) as that for coal in PC. The calculated generating cost of electricity in an E-MATIANT plant is found to be 50 to 100% higher than the cost of a current CC kWh without CO₂ removal.
(55% efficiency) but now with nearly zero emission of CO₂ in the atmosphere. This cost would be slightly higher than that of a current combined cycle plant equipped with a CO₂ scrubber and of the same order of magnitude of that of coastal and offshore windmills (see Figure 6).

Table III shows the generating costs in € (value in the year 2000)/kWhₑ of coal-fired power plants (PC/SC), IGCC, and of gas-fired plants (CC) without CO₂ removal. The external costs due to CO₂ and to the other pollutants (NOₓ, SOₓ) are provided for the different fuels and technologies (AMPERE Report, 2000; JOULE ExternE, 1995). The total or social costs without CO₂ removal are obtained by adding the generating and external costs. These costs are 40% higher for coal-based conversion systems (around 6 € 2000/kWhe) than for gas-based plants (around 4.3 € 2000/kWhe). The cost of CO₂ capture is given for the MEA chemical scrubber with 90% CO₂ retention (line 5). By adding lines 1 and 5, the generating costs with CO₂ capture is obtained. Capture increases this cost by 70% for PC/SC, by 30% for IGCC, and by 50% for CC, in good agreement with the figures given in Table II. The total costs are given when CO₂ removal and sequestration are taken into account. The sequestration costs range from 5% to 40% of the capture costs (IEA Green House R&D Programme 2000–2001; Freund, 2000; Herzog et al., 1997). It appears that the total costs with CO₂ removal and sequestration are 23 to 24% higher for coal-fired plants (PC/SC) than for gas-fired plants and only 6 to 9% higher for coal gasification in IGCC plants than for gas-fired plants (see Figure 6). In conclusion, when external costs (here CO₂ environmental impact) are internalized, the total costs for coal-based technologies come closer to those of natural gas-based technologies.

Figure 6 shows the total cost (generating + external costs) in €2000/kWhₑ ($1 = 1.041 € in the year 2000) against specific emissions in gCO₂/kWhe for the coal-based (PC/SC, Advanced SC, UltraSC, IGCC) and natural gas-based (CC, MATIANT) conversion techniques considered here without and with CO₂ capture and sequestration. When these technologies are compared without including the costs of CO₂ capture and sequestration (diamond points in Figure 6), the total or social costs of coal-fired plants range from 5.8, 5.48, 5.2 for PC/SC, PS/ASC, PC/UUSC respectively and 6 for IGCC down to 4.3 for CC. The specific emissions are in the range of 700–900 gCO₂/kWhe for coal plants and more than half that (350) for CC. With CO₂ capture and sequestration (bars with circles in Figure 6), the total costs increase whereas the CO₂ emissions are cut by 90% (70–90 gCO₂/kWhe for coal and 35 for gas). In the total cost, the sequestration cost and the decrease of the external cost due to CO₂ capture are taken into account, the external costs associated with the other pollutants being kept the same. The sequestration cost varies from a minimum of 5% up to a maximum of 40% of the
CO₂ capture cost; the share of transportation and sequestration is then much smaller than the cost of capture (5 to 20%). The circles at the end of the bars represent these extremes. For comparison purposes, the costs of windmills (squares) on the coast (4.6), offshore (5.9) and inland (8.1) as well as PWR nuclear reactors (triangles, 2.6) are indicated on the x-axis as zero-emission plants.

First, all the techniques based on fossil fuels with CO₂ capture and sequestration are in the same range as the windmills in terms of total costs. Second, IGCC is confirmed as the best technology to burn coal. Third, the CC remains better than PC but also IGCC and is less costly than windmills installed offshore.

Finally, the MATIANT plant is as good as the cheapest windmill at its lower cost and competitive with an offshore windmill at its upper cost. A distinct advantage is that it allows the use of fossil fuels at nearly zero emission of CO₂ and NOₓ.

These total costs calculated for various gas- and coal-fired plants (PC/SC, IGCC, CC, MATIANT cycle) compare favorably with other options such as wind energy and are expected to decrease as the technology gets maturer and as the scales of application increase.

If CO₂ is used for enhanced oil recovery (EOR) or enhanced recovery of coal bed methane (ERCBM), there is a valuable product (oil or methane, respectively) which could offset the cost of CO₂ capture and transport. In most of EOR projects (but not for ERCBM), the net cost of CO₂ capture and storage might be negative. Other ideas for utilizing CO₂ to make valuable products have not proved to be as useful as sequestration measures, because of the amount of energy consumed in the process and the relatively insignificant quantities of CO₂ that would be used.

**CONCLUSIONS**

To ensure that the CO₂ capture and storage technology option is available in the coming decades, a major effort is justified. New technology ideas and approaches to capture and storage as well as alternatives to postcombustion CO₂ removal and development of novel ideas on advanced systems (such as precombustion decarbonization, zero emission power cycles, fuel cells and their integration in hybrid energy systems) should be vigorously pursued. Deep reductions in emissions of CO₂ into the atmosphere will be needed to avoid major climate change. Capture and storage of CO₂ is particularly well suited to use in power generation and, in combination with other CO₂ abatement techniques, could enable these deep reductions to be achieved with least impact on the global economy. It allows continued use of fossil fuels and energy infrastructure. It also provides a means of introduc-
ing hydrogen as an energy carrier for distributed and mobile energy users. The overall cost amounts to 40 to 70 €/ton CO₂ removed.

CO₂ can be captured using available and proven technology. Long-term storage is not yet a proven technology, however, it is comparatively inexpensive and the estimated capacity of potential sites for CO₂ sequestration, for example natural underground reservoirs, is sufficient for many years’ emissions.

Substantial quantities of CO₂ from fossil fuel combustion could be captured in future and sequestered in natural reservoirs. Potentially, this approach could achieve deep reductions in emissions of CO₂ and offers significant reduction in overall cost compared with strategies that do not include this option of capture and storage of CO₂. ZEPP like MATIANT cycles appear as attractive alternatives, especially when combined with EOR or ERCBM.

There is considerable scope for new ideas to reduce energy consumption and costs and accelerate the development and introduction of capture and storage technology.

References


