



# Bridging the gap: improving the economic and policy framework for carbon capture and storage in the European Union

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This policy paper is intended to inform decision-makers in the public, private and third sectors. It has been reviewed by two internal and external referees before publication. The views expressed in this paper represent those of the author(s) and do not necessarily represent those of the host institutions or funders.

# Executive summary

**Carbon capture and storage (CCS) could be an essential technology to tackle global climate change.** By capturing carbon dioxide before it is released into the atmosphere and storing it underground, CCS can provide low-carbon electricity generation when applied to power stations. It is also, to date, the only technology that can help reduce emissions from large industrial installations. Furthermore, if successfully combined with bio-energy, it has the potential to generate 'negative emissions' (that is, to remove carbon dioxide from the atmosphere), which is pivotal in most of the 2°C scenarios<sup>1</sup> published by the Intergovernmental Panel on Climate Change (IPCC, 2014b).

**In the European Union, CCS is expected to play a crucial role in achieving emissions reduction targets at the lowest cost.** Notably, CCS is part of the European energy mix in all the emission reductions scenarios envisaged by the Energy Roadmap 2050 (European Commission, 2011b). Nevertheless, in the past 10 years the scale of action on CCS by the public and the private sectors has been small. Strong action is now required if the potential contribution of CCS to European Union climate policy is to be realised.

**Although the development of CCS technology is well understood, the main barrier to progress is the high cost of deployment.** Installing 11 GW of CCS electricity generation in Europe by 2030, as envisaged by the Energy Roadmap, could cost between €18 and €35 billion. Furthermore, installing the 100 GW of CCS electricity generation planned for 2050 could cost between €160 and €320 billion (although costs are expected to come down). Transport infrastructure would add another €2 to €11 billion by 2030, or €7 to €20 billion by 2050 (Arup, 2010).

**European Union policies, namely the New Entrant Reserve (NER) 300 and the European Energy Programme for Recovery (EEPR), have so far provided only €1.3 billion for CCS development.** Few Member States have put forward domestic incentives to support the technology. As a result, few projects are under development and to date there are no commercial-scale CCS installations operating in the European Union. By comparison, North America has already 13 CCS installations in operation and six under construction.

**The new incentives that will be introduced to support CCS, mostly via a reform of the European Union Emissions Trading System and the NER 400 (or Innovation Fund), are likely to be insufficient to accelerate investment.** CCS also does not feature strongly in the objectives of the new Energy Union (European Commission, 2015), although this would provide an ideal opportunity to stimulate action on CCS.

**The public and private sectors, including large utilities and industries, both have stronger roles to play.** Upstream producers of fossil fuels should also contribute, as ultimately CCS will increase the amount of their assets that can be potentially realised.

**Based on a review of the latest evidence on CCS, this policy brief recommends the development of a new strategy for the European Union to increase ambition and accelerate action on CCS.** This strategy should deliver a number of key results.

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<sup>1</sup> Decarbonisation scenarios consistent with the international goal of limiting the rise in global average temperature to no more than 2°C

**1. Stronger policies to incentivise investment in CCS.** The European Commission and Member States should develop a portfolio of measures tailored to different phases of CCS development in order to overcome critical barriers to deployment and facilitate investment. Priority actions in the next five years include:

- **Direct funding for research and development**, both at European Union or Member State level. Bioenergy with CSS (BECCS) should be a priority area of research, given the pivotal role of negative emissions in several global scenarios (IPCC, 2014b).
- **A new funding mechanism to finance early stage development projects** to overcome the ‘valley of death’ until full technology deployment. The European Commission, in consultation with the Member States, should devise a time-bound credible support programme, with periodic revision and an exit strategy. Funds should be complementary and additional to existing resources. The Commission should also consider increasing the use of the European Structural and Investment Funds to support investment in less developed regions that would most benefit from CCS (for example, those which rely more heavily on domestic supplies of fossil fuels).
- **Carbon pricing** to level the playing field between high- and low-carbon technologies and to stimulate private investment. To make CCS projects cost-competitive in the European Union’s electricity generation markets; however, the carbon price would need to be about €35-60/tCO<sub>2</sub> for CCS coal-fired power plants to compete against coal-fired plants with unabated emissions, and €90–105/tCO<sub>2</sub> for CCS gas-fired plants to compete against gas-fired plants with unabated emissions. The carbon price in the European Union Emissions Trading System is unlikely to hit this level for at least the next decade, so additional policies are required.
- **Financial incentives for CCS electricity generation** that complement the carbon price to make CCS power stations bankable. Member States should design and implement financial incentives, such as feed-in tariffs or ‘contracts-for-difference’, to provide a reliable and steady stream of revenue. Preliminary estimates for the UK suggest strike prices for CCS could be around €140-190/MWh<sup>2</sup> (for coal and gas CCS respectively) in the early 2020s, decreasing to €110/MWh (for both coal and gas) in the late 2020s (ETI, 2015). These are not dissimilar to the strike prices that the UK government is granting to offshore wind installations, which are around €190/MWh in 2014/15 (DECC, 2013b).
- **Increased financial support from public financial institutions**, such as the European Investment Bank, to help leverage private finance at lower cost. This would help overcome the barriers posed by the relatively high cost of capital.
- **Mandatory targets** to further stimulate action by the private sector. Emission intensity targets or emissions performance standards could be introduced by the European Commission to ensure that new fossil-fuel power plants are fitted with carbon capture technology.
- **Tailored incentives, either at European Union or Member State level, to support CCS uptake in industrial sectors**, starting with those that already capture carbon dioxide as part of their production process. However, for some of the most energy-intensive industries, such as cement and steel, CCS may have to wait until the cost of capture technology has significantly reduced and transport and storage infrastructure is in place for the power sector for them to tap into. Sectoral agreements set at international level may also help to accelerate CCS in energy-intensive sectors.

2 The average exchange rate used in this paragraph is: £1 = €1.241 in 2014.



**2. More ambitious and coordinated action.** Member States have shown very different attitudes towards CCS, with only a few taking concrete action. Notably, some of the countries that could benefit from CCS the most, such as those most reliant on domestic supplies of fossil fuels, have shown little appetite for large investments in this area. Accelerating development and increasing ambition will require a coordinated approach. Key activities that the European Commission and European Council should initiate are:

- **An assessment by each Member State** of its potential for capture and storage of carbon dioxide, as well as the identification of alternative routes for decarbonisation, and their costs. This could lead to the identification of a coalition of countries willing to collaborate more closely on CCS.
- **Ensuring coherence across national policies** to support CCS. For instance, the European Commission could recommend a portfolio of viable policy instruments.
- **Enabling shared learning on innovation** between the public and private sectors, while being responsive to concerns about intellectual property.
- **Setting milestones against which progress can be measured**, as well as devising contingency plans to avoid the lock-in of fossil fuel technology in case CCS fails to progress.
- **Facilitating and supporting** concerted action by the public and private sectors on the development of CCS infrastructure, including carbon dioxide pipelines.
- **Encouraging further exploration, characterisation and development of carbon dioxide storage sites**, to refine existing estimates and clarify storage availability (or, importantly, scarcity) in the long run.

**3. Improved legislation on carbon dioxide transport and storage infrastructure.** Improvements to the existing European legislation will be required to allow the first demonstration projects to be developed in a timely manner and to create the right conditions for future investment. In particular, the development of innovative insurance instruments, coupled with risk-sharing between private operators and national governments, will help mitigate some of the business risks of CCS, especially in relation to carbon dioxide storage and potential leakage. Possible solutions that should receive prioritised consideration include:

- **An initial cap on long-term liability for carbon dioxide leakage**, to be reviewed as risks become better understood and private insurance mechanisms develop.
- **A financial mechanism for damage remediation**, such as a liability fund or private insurance.
- **Special treatment of demonstration projects** through a public liability scheme.
- In the longer run, the European Commission should consider **relying on the Environmental Liability Directive**, rather than the European Union Emissions Trading System, to determine the size of remediation costs caused by carbon dioxide leakage from storage sites.

**Above all, the European Union and its Member States must show much greater urgency and determination to develop and deploy CCS, otherwise it will not be able to contribute towards the demanding targets for reducing emissions of greenhouse gases, perhaps making them significantly more difficult and/or expensive to achieve.**



# 1. Introduction

Economic models indicate that CCS is crucial to the cost-effectiveness of Europe's emissions reduction targets. CCS can provide flexible, mid-merit electricity generation, which will be much needed as the share of electricity from variable renewable sources increases. It is also, to date, the only technology that can help reduce emissions from industrial installations.

Furthermore, it has important applications, in combination with bioenergy (BECCS), to achieve negative emissions – the latter being pivotal in several of the decarbonisation scenarios investigated by the IPCC (IPCC, 2014b). Indeed, some economic models suggest that without CCS it may be much more expensive, if not infeasible, to achieve an emissions pathway consistent with the goal of limiting a rise in global average surface temperature to no more than 2°C.

CCS technology and infrastructure, however, are not yet mature and still relatively expensive. Finding out whether CCS is economically viable as a mitigation option requires the development of several large-scale projects over the next five to ten years. Yet, mobilising large amounts of finance for these capital-intensive projects, both from the public and private sector, is challenging and hampered by a lack of credible policy.

This policy brief identifies the key factors that currently hold back CCS investment in the European Union and explores ways that CCS can be made viable. A simple cash flow model is used to test various cost sensitivities on the only operating CCS power plant (Boundary Dam, in Canada), providing insights on the levels of investment required for CCS demonstration and the carbon price levels required for CCS to be cost competitive with other energy generation technologies.

The paper is structured as follows: chapter 2 sets out the context around energy policy and CCS in the European Union; chapters 3 to 6 outline the main challenges surrounding CCS investment, namely on technology, infrastructure and storage (chapter 3), costs (chapter 4), access to finance (chapter 5), and regulation and policy (chapter 6). Chapter 7 identifies key conclusions and policy recommendations.

# 2. The gap between ambition and reality

The following sections investigate the role that CCS plays in some of the most reputable energy modelling scenarios (section 2.1), the main features of the European energy system (section 2.2), and the current status of CCS projects globally and in the European Union (section 2.3). The key findings of this analysis are:

- Several authoritative studies (such as IEA, 2012; IPCC, 2014b), agree that CCS will be a crucial component of a low carbon future, both in the European Union and globally, in order to keep the costs decarbonisation to a minimum.
- The case for CCS in the European Union is reinforced by the significant reliance of several Member States on domestic fossil fuel reserves for energy generation. CCS could lower the risks of these assets becoming stranded, if retrofitted or installed in new planned plants.
- The pace of development of CCS has been very slow, and no commercial scale CCS installation is currently in place in the European Union.
- It will be particularly important for Member States to scope their potential for CCS, carefully assessing costs and benefits in the short, medium and long run.

## 2.1 Future energy scenarios

Several studies have estimated how the current energy system could evolve to be compatible with climate change objectives. The analysis presented here examines some of the most authoritative scenarios for global, European and national (UK) energy systems. The main scenarios are shown in Table 1. Most of them suggest that CCS will be crucial to meet the 2°C limit cost-effectively.

One of the most comprehensive reviews of model projections has been undertaken by Working Group III of the IPCC in its contribution to the Fifth Assessment Report (IPCC, 2014b), which considered around 900 mitigation scenarios. The review reveals that those scenarios in which CCS is not available are by far the most expensive. According to the IPCC, total discounted mitigation costs (between 2015 and 2100) of scenarios without CCS are estimated to be between 30 and 300 per cent<sup>3</sup> higher than those which include CCS. This is because CCS is assumed to create a wider range of options for reducing emissions. Most importantly, when used with bioenergy (BECCS) to generate electricity, it can achieve ‘negative emissions’ by effectively removing carbon dioxide from the atmosphere, reducing the need for more expensive emissions cuts from sectors like industry and transport. In addition, the models assume that CCS would allow longer use of fossil fuels, if these turn out to be significantly cheaper than alternative energy sources for the next few decades.

Some of the studies reviewed in the IPCC report (Krey et al., 2013; Dessens et al. 2014), emphasise that CCS will be an essential technology to achieve a mitigation target of preventing atmospheric concentrations of greenhouse gases from rising above 450 parts per million (ppm)<sup>4</sup> of carbon-dioxide-equivalent, which is compatible with a reasonable chance of stopping global warming of more than 2°C. In particular, analysis by Krey et al. (2013) indicates that, without CCS, a substantial number of models are unable to produce a 450 ppm scenario.

<sup>3</sup> The range was 29 per cent to 297 per cent, with a median value of 138 per cent.

<sup>4</sup> The ratio of carbon dioxide molecules to all of the other molecules in the atmosphere.

A key reference for global energy forecasts are also the scenarios developed by the International Energy Agency (IEA) (IEA, 2012). In the 2DS 'base' scenario, consistent with an 80 per cent chance of limiting global average temperature to 2°C,<sup>5</sup> CCS provides 14 per cent of global electricity generation by 2050, and accounts for up to 20 per cent of cumulative carbon dioxide reductions. Achieving the 2°C target without CCS is considered possible, but would increase costs by at least 40 per cent.

At the European level, the scenarios developed by the European Commission (EC, 2011b) in the 2050 Energy Roadmap explore routes towards reducing emissions by 80 to 95 per cent below 1990 levels by 2050. All the scenarios include power stations with CCS, with a contribution varying from 7 to 32 per cent of electricity generation. To achieve these levels, CCS will have to be deployed as from 2020 onwards.

The Energy Roadmap scenarios have been tested in a study by the Energy Modelling Forum (EMF28) (Knopf et al., 2013). Its findings support the general conclusions of the roadmap, although it shows that a broader range of pathways is possible, with CCS contribution ranging from 0 to 14 per cent of electricity generation. But while Europe's emissions reduction targets appear feasible also without CCS, this study also supports the theory that mitigation costs would be significantly higher if CCS is not available.

Energy modelling with and without CCS has also been carried out at national level. In the UK, for instance, climate change mitigation scenarios by the Government (HMG, 2011), the Committee on Climate Change (CCC, 2010) and the UK Energy Research Centre (UKERC, 2013) include CCS, with penetration rates from 10 to 50 per cent of electricity generation by 2050.

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5 The IEA's 2SD scenarios are also broadly consistent with the IEA's (2013a) World Energy Outlook 450 Scenario through 2035.

**Table 1 The role of CCS in the power sector in key energy modelling scenarios compatible with 2°C, in 2050**

Source	Scenario	CCS generation	Share of total generation	CCS capacity
World		TWh	%	GW
International Energy Agency (IEA)	2DS base	6,299	15%	960
	2DS hiRen	2,945	7%	460
	2DS hiNuc	3,055	7%	470
	2DS no CCS	0	0%	0
Global Energy Assessment	Mix	18,158	35%	n/a
	Efficiency	9,441	22%	n/a
	Supply	11,761	20%	n/a
European Union				
EU Commission	Low nuclear	1,548	32%	248
	Diversified	1,189	24%	193
	High energy efficiency	878	21%	149
	Delayed CCS	926	19%	148
	High RES	355	7%	53
Energy Modelling Forum (EMF28)	80% DEF	570	14%	n/a
	80%EFF	536	14%	n/a
	80% PESS	0	0%	0
	80% GREEN	0	0%	0
Global Energy Assessment	Mix	2,470	37%	n/a
	Supply	1,841	26%	n/a
	Efficiency	990	19%	n/a
United Kingdom				
UK Government	AEA DECC 1a	221	34%	29
	AEA DECC 1a IAB 2a	76	11%	12
UK Committee on Climate Change	C90	402	50%	57
	C90+	402	47%	56
UK Energy Research Centre (UKERC)	UKERC2: LC	106	22%	14
	UKERC2: LC-GAS	105	22%	13
	Energy 2050: CSAM	62	10%	12

**Notes:** IEA scenarios: 2DS base: 2°C scenario base case; 2DS hiREn: variant with higher renewable share; 2DS hiNuc: variant with higher generation from nuclear power; 2DS no CCS: variant without CCS. GEA scenarios: GEA-Efficiency: it assumes demand-side policies to enhance efficiency leading to relatively low energy demand; GEA-Mix: variant assuming intermediate demand; GEA-Supply: variant assuming high demand. European Commission scenarios: Diversified: it assumes all energy sources compete on a market basis with no specific support measures; Low nuclear: variant with lower nuclear acceptability; High energy efficiency: variant with stronger energy efficiency support policies; Delayed CCS: variant assuming difficulties in CCS storage and transport; High RES: variant with stronger renewable energy penetration. EMF28 scenarios: 80% DEF: it assumes 80 per cent reduction in emissions from 1990's level by 2050; 80% EFF: variant assuming greater energy efficiency improvements; 80% PESS: variant assuming both CCS and nuclear fission are excluded; 80% GREEN: variant assuming high energy efficiency and a more rapid technology development for renewable energy. UK Government: DECC-1A: it assumes 90 per cent emission reduction from 1990's level by 2050; DECC-1A-IAB-2A: variant including various constraints and frictions, to better emulate the dynamics of uptake of technologies. UK CCC: C90: it assumes 90 per cent emission reduction from 1990's level by 2050; C90+: variant assuming more ambitious energy efficiency improvements and other low carbon measures ('extended ambition', as in CCC, 2008). UKERC: UKERC2: LC: low-carbon scenario assuming 80 per cent reduction in UK emissions from 1990's level by 2050, binding carbon constraints and other low carbon policies; UKERC2: LC-GAS: variance with lower gas prices; Energy 2050: CSAM: it assumes 32 per cent UK emission reduction by 2020 and 90 per cent by 2050, compared to 1990 levels.

**Sources:** IEA (2012); Knopf et al. (2013); European Commission (2011b); UKERC (2013); GEA (2012)

## 2.2 The European Union energy system

The European Union energy system is still a relatively high-emission fossil fuel-heavy portfolio when compared to the feasible low-carbon energy scenarios outlined above. There are several hotspots of continued heavy reliance on coal, which means CCS is essential for the European Union to meet its decarbonisation targets.

There are large disparities across Member States' energy use (see Figure 1), largely due to the geographic distribution of energy sources. On average, in 2012 fossil fuels provided around 74 per cent of the European Union's energy demand,<sup>6</sup> including for electricity generation, heating and transportation. About 17 per cent of it was met by coal, 23 per cent by gas and 34 per cent by oil (Eurostat, 2014a).

While the European Union is a net importer of fossil fuels (especially from Russia),<sup>7</sup> domestic sources of coal and gas remain an important economic asset. In 2013 total coal reserves stood at just over 56 billion tonnes. These would be sufficient to meet current rates of coal demand for about a hundred years.<sup>8</sup> Notably, over 90 per cent of these reserves are lower quality sub-bituminous or lignite coals, which burn with a lower thermal efficiency, and consequently produce higher emissions per unit of electricity generated than hard coal (Hong and Slatick, 1994; IEA, 2010a).

Proven natural gas reserves are more modest, but still important significant. In 2013 they stood at around 1.6 trillion cubic metres, enough to meet the European Union's gas demand for a little less than 11 years<sup>9</sup> (BP, 2014).

6 Eurostat measures it in terms of 'gross inland consumption'. This is calculated as: primary production + recovered products + total imports + variations of stocks – total exports – bunkers. It corresponds to the addition of final consumption, distribution losses, transformation losses and statistical differences.

7 The European Union is responsible for almost 13 percent of global final energy consumption, but produces only about six percent of the world energy. Russia provides about a third of the crude oil, natural gas and solid fuels imported into the European Union. Other major suppliers of natural gas are Norway (31 per cent), Algeria (13 per cent) and Qatar (8 per cent); of solid fuels are Colombia (24 per cent), United States (23 per cent) and Australia (7 per cent); and of crude oil are Norway (11 per cent), Saudi Arabia (9 per cent), Nigeria (8 per cent) and Libya (8 per cent) (European Commission (EC), 2014b).

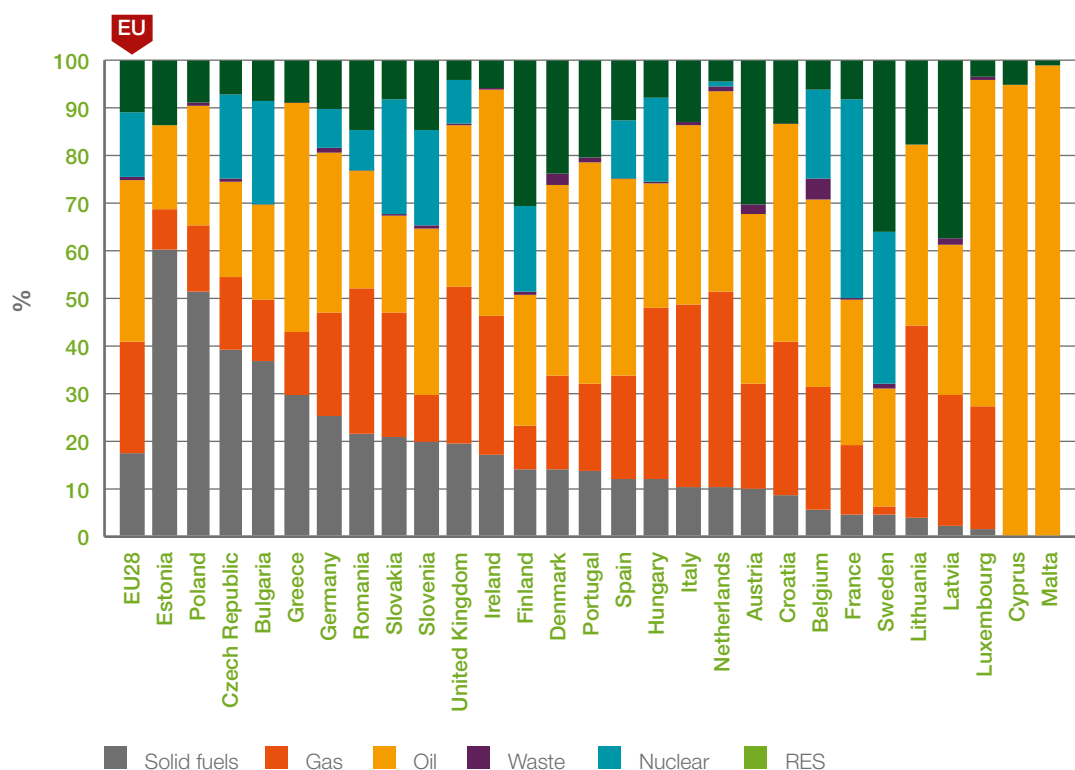
8 This is the reserve-to production ratio, that is, the amount of available resources which are economically recoverable (proved reserves) divided by the amount of resources used in one year at the current rate.

9 See footnote above.

## 2. The gap between ambition and reality

According to the European Commission (EC, 2013b) and the IEA (IEA, 2013c), fossil fuels may still represent more than 50 per cent of the European Union's energy mix by 2030. Such a heavy reliance on fossil fuels appears unlikely to be compatible with European climate change objectives. This discrepancy highlights the risk that fossil fuel assets may become stranded, and/or that countries that are heavily reliant on fossil fuels may slow down the pace of European Union climate change policy, unless CCS is implemented widely at a large scale.

**Figure 1. Gross inland consumption by Member State and by energy source, 2012**



**Note:** 'Solid fuels' include hard coal and derivatives, lignite and derivatives, peat and derivatives; 'oil' includes all petroleum products, such as liquefied petroleum gas, refinery gas, motor spirit, kerosene, gas/diesel oil, residual fuel oil. 'Gas' includes natural gas, and manufactured gases; renewable energy sources (RES) include hydro power, thermal solar and photovoltaic power, wind energy, solid and liquid biofuels, renewable wastes, geothermal energy, tide, wave and ocean; 'waste' refers to non-renewable energy from waste

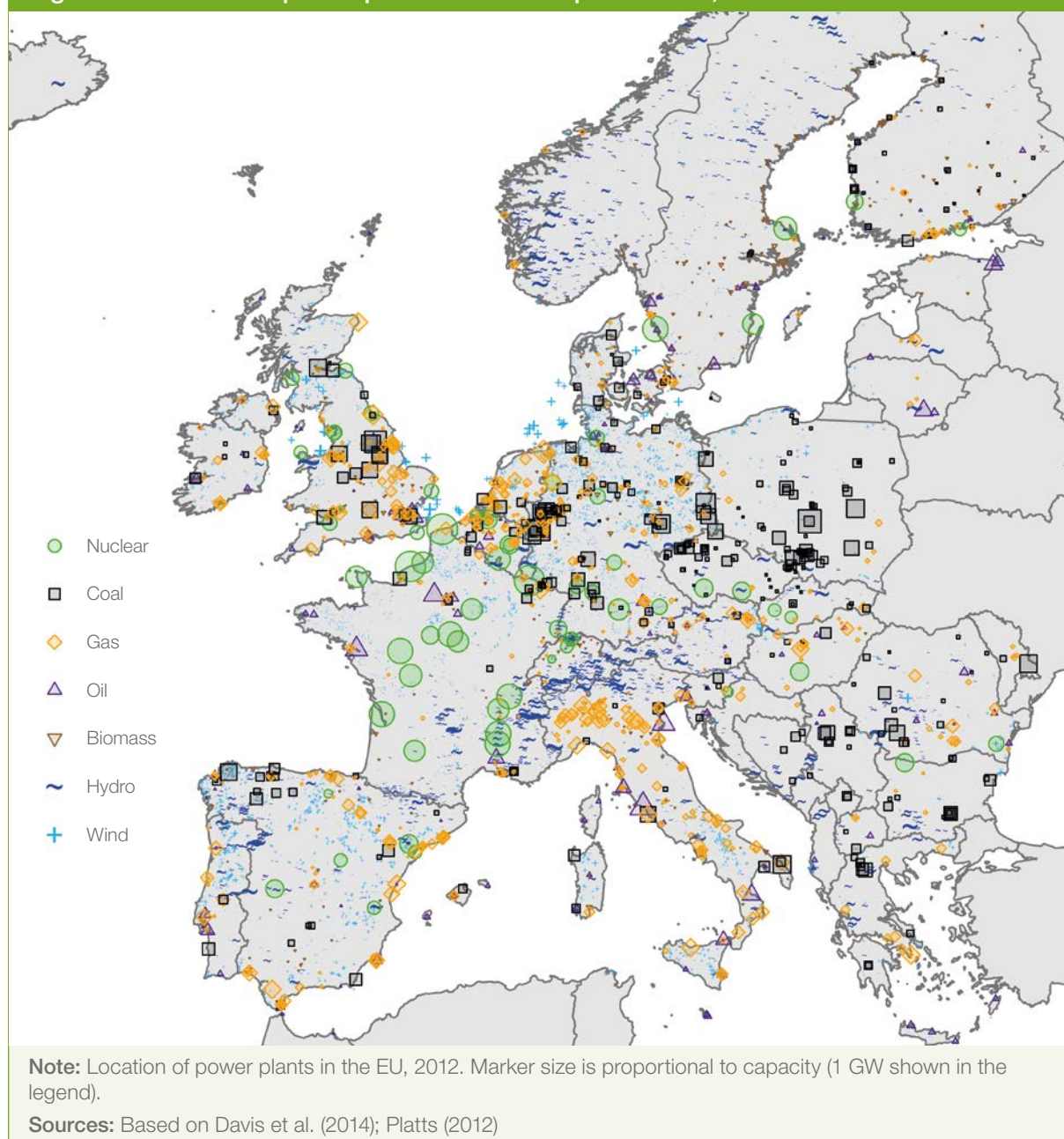
**Source:** Based on Eurostat (2014b)

The availability of energy resources also affects the distribution of power plant capacity across Member States (see the map in Figure 2). For instance, large concentrations of coal-fired generation plants are located in northern Europe (UK, Belgium, Netherlands, Germany, Czech Republic, Poland) and the Balkans. Gas-fired production is similarly concentrated around the major production region of the North Sea (UK, Belgium and Netherlands) and around the Mediterranean (Italy, Spain). These areas are likely to retain a significant fossil generation capacity in the coming decades, because of slow turnover in the capital equipment and, in some countries, strategic interests in domestic mining industries.

Of the 390 GW of fossil fuel power plants which are currently operating in the European Union (Platts, 2012), about 55 to 60 GW do not meet the requirements of the European Union Large



Figure 2. Location of power plants in the European Union, 2012



Combustion Plant Directive (2001/80/EC)<sup>10</sup> and will likely be shut down by the end of 2015. An additional 20 to 30 GW may be retired when the more stringent limits of the Industrial Emissions Directive (2010/75/EU)<sup>11</sup> come into force in the second half of 2020 (Honoré, 2014).

Some plants may also close down due to national legislation, or simply because they reach the end of their working life. Notably, 80 GW of fossil fuel power plants (predominantly coal) are more than 40 years old and nearing closure, as shown in Figure 3.

10 The purpose of the Large Combustion Plant Directive is to limit the amount of sulphur dioxide, nitrogen oxides and dust emitted from large combustion plants each year. It applies to combustion plants with a thermal input equal to or greater than 50 MW.

11 The industrial Emissions Directive regulates emissions from industrial activities with a major pollution potential, including combustion plants with a thermal input equal to or greater than 50 MW.



However, while several fossil fuel plants will be gradually retired, about 223 GW of new capacity is planned<sup>12</sup> (Platts, 2013). Also, several of the existing plants, especially the younger gas-fired installations, are likely to remain in the system for at least the next 20 to 30 years. About 170 GW of installed capacity, for instance, is no more than 20 years old.

The construction of new, long lived power plants, in combination with the significant reliance of some Member States' economies on domestic fossil fuel reserves, raises an important question as to whether some Member States will be able to meet their 2030, 2040 and even 2050 domestic climate change targets. For some countries, replacing a large part of their fossil fuel assets, for example with nuclear or renewable sources, may turn out to be expensive and/or politically sensitive.

Furthermore, when a larger share of intermittent renewable resources (like solar and wind) is added to the system, additional flexible capacity will be needed to 'balance' the system when those renewables are not available. This becomes particularly sensitive when intermittent renewables represent more than 15 per cent of a country's electricity capacity. In some Member States this additional balancing capacity can be provided by hydropower stations or, to some extent, pumped storage, but most typically this comes from unabated fossil fuel plants. This would have the effect of increasing the overall carbon intensity of intermittent renewables backed up by unabated thermal plants.

Estimates in Canada, for instance, suggest that the combined emissions of a wind farm and gas-fired power capacity used for balancing can reach up to 300g/kWh (SaskPower, 2015a).<sup>13</sup> Emissions could be higher if coal-fired generation plants are used for balancing. For instance, Germany heavily relies on lignite coal-fired plants, which emits about twice as much as gas-fired combined cycle power stations. Thus, intermittent renewable sources backed up by unabated lignite-based coal-fired power plants are likely to have, on average, a higher carbon intensity than unabated gas-fired plants.

Electricity systems cannot operate without these balancing services. But when these are provided by unabated thermal plants, the resulting emissions could be inconsistent with the decarbonisation path of the European Union electricity system. CCS power plants can provide this additional capacity, which is necessary to keep the system working, while keeping the system overall carbon intensity low.

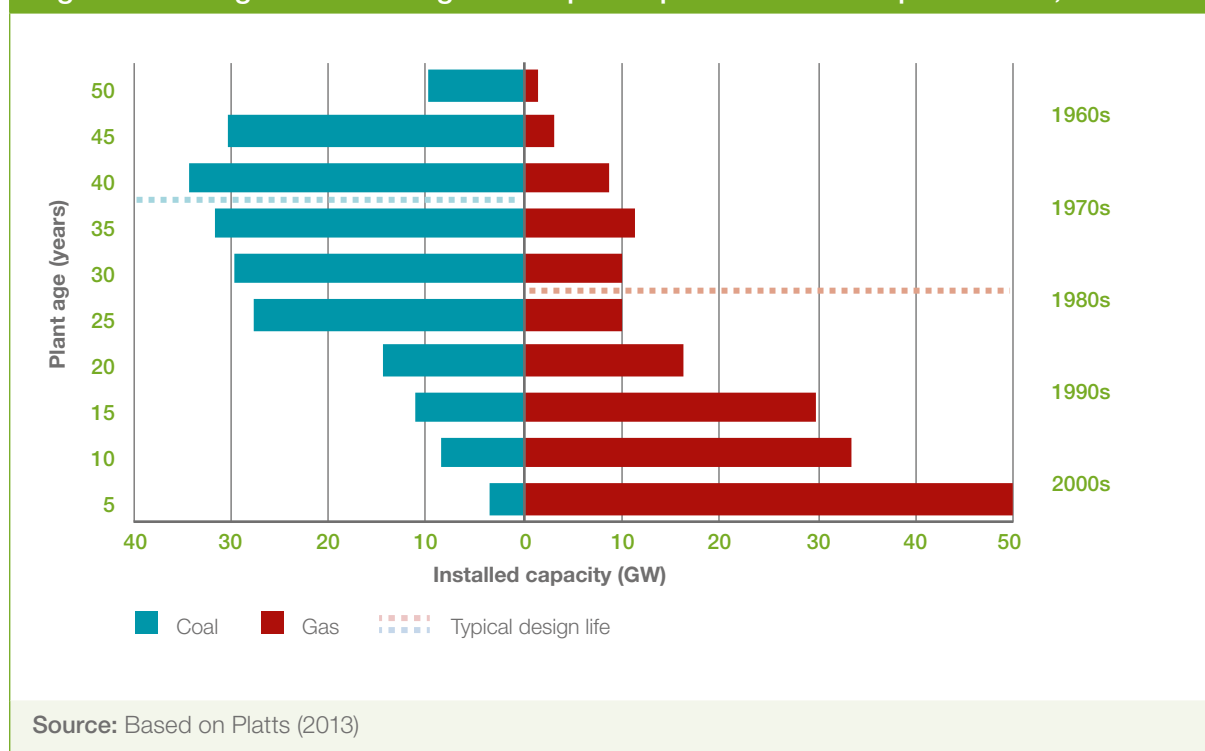
This could mean that CCS may be the most cost efficient and palatable solution to reduce emissions. However, very few countries have, to date, estimated their needs and opportunities for CCS in the coming decades, and its cost in comparison to other mitigation options. It will be particularly important for Member States to scope their potential for CCS, carefully assessing costs and benefits in the short, medium and long run.

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12 Planned capacity is taken to be in design, development, permitting or financing stages; with no groundwork commenced. Expected construction time varies, depending on the planning horizon of individual countries.

13 This is predicated on a wind capacity factor of 58 per cent, which is relatively high. In the UK, for instance, it is in the range of 27 per cent, for onshore wind, to 37 per cent, for offshore wind (DECC, 2015).

Figure 3. The age of coal and gas-fired power plants in the European Union, 2012.



### 2.3 The status of CCS projects

CCS development is lagging behind, both in the European Union and globally. As of October 2014, 17 projects are operational across the world (GCCSI, 2014b; MIT, 2013).<sup>14</sup> About two-thirds have been driven, in some measure, by revenue opportunity from mature markets for carbon dioxide used for enhanced oil recovery (EOR) (see section 3.4).

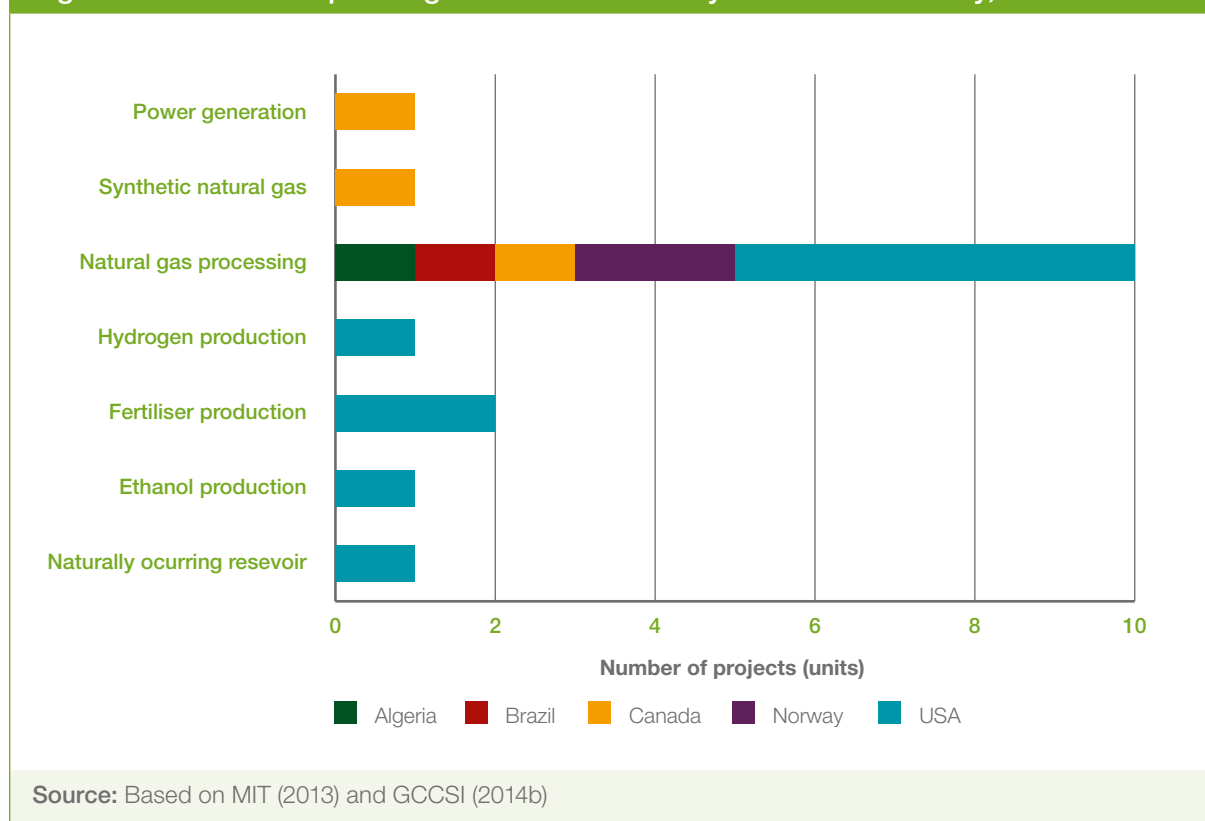
Almost all operating projects are on industrial installations, the majority of which (10 projects) are located in the US (see Figure 4). These are in sectors where carbon dioxide separation is already part of the normal production process, such as natural gas processing and fertiliser production. Little progress has been achieved in other industrial sectors, like cement and steel production, for which CCS would be more expensive (see section 4.2).

The first large-scale EOR iron and steel sector project, the Abu Dhabi CCS Project, is now under construction in the United Arab Emirates, but there are no further steel projects planned across the world. No large-scale projects have so far been planned in the cement sector, although a pilot project is underway in Brevik, Norway.

Large-scale power plant applications, on the other hand, are relatively new, but a few are in the pipeline. The first application became operational in October 2014, at the Canadian coal-fired Boundary Dam plant. A short description of the project is in Box 1.

<sup>14</sup> Data have been obtained by the authors by compiling the information from two recent data sets, the (Global CCS Institute (GCCSI), 2014b) Status of CCS Project Database and the (Massachusetts Institute of Technology (MIT), 2013) CCS Project Database.

Figure 4. Number of operating CCS installations by sector and country, 2014



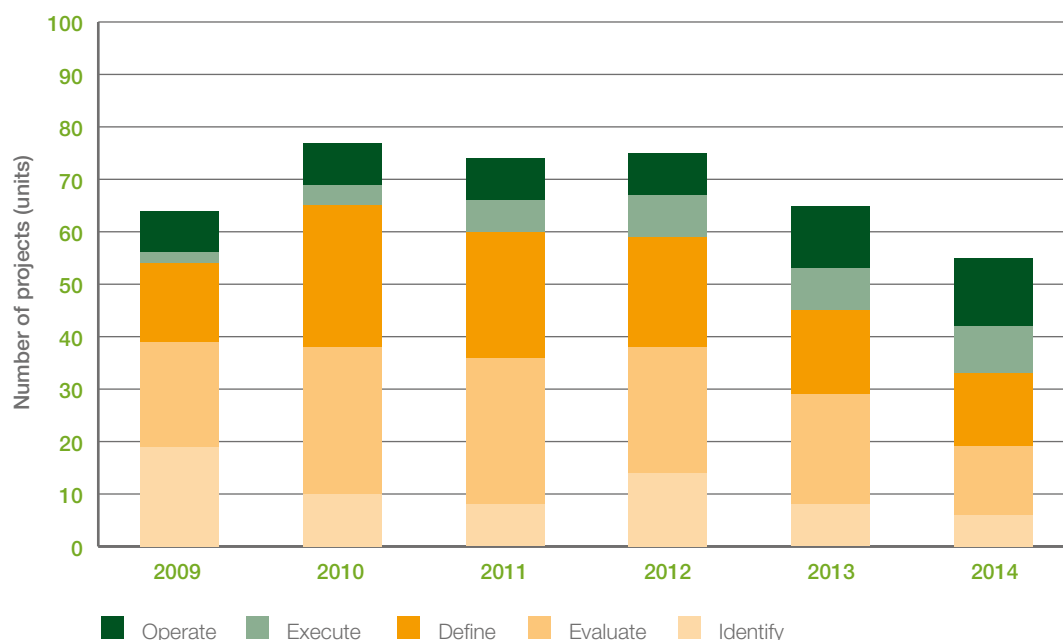
The number of existing applications is broadly in line with an early forecast by the IEA (IEA, 2009), which envisaged 18 projects would be up and running by 2015. However, the real challenge is in the medium and long term.

To limit the rise in global average temperature to 2°C, the IEA initially envisaged that about 100 projects, across the power and industrial sectors, should be operating by 2020 worldwide (with 14 in Europe), and 3,400 by 2050 (with 320 in Europe) (IEA, 2009). But as the proposal of new projects is slowing and the pace of change is highly uncertain, the expectations have been already reduced to 30 projects by 2020 (IEA, 2013a).

Effectively, only nine large-scale CCS plants are under construction in North America, Australia and in the Middle East, of which two are power plants.<sup>15</sup> Another 33 projects were at various stages of planning at the end of 2014, but it is unclear how many of them will become operational and by when. Importantly, the pipeline of new projects has reduced: in the past five years the number of projects in the early 'evaluate' and 'identify' phases has halved, from almost 40 in 2009 to less than 20 in 2014 (see Figure 5).

<sup>15</sup> The Kemper County Energy Facility in Mississippi and the Petra Nova Carbon Capture Project in Texas.

**Figure 5. Number of CCS large-scale integrated projects by development phase, 2009-2014**



**Note:** Project development stages: 'Operate': In operation; 'Execute': Under construction; 'Define': Feasibility/ Front End Engineering Design (FEED Study); 'Evaluate': Pre-Feasibility Study; 'Identify': Concept Study. Note the number of operating projects is based on GCCSI data only. Four additional operating projects listed in MIT (2013) were not included to ensure consistency across years.

**Source:** Based on GCCSI (2014a; 2014b)

In Europe, two industrial installations are operating in Norway<sup>16</sup>, while none are operating in the 28 European Union Member States, although some are in the pipeline.

Two projects are at an advanced planning stage: the White Rose oxy-combustion coal and biomass power plant and the Peterhead gas-fired combined cycle gas turbine (CCGT) plant, both in the UK. The projects are currently carrying out Front End Engineering Design (FEED) studies and by 2016 are expected to decide whether to move ahead to a final investment decision. If they do, Peterhead could become operational in 2018 or 2019, while White Rose may not become fully operational until 2023.

A further two CCS power plants, Don Valley in the UK and ROAD in the Netherlands, have completed FEED studies, but their future is currently uncertain. In the UK, another two projects, C. GEN North Killingholme Power Project and the Caledonia Clean Energy Project, are under evaluation. A few more projects have been initiated by other Member States (such as Germany, Italy, Poland and Spain), but have been either cancelled or put on hold, mostly for financial reasons or public opposition associated with environmental and safety concerns.

While more projects are needed to prove the feasibility of CCS at large scale, several challenges are hampering investment. These are the subject of the following chapters.

16 The Sleipner CO<sub>2</sub> Storage Project and the Snøhvit CO<sub>2</sub> Storage Project (GCCSI, 2014b).

### Box 1 The Boundary Dam project in Canada

The Boundary Dam CCS project in Canada is the world's first large-scale CCS application to a power plant (Saskpower, 2014). The CCS-fitted unit was commissioned in October 2014, and is expected to operate for approximately 35 years. It has a net capacity of 110 MW, delivering around 820 GWh of electricity per year (assuming an 85 per cent availability factor<sup>17</sup>).

The project captures 90 per cent of the emissions after coal combustion, equivalent to approximately one million tonnes of carbon dioxide per year. Carbon dioxide is used for EOR in an onshore deep saline formation – the Weyburn Oil Unit - some 40 miles from the capture plant. CCS was retrofitted during the re-powering and renewal of one of the units of an existing coal station belonging to the publicly-owned energy utility SaskPower, in the Saskatchewan province.

17

17 The amount of time that a power plant is able to produce electricity over a certain period, divided by the amount of the time in the period.

## 3. Technology, infrastructure and storage challenges

This section focuses on the scientific, technological and engineering challenges faced by each part of the CCS chain; carbon dioxide capture (section 3.1), transport (section 3.2) and sequestration (section 3.3.) or utilisation (section 3.4). The key findings of this analysis are:

- While the individual elements involved in the capture, transport and storage of carbon dioxide are already in use and well understood, the integration and deployment of these technologies at commercial scale remains a major challenge.
- Transport infrastructures for carbon dioxide are complex and will require regulation in a similar way as electricity and gas networks. Public co-funding may be needed, especially to support the development of clusters and transport networks.
- Storage capacity is unevenly distributed across Member States. Conservative estimates suggest it could be greater than 122 GtCO<sub>2</sub> across the European Union, of which 83 GtCO<sub>2</sub> would be offshore (Arup, 2010). This is equivalent to the amount of carbon dioxide produced in 60 years by today's fleet of fossil fuel power plants across the European Union.
- Using captured carbon dioxide for enhanced oil recovery (EOR) can make the economics of CCS look more attractive. However, the potential for EOR and carbon dioxide utilisation in the European Union is limited, at least in the short-medium term.

### 3.1 Carbon dioxide capture

Capture is the first and most expensive element in the CCS chain. For power plants, the capture step involves separating carbon dioxide from a flue gas stream that includes nitrogen, water vapour and minor impurities. The near pure carbon dioxide is then compressed to high pressure (around 10 megapascal, MPa) for transport to a storage site where it is injected into geological formations, either onshore or offshore.

The capture process imposes a significant energy penalty. In power plants, this results in an efficiency penalty of between 8 to 13 per cent,<sup>18</sup> that is approximately 15 to 30 per cent less power output, depending on the type of plant and capture technology applied. For instance, prior to initiation of operations, the energy penalty estimated for the Canadian Boundary Dam project, the first operational large-scale power plant application, was around 21 per cent (Daverne, 2013), although early operational data suggest that the actual penalty may be lower, at around 13 to 14 per cent (SaskPower, 2015b).<sup>19</sup>

Two capture technologies appear particularly promising for near term deployment in the European Union: oxy-combustion and post-combustion capture. A third option, pre-combustion capture, is less likely to be adopted in the short term, due to high capital cost and plant complexity. See Box 2 for a short description of these technologies.

<sup>18</sup> Of this, about 60 per cent of the penalty is attributed to solvent regeneration, 30 per cent to compression and 10 per cent to mechanical operations (such as solvent pumping and gas blowing).

<sup>19</sup> The CCS-enabled power plant was expected to supply about 110 megawatts (MW) of electricity to the grid compared with 139 MW before retrofitting (Daverne, 2013), while actual figures following the launch of Boundary Dam show a power generation output of 120 MW (SaskPower, 2015a).

#### Box 2 Near-term carbon dioxide capture technologies

**Post-combustion** capture involves the use of a solvent, solid sorbent, or membrane-based capture medium, which separates the carbon dioxide from the exhaust gas produced by a power plant. Solvents are currently the most widely used capture medium. The captured carbon dioxide is recovered by heating the solvent. The solvent is then recycled and the recovered nearly pure carbon dioxide stream (>99 per cent purity) is made ready for transport. Alkanolamine gas scrubbing, the most mature solvent-based capture process, was first patented in the 1930s and has since been widely used at large scale, especially for natural gas purification (Rochelle, 2009).

**Oxy-combustion** involves the combustion of fossil fuels in a high oxygen concentration environment, instead of air. This produces an exhaust gas consisting of water vapour and carbon dioxide. After condensation of the water vapour, a high (>90 – 95 per cent) purity carbon dioxide stream is left, which is subsequently compressed and made ready for transport. Cryogenic air separation, used for oxygen production, was first developed in 1902 and is a mature technology.

**Pre-combustion** involves the gasification of coal to produce a mixture known as synthetic gas or 'syngas'. This consists mainly of carbon monoxide, hydrogen and carbon dioxide. A series of reactions, known as water-gas shift, converts these gases to a mixture of carbon dioxide and hydrogen. After separation, the carbon dioxide is made ready for transport, while the hydrogen-rich fuel gas can be used to fire a gas turbine or run a fuel cell.

While both post-combustion and oxy-combustion are mature technologies and already used in some industrial applications, their deployment in the context of power generation and in other industrial sectors significantly increases already high capital and operating costs (see section 4).

At present, research efforts are particularly aimed at reducing the energy cost of these capture technologies via the development of new solvent or sorbent materials and new approaches for the separation of air (Boot-Handford et al., 2014).

Another approach in need of further development and testing is bioenergy with CCS (BECCS). In a BECCS power plant biomass is combusted, either as a single source (in dedicated biomass plants) or in combination with coal (in co-firing plants). The resulting carbon dioxide is then captured using the same technologies described in Box 2. By capturing atmospheric carbon dioxide temporarily locked in plants and storing it permanently in geological formations, BECCS has the potential to generate carbon negative electricity (McGlashan et al., 2012). However, the amount of emissions avoided would depend on the sustainability of the biomass sources, and on the associated land-use changes (IEA, 2011a).

BECCS is more expensive than other CCS applications, both in terms of fuel and efficiency penalties imposed upon the power plant. However, it could avoid implementing some of the most costly mitigation measures in hard-to-reach sectors, such as transport (Rhodes and Keith, 2008). The IPCC (IPCC, 2014b) also stresses that the use of BECCS will likely be essential to prevent temperatures to increase beyond 2°C, especially if emissions exceed 450 ppm.

Its development is lagging behind gas and coal applications, although some progress is being achieved. Research on biomass oxyfuel firing is ongoing (Bhave, 2012), while Drax Power Station in the UK has converted two of its power units from coal to biomass, which could be amenable to be retrofitted with CCS (Drax, 2015).



Ultimately, the scale to which BECCS could be expanded will depend on its costs relative to other options, on the need for negative emissions, as well as on how society balances the multiple demands on water and land use for energy, food and carbon management, including through natural carbon sinks.

CCS development in some industrial sectors, such as iron and steel, cement, and some aspects of oil refining (among others), is also lagging behind, both in terms of our understanding of the technology options available, and the means by which CCS can be integrated within a given facility. This is because emitters in these sectors are heterogeneous and can be of smaller scale than power plants. Furthermore, industrial installations face specific challenges which are harder to address (see Box 3). CCS for these sectors may therefore need to be more bespoke, to take account of these disparities.

Finally, a key challenge for both power and non-power sectors is the interaction of the entire CCS system, from carbon dioxide capture to sequestration. This will require a combination of research activities and real-world deployment of commercial-scale plants to facilitate cost reduction through learning-by-doing.

#### **Box 3 Specific issues with the deployment of industrial applications**

Although industrial applications have been pioneered in carbon capture, especially in the US (see section 2.3), there has been a notable lack of progress in both technology and policy for industrial applications compared to the electricity sector (IEA, 2014b). Several factors, specific to the industrial sector, are hampering further development.

First, unlike the power sector, several manufacturing sectors are exposed to international trade. One important implication is that CCS costs cannot be passed easily on to customers, as this would affect their competitiveness, unless a border tariff was applied on the basis of embedded carbon dioxide.

Furthermore, the long-lived nature of manufacturing infrastructure and the slow turnover of stock mean that large-scale commercial deployment of CCS technology in the industrial sector could take several years over and above the power sector. A large number of cement and steel plants, for instance, usually only undergo major refurbishment in line with the lifetimes of key pieces of equipment, often around twenty years (IEA, 2014b).

It is also challenging to integrate CCS while also optimising manufacturing processes and meeting production specifications, especially when installations are part of supply chains that are already highly integrated and specialised.

In addition, current overcapacity in some sectors, such as steel, leads to low profit margins, leaving little capital available for long-term technology development. This, together with a lack of clear first-mover advantage, reduces firms' appetite for large investments in new CCS equipment.

### 3.2 Transport

Large-scale transport of captured carbon dioxide, both on- and off-shore, can be achieved through pressurised pipelines. This is a relatively safe operation, since the fossil fuel industry and energy system operators already have the experience required to transport gases (including carbon dioxide) at high pressures and maintaining high levels of purity. In addition, carbon dioxide transport has effectively been conducted at scale for enhanced oil recovery (EOR) at least since the 1970s. As of 2013, there are over 3,000 miles (5,000 km) of high-pressure pipelines which transport over 60 million tonnes of carbon dioxide per year globally.

But although transport technology is well understood and demonstrably safe, the large volumes of carbon dioxide that will need to be transported if CCS is to make a major contribution to climate change mitigation will make transport a particularly strategic and potentially challenging issue from a regulatory and planning perspective.

Careful planning will be required to develop a carbon dioxide transport network that connects the locations (actual or planned) of major power generation plants and industrial facilities emitting carbon dioxide.

As individual pipelines are developed for the initial handful of commercial demonstration programmes in different Member States, consideration needs to be given to network effects and the implications for future CCS capture sites. In most cases, overbuilding or oversizing – that is, investing in transport infrastructure capacity that exceeds current demand but anticipates a larger demand in the future – would make good economic sense. Notably, the clustering of early demonstration sites, for capture as well as for storage, could facilitate the development of the necessary infrastructure and skills, leading to improved operability and reduced costs.

For instance, in the UK, the Energy Technologies Institute (Gammer, 2014) estimates that linking and oversizing pipeline infrastructure around a cluster of users (energy generators and industrial installations) could reduce pipeline costs by 64 per cent. Similarly, a recent study for the UK Humber area (Benton, 2015) shows that a CCS industrial cluster, piggybacking on the infrastructure for the proposed White Rose CCS power plant, could cost two thirds less per tonne of carbon dioxide stored, compared to a power plant alone<sup>20</sup> (see also section 4.4 on costs reductions).

However, although more cost effective, building infrastructures beyond current demand requires introduces non-utilisation risks and potential asset stranding issues, and requires higher upfront investment. In the UK Humber area, for instance, costs could be up to four times higher (Benton, 2015). In the absence of adequate market signals, project developers may choose to undersize their infrastructure in order to lower the cost of their individual projects.

Liabilities in case of accidents or leakage also need to be considered. In the European Union, carbon dioxide transportation networks are likely to cross national borders (Morbee et al., 2010). This will require efficient regulation, design and co-ordination across Member States (see also section 6.3 on regulatory issues).

Overall, the planning and construction infrastructures for carbon dioxide, either for individual projects or for clusters, will require regulation in a similar way as electricity and gas networks. It will also likely face the same challenges, such as cost recovery processes and price controls. Public co-funding may be needed to support the development of clusters.

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<sup>20</sup> Costs could be reduced from £250/tCO<sub>2</sub> for the White Rose power plant alone, to around £90/tCO<sub>2</sub> if the White Rose plant was to become part of a broader industrial cluster in the Humber area.

### 3.3 Carbon dioxide sequestration

Captured carbon dioxide can be injected into depleted oil and gas reservoirs, coalbeds or deep saline aquifers. These consist of deep (around 1 km or more) permeable rock formations, which typically contain either oil and gas or salty water that can be displaced to store carbon dioxide.

Carbon dioxide injection into oil and gas reservoirs already takes place on a large scale in several operating CCS projects. Currently around 28 million tonnes of carbon dioxide are stored in geological formations every year, of which 25 are used for enhanced oil recovery (EOR) (GCCSI, 2014b; MIT, 2013). But if CCS is proven to be economically viable, it will need to store several thousand times more carbon dioxide than is captured by current and planned projects, if it is to have a significant impact on emissions (Blunt, 2010).

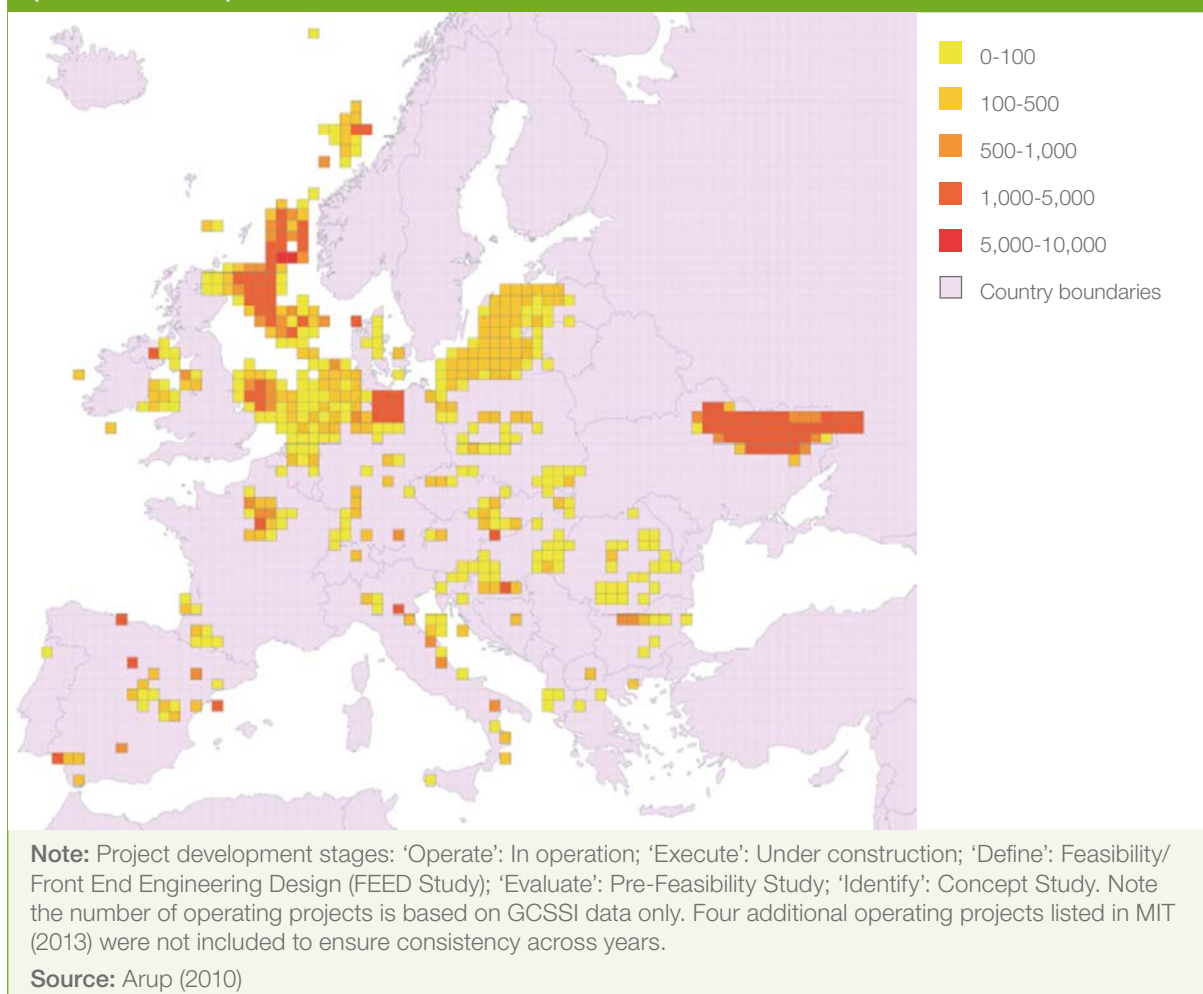
In the European Union, the location and capacity of carbon dioxide storage is becoming increasingly more defined, although further site-specific characterisation is needed (GCCSI, 2014c). Conservative estimates suggest that storage potential could be greater than 122 GtCO<sub>2</sub>, of which about 83 Gt is offshore beneath the Scottish, English and Norwegian North Sea and the Baltic Sea (Arup, 2010).<sup>21</sup> With the European Union's existing fleet of coal power stations emitting roughly 2 Gt CO<sub>2</sub> per year, this would be equivalent to more than 60 years of emissions at current levels (see section 2.2).<sup>22</sup>

However, there is a great variation in storage capacity across the European Union. Some Member States, such as the UK, Spain and France, appear to have abundant storage suitable for their domestic needs beyond 2060. Other countries, such as Poland, the Czech Republic and to some extent Germany, have limited domestic storage, most of which is onshore (Arup, 2010) and therefore more likely to encounter public opposition. Onshore storage has indeed proved contentious in Germany. The map in Figure 6 shows that the storage sites are rarely contained entirely within national borders. Thus, should CCS be developed at large scale, some countries may require storage outside their political boundaries (Arup, 2010).

21 Arup (2010) derived auditable conservative estimates based on publicly available storage estimates calculated under the EU-funded GeoCapacity project (GEUS, 2008).

22 Assuming these operate with a 85 per cent availability, and their emission intensity is 800g CO<sub>2</sub>/kWh for coal-fired plants and 500g CO<sub>2</sub>/kWh for gas-fired plants.

**Figure 6. Potential Carbon dioxide storage sites and volumes in the European Union (million tonnes)**



A key challenge for carbon dioxide sequestration will be to handle potentially large volumes of carbon dioxide and prevent any significant leaks. The oil and gas industry is generally experienced at dealing with such difficulties, with a long track record of combining different well placement, orientation and injection designs, and adjusting for local conditions, which should allow storage projects to overcome technological challenges. Careful site characterisation will nevertheless be essential to ensure that appropriate sealing layers of impermeable rocks prevent the upward migration of carbon dioxide. Once within the rock, the great depth of injection combined with the typically low flow rates of carbon dioxide in porous rock would prevent fast, dangerous releases of the carbon dioxide to the surface.

Storage security also improves with time. While it may take over hundreds of years or more for the high pressure near injection wells to equilibrate, the maximum pressure in the formation will gradually diffuse out. Furthermore, a number of storage mechanisms, described in Box 4, can render the carbon dioxide less mobile over timescales of decades to hundreds of years.

While leakage risks can be minimised using well established techniques from the oil and gas industries, monitoring of the behaviour of the carbon dioxide underground and the integrity of the storage site will be a crucial on-going activity. A recent study (Blackford et al., 2014) examined the issues surrounding the detection and impact of any potential leakage from undersea carbon dioxide storage. It concluded that biological effects from a small short-term leak would be detectable, but limited, and that recovery would be measurable in days to weeks. However, impacts are likely to increase step-wise if a greater quantity of carbon dioxide is emitted. Overall, the study concludes that monitoring carbon dioxide can be complex but tractable.

#### Box 4 Carbon dioxide trapping mechanisms

**Trapping by low permeability cap rocks** prevents the upward movement of carbon dioxide. Similar traps have held oil and gas underground for millions of years. In well-characterised formations, this is a good way to ensure storage.

**Dissolution:** Over hundreds to thousands of years, the carbon dioxide will dissolve in the formation brine, at rates determined by site-specific factors, forming a denser phase that will sink. The increase in density may induce some downward flow within the reservoir over long periods of time, subject to reservoir properties.

**Reaction:** The carbon dioxide dissolved in brine may react over thousands to millions of years with the host rock, precipitating solid carbonate. The opposite can also occur, in that the acidic brine dissolves part of the rock, increasing the volume of the pore space and the permeability. The speed, extent and nature of these reactions depend principally on the mineralogy of the rock and the local volume flux of injected carbon dioxide.

**Capillary trapping:** Dissolution and precipitation both render the carbon dioxide less mobile over time, but are slow processes. Capillary trapping is more rapid and occurs when the carbon dioxide migrates through the aquifer, leaving behind bubbles of the carbon dioxide trapped in the pore space. This process is well established in the oil industry.

Source: Blunt (2010)

### 3.4 Enhanced Oil Recovery (EOR) and carbon dioxide utilisation

Carbon dioxide utilisation is a way of using captured carbon dioxide to produce commercially marketable products. Recently this has generated significant attention, although it is not a new area of enquiry. Rather, there has been active interest in the chemical conversion of carbon dioxide into petrochemicals, plastics and other materials and fuels since the 1850s.<sup>23</sup>

Perhaps the most well known form of carbon dioxide utilisation, enhanced oil recovery (EOR) is often touted as the most promising option for a near term, large-scale carbon dioxide utilisation. This can be controversial in terms of emission reductions, since for each tonne of carbon dioxide injected, the associated oil extracted through EOR is likely to emit more than 1 tonne of carbon dioxide once consumed (Aycaguer et al, 2001). However, EOR of conventional crude oil can prevent the exploitation of dirtier intensive oils, such as tar sands.<sup>24</sup> Looked at in this way, 1 tonne of carbon dioxide utilised for EOR could lead to more than 1 tonne of carbon dioxide avoided.

<sup>23</sup> With the synthesis of salicylic acid, the Solvay process, and urea discovered in 1869, 1882 and 1922 respectively.

<sup>24</sup> Average greenhouse gas emissions for oil sands extraction and upgrading are estimated to be 3.2 to 4.5 times as intensive per barrel as for conventional crude oil produced in Canada or the US (Pembina Institute, 2015).

To date, 11 CCS projects use EOR, mostly in North America (GCCSI, 2014b; MIT, 2013), generating revenues that offset some of the costs of capture and storage, and helping to build a stronger economic business case for CCS projects.

But while EOR using anthropogenic (and also natural) carbon dioxide has been relatively successful in the US, this experience may not be directly transferrable to the European Union.

There are several mature oil and gas fields in Europe, where EOR could be applied (EASAC, 2013). However, overall OECD-Europe has modest EOR capacity. Estimates suggest this would be of approximately 2.4 – 4.7 GtCO<sub>2</sub><sup>25</sup> (IEA GHG R&D Programme, 2009). In addition, EOR potential would be mostly offshore (especially in the North Sea), making the process substantially more complicated and expensive than current examples in North America.

Furthermore, some oil fields in the North Sea are due to close within the next few years and may be sealed as part of the standard decommissioning process, which may reduce their utility for subsequent carbon dioxide storage (CCSA, 2011). There is therefore a quite narrow window of opportunity for EOR in these fields.

EOR activities are also sensitive to oil prices. For an oil price of \$100 per barrel (bbl), break-even prices for carbon dioxide in EOR projects in the US were on the order of \$45/tonne of carbon dioxide (Godec, 2011). With oil prices below \$50/bbl in early 2015 (Nasdaq, 2015), the price of carbon dioxide used for EOR would have to decrease to keep extraction profitable. This would in turn affect the business case of a CCS installation (see section 5.4 on the impact of carbon prices on profitability).

Other forms of carbon dioxide utilisation are still under investigation. These include: the use of flue gases for the cultivation of algae (used, for example, as biofuels); carbon dioxide carbonation for the production of plastics, petrochemicals (such as methanol or formic acid) or construction material via the remediation of waste; and, the storage of carbon as biochar.

Some applications, like the conversion of carbon dioxide into petrochemicals, requires a significant amount of energy, is exceptionally costly and, as of today, uncompetitive with conventional approaches. The conversion of carbon dioxide to polycarbonate polyols or building materials, on the other hand, has more potential to become competitive and achieve some market penetration.

The global demand for carbon dioxide, however, is currently small – around 200 MtCO<sub>2</sub>/year (Mac Dowell, forthcoming) compared to the amount CCS installations could supply, if developed at scale (around 2,000 Mt CO<sub>2</sub>/year by 2030, and over 7,000 MtCO<sub>2</sub>/year by 2050 globally, according to IEA, 2013a). Furthermore, some forms of carbon dioxide utilisation may not lead to long-term sequestration of carbon dioxide. For example, the carbon dioxide used to produce urea-based fertilizer will be released once applied to a field.

Overall, carbon dioxide utilisation in Europe can have interesting applications, especially in those Member States where storage opportunities may be limited. However, the potential for utilisation should not be overstated, in particular in the short term. EOR and, to some extent, carbon dioxide utilisation as a building material, could provide a first-mover incentive to the industry, but their potential in the European Union appears limited; while carbon dioxide conversion to petrochemicals seems unlikely to make a meaningful contribution to global carbon dioxide mitigation (see also section 5.4 on revenues potential).

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25 Based on two oil basins: the Carpathian-Balkian Basin, located across Ukraine, Moldova, Bulgaria, Turkey and Serbia; and the North Sea Graben, in Norway and the UK.



## 4. Cost related challenges

This chapter outlines a range of cost estimates from selected literature sources, following three approaches: the levelised cost of electricity (LCOE), the cost of avoided carbon, and capital and infrastructure costs. An overview of estimates for CCS and, for comparison, other low carbon technologies (although at different stages of maturity) is shown in Table 2 below and described in more detail in sections 4.1 – 4.3. Section 4.4 outlines the change in CCS costs over time. The key findings of this analysis are:

- CCS significantly increases capital, operating and maintenance costs of coal- and gas-fired electricity generation and industrial production processes.
- Cost reductions can be achieved in some specific areas of CCS projects, such as transport and finance. Available estimates suggest overall costs could decrease by 15 and 40 per cent by 2030.
- Limited publically available and reliable data mean cost analysis is still largely theoretical for large-scale projects and costs will continue to be difficult to evaluate with accuracy until more CCS units are demonstrated. Public and private funding will be needed to accelerate cost discoveries.

**Table 2 Cost of CCS vs. other technologies: various approaches (€ 2013)**

		LCOE	Avoided carbon	Capital cost
		(€/MWh)	(€/tCO <sub>2</sub> )	€/kW
Power sector	CCS coal	83-209 (115)	35-91	2,700-4,500 (3,200)
	CCS gas	69-179 (102)	65-125	1,300-2,000 (1,600)
	Unabated coal	49-87 (68)	n/a	1,600-2,100 (1,900)
	Unabated gas	46-83 (68)	n/a	600-900 (700)
	Nuclear	>80	-6;12	3500
	Onshore wind	68	-5;8	1700
	Offshore wind	138	65-127	3600
Industrial sector	CCS Fertiliser	n/a	7-15	n/a
	CCS Gas processing	n/a	12-16	n/a
	CCS pulp & paper	n/a	37	n/a
	CCS Steel	n/a	47-51	n/a
	CCS oil refineries	n/a	38-58	n/a
	CCS Cement	n/a	26-182	n/a

**Note:** n/a = not available; ( ) = average in case of multiple data sources. The cost of avoided carbon is calculated as the additional cost in comparison to equivalent unabated technologies; for the power sector, the reference plant for all technologies is a supercritical pulverised coal plant.

**Sources:** CCS-related costs based on CCS CRT (2013); Léandri et al. (2011); NETL (2013); WorleyParsons (2011); IEA (2011b); IPCC (2014a); GCCSI (2011b; 2012); ZEP (2011); and Leeson et al. (2014). Nuclear, onshore wind and offshore wind costs based on IPCC (2014a).



### 4.1 Levelised cost of electricity (LCOE)

A common approach used to assess and compare the cost of the electricity from different sources is the levelised cost of electricity (LCOE). This is the cost per unit of electricity averaged over the lifetime of a project. It incorporates all the costs incurred during the lifetime of a power station, such as capital costs (CAPEX), operation and maintenance costs (OPEX), and decommissioning costs. This can be expressed in terms of Euros per megawatt-hour (€/MWh) of electricity produced.

Considered here are the most recent analyses of first generation (first-of-a-kind) CCS projects published from 2010, which are listed in Figure 7. Different studies use different methodologies and techno-economic assumptions, for example on plant lifetimes, capacity factors, fuel prices and cost of capital (on the latter, see section 5.2), which makes them difficult to compare. All of them, though, envisage a capture rate between 85 to 90 per cent. This means that, for existing coal-fired power plants emitting an average of 1000g of CO<sub>2</sub>/kWh and gas-fired plants emitting 450g/kWh (based on IEA, 2014c),<sup>26</sup> CCS can capture respectively up to 900 and 400 gCO<sub>2</sub>/kWh.

Most studies estimate that endowing a conventional gas power plant with carbon capture, transport and storage equipment would raise the cost by between 30-50 per cent. Analysis by the UK CCS Cost Reduction Taskforce (CCS CRT, 2013) suggests this could be much higher, at almost 120 per cent, which is largely explained by their assumption that the economic life of first-of-a-kind projects would only be 15 years. This is much shorter than assumptions made by other models, which are generally between 25 and 40 years. This once more points to the difficulty of comparing estimates (see also Box 5 below on the sensitivity of LCOE to a project's lifetime).

Overall, the studies reviewed point to LCOEs for CCS combined cycle gas turbines (CCGT) plants in the range of €70 to €180 per MWh generated (in 2013), with an average of €100/MWh.

Estimates for coal plants are differentiated by the employed CCS technology: post-combustion, oxy-combustion, or pre-combustion – the latter applying to integrated gasification combined cycle (IGCC) plants. The differences in cost among them are relatively small, therefore it is as yet difficult to identify a single technology with a clear cost advantage (GCCSI, 2011c).

Most studies indicate CCS would raise the costs of coal-fired plants by 40 to 80 per cent. Higher estimates carried out by the UK CCS Cost Reduction Taskforce (CCS CRT, 2013) and the Zero Emission Platform (ZEP, 2011) suggest CCS could more than double the cost of a conventional plant, although again these depend largely on the assumptions made on plants' economic life, technology maturity, and project developer circumstances.

Overall, the LCOEs of CCS coal-fired plants in the literature reviewed range from about €80 to €210 per MWh generated (in 2013), with an average of €115/MWh.

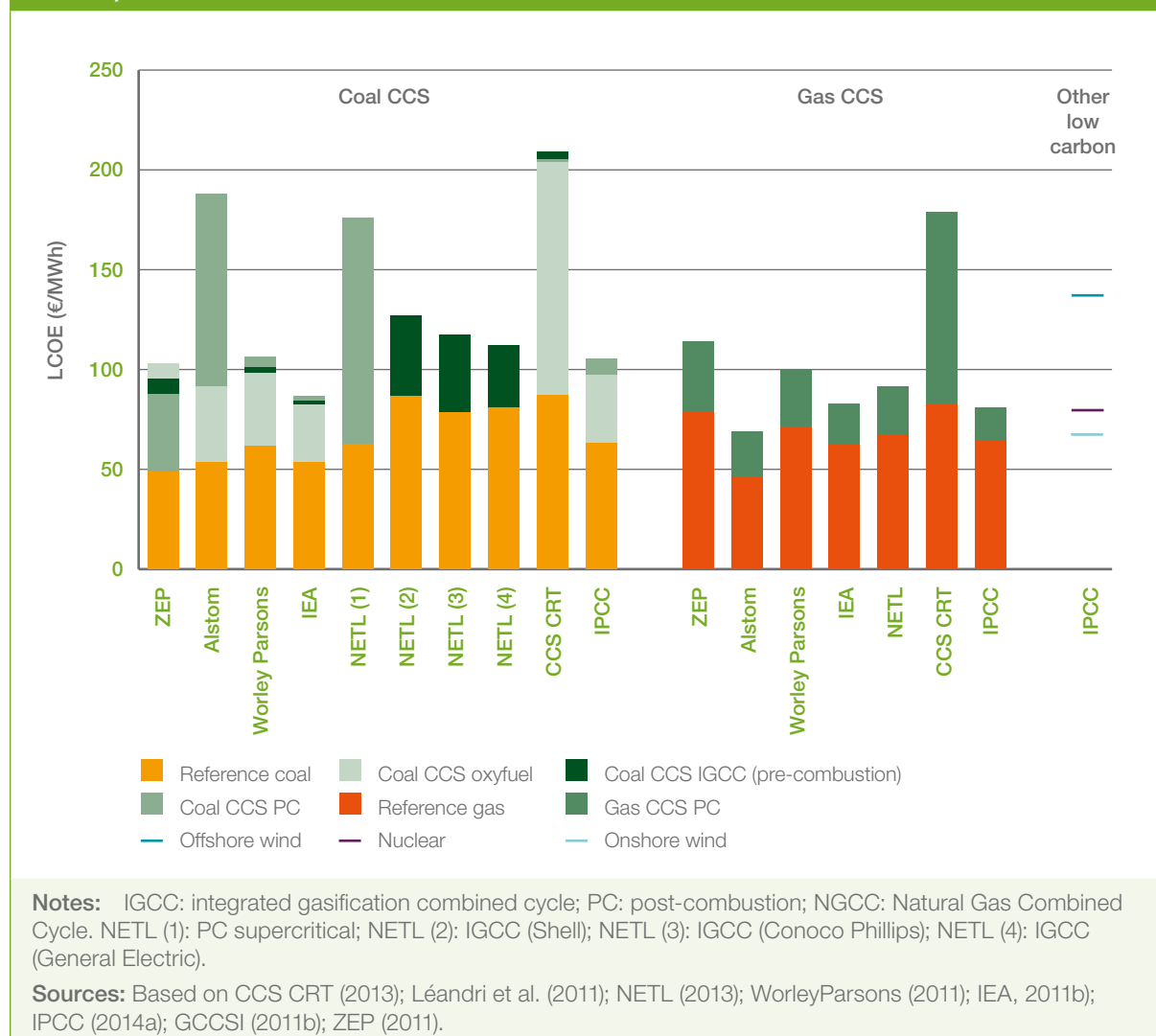
Because carbon dioxide emissions from coal plants are generally almost twice as high as those from gas plants per unit of electricity produced, the contribution of CCS equipment to the LCOE tend to be higher for coal-fired than for gas-fired ones (Léandri et al., 2011).

Total LCOE costs are shown in Figure 7. For comparison we have included the estimated levelised costs of some other low-carbon technologies (lines on right of graph), based on data from the IPCC (IPCC, 2014a). These suggest that levelised costs are generally higher for CCS than for onshore wind and nuclear power, but can be lower or of the same order of magnitude as offshore wind.

<sup>26</sup> Average carbon intensities are obtained by comparing carbon dioxide emissions from coal-fired and gas-fired power plants (987Mt and 303Mt, respectively) to the amount of power generated by those plants (994 TWh and TWh 682) in OECD Europe in 2012, according to the World Energy Outlook 2014 (IEA, 2014c).

It is worth stressing, however, that LCOE comparisons across different technologies do not give a complete picture, especially when comparing technologies which are at different stages of maturity (which means their relative cost may change significantly over time) and/or operates in different modes (for example, if they operates all the time or only for short periods of peak demand). Overall, LCOE has several major limitations, which are briefly discussed in Box 5, and should be taken with caution when comparing investment alternatives.

**Figure 7. Levelised costs of CCS in first-of-a-kind projects, various sources (2013 values)**



For both coal and gas power plants, the most significant cost component is the capture phase. This represents about 75 per cent of the additional LCOE cost imposed by CCS (ZEP, 2011).

The costs for transport and storage are relatively small compared to the capture phase. However, the range of estimates is broad, depending on geological setting and locations. Notably, for transport, costs increase with the volume transported and the distance of the plants to the storage facilities. For storage, costs are higher for offshore than for onshore locations, and higher for saline aquifers than for depleted oil and gas fields (ZEP, 2011).

In the studies reviewed, transport costs range from €1 to 28 /MWh (around €10/MWh on average), and storage costs from €4 to 32/MWh (around €12/MWh on average). The highest estimates are again by the UK CCS Cost Reduction Task Force (CCS CRT, 2013), which are based on offshore storage.

### Box 5 The limitations of LCOE estimates

The LCOE is useful for comparing the costs of generating energy from different energy sources; however, it is not without its limitations, and is most accurate only when comparing 'like with like', such as technologies sharing similar assumptions on their capital and operational characteristics or their technological maturity. Since this is rarely the case, LCOE comparisons can be inaccurate.

LCOE also fails to account for a range of factors which may affect the relative value of fossil and different renewable energy sources. These include: commercial factors, such as environmental legislation (which may act in favour of certain technologies); current and future fossil fuel prices; system factors, such as transmission costs, balancing costs and capacity factors (which may depend, for example, on location, age of assets, etc.); and, economic externalities, such as health damages associated to air pollution from burning fossil fuels (Gross et al., 2013).

An important limitation to LCOE methodology is that it assumes power sources generate electricity consistently and smoothly. This is not the case, as technologies have different degrees of flexibility to meet demand. This means some may not be always available, especially at peak demand times, when electricity prices are theoretically highest.

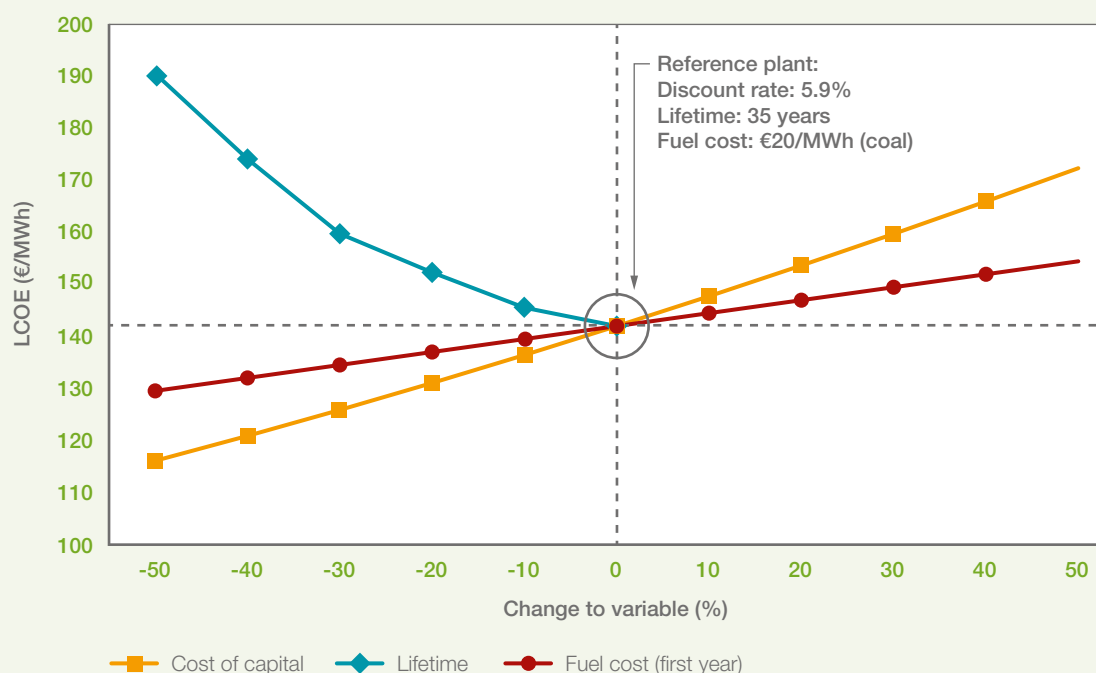
Notably, fossil fuel power plants are relatively flexible, although CCS may partially reduce this flexibility. Nuclear power plants, on the other hand, provide nearly constant supply and they are inflexible to rapidly change their electrical output. Electricity from some renewables resources, like solar and wind, is variable and less able to respond to demand because it depends on factors outside the control of suppliers like the wind blowing or the sun shining.

LCOE therefore fails to account for the ability of taking advantage of high prices, which in turn affects their capability to recoup costs. Some argue that this means the economics of inflexible or variable low carbon sources may look more appealing than they are in practice (see, for example, Joskow, 2011).

Indeed, our cash-flow model of a CCS project, based on the Boundary Dam project in Canada (see section 5.2), reveals that the modelled LCOE is very sensitive to the assumptions used. Figure 8 highlights how the LCOE is affected when three inputs are changed: project lifetime (blue line), the cost of financing the asset (cost of capital, red line), and, fuel cost (green line). For instance, starting from a reference project with a LCOE of €140, a reduction of its economic lifetime from 35 years to 25 years (a 30 per cent reduction) will increase the LCOE by over 10 per cent. An increase of the assumed cost of capital from 5.9 per cent to 8.9 per cent (a 50 per cent increase) would raise the LCOE to €170/MWh (a 20 per cent increase).

As the LCOE is not able to account for the dynamic nature of electricity pricing (nor for unplanned outages from any energy generation source), and is highly sensible to the assumptions behind each technology assessed, it should be used carefully.

Figure 8. Sensitivity of LCOE to cost of capital, lifetime and fuel cost assumptions



Sources: Authors

## 4.2 Cost of avoided carbon

Although the LCOE is an important element of investment decisions, it is only suitable for power generation plants and cannot be used to assess the cost of CCS industrial applications. Both electricity and industrial CCS applications, however, can be assessed by how cost effectively they reduce carbon dioxide, which can be measured in terms of € per tonne of carbon dioxide avoided. This involves estimating the difference in cost between the output of an unabated installation (for example, electricity from a coal-fired power station or steel from a reference plant) that would emit one tonne of carbon dioxide<sup>27</sup> and the equivalent output produced by CCS installations and other low-carbon technologies, such as renewable energy sources or nuclear power plants.

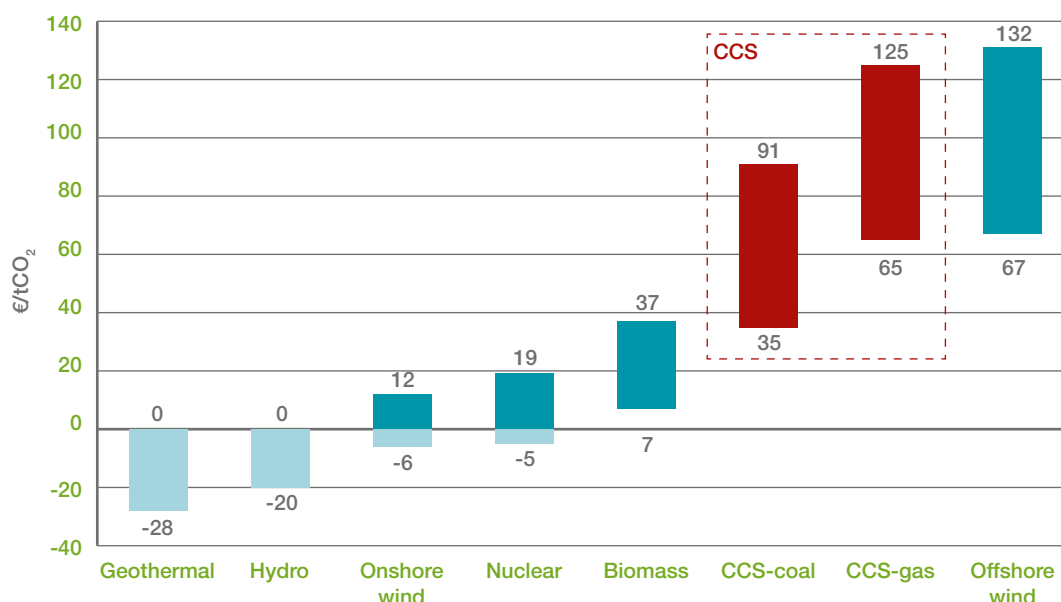
For power plants, only a few of the sources reviewed in section 4.1 report data on avoided carbon costs (IEA, 2011b; Léandri et al., 2011; NETL, 2013; WorleyParsons, 2011; ZEP, 2011). Estimates for coal-fired CCS power plants range between €35 and €91/tCO<sub>2</sub> (in 2013 terms), while for gas-fired CCS figures are between €65 and €125/tCO<sub>2</sub>.

It is worth noting that, when measured in terms of cost per tonne of carbon dioxide avoided, CCS coal-fired plants are cheaper than gas-fired versions, which is contrary to using LCOEs (as seen in section 4.1). As discussed above, this is because coal-fired plants emit almost twice as much carbon dioxide as gas-fired ones per unit of electricity produced, and thus by definition coal-CCS abates more carbon dioxide for each unit of electricity produced.

27 In the case of CCS power plants, the cost of carbon dioxide avoided is determined by combining the difference in the levelised costs with and without CCS, with the decrease in emissions in the reference case (Global CCS Institute (GCCSI), 2009).

Figure 9 compares the range of estimates for CCS found in the above mentioned literature with comparable values for other low carbon technologies,<sup>28</sup> based on the Global CCS Institute (GCCSI, 2011a). These estimates suggest that CCS is more expensive than some of the more mature low-carbon options, such as geothermal, hydro, onshore wind, nuclear and biomass, but can be competitive with technologies like offshore wind.

**Figure 9. Cost per tonne of carbon dioxide avoided (€2013)**



**Note:** For all technologies, except gas-fired CCS, the amount of carbon dioxide avoided is relative to the emissions of a supercritical pulverised coal plant. For gas-fired CCS, the reference plant is an unabated combined cycle plant.

**Source:** Based on GCCSI (2011a); IEA (2011b); Léandri et al. (2011); NETL (2013); WorleyParsons (2011); ZEP (2011).

Due to large differences in sector applications and uses, the cost of CCS applications to industrial installations has been less comprehensively investigated than CCS for power generation.

In some industrial processes, carbon dioxide can be captured at a reasonably high purity for low-unit cost. For instance, in natural gas processing and in ammonia and hydrogen production, carbon dioxide is produced as a part of normal operation, hence little additional expense is required to purify and compress it for storage or sale (IEA, 2014b). The increase in production costs associated with CCS can be as low as 1 per cent for natural gas processing and 3 per cent for fertiliser production (WorleyParsons, 2011).

According to the Global CCS Institute (GCCSI, 2012) the cost of applying CCS to liquefied natural gas (LNG) is around €7/tCO<sub>2</sub> (in 2013 values), €7-15/tCO<sub>2</sub> for fertiliser production, €12-16/tCO<sub>2</sub> for natural gas processing, and above €19/tCO<sub>2</sub> for coal-to-liquid processes.

For those sectors in which CCS applications are relatively cheap, especially when carbon dioxide capture is already part of the production process and/or it is highly concentrated in flue gases, investment in CCS can be more appealing than in the power generation sector. It is perhaps not surprising, therefore, that almost all the CCS projects currently operating are in this kind of industrial installations – as seen in section 2.3.

<sup>28</sup> For all low carbon technologies estimated by (Global CCS Institute (GCCSI), 2011a), the amount of carbon dioxide avoided is relative to the emissions of a supercritical pulverised coal plant.

However, low costs do not necessarily mean CCS always makes economic sense for an industrial installation, even for those with low unit costs. The need for transport links and access to a market for the captured carbon dioxide may still represent significant barriers, especially in the absence of enhanced oil recovery (EOR) opportunities or sufficiently high carbon prices.

Furthermore, in some industrial sectors the capture of carbon dioxide can be expensive, especially when plants include several small sources of emissions, some of which may be less amenable to capture than others. In these sectors the business case for CCS is currently very weak.

A recent review of the literature on the cost of industrial CCS (Leeson et al., 2014) indicates that average costs for the pulp and paper industry is about €37/tCO<sub>2</sub>,<sup>29</sup> for the iron and steel manufacturing €47-51/tCO<sub>2</sub>, for oil refineries €38-58/tCO<sub>2</sub>, and for the cement sector €26-82/tCO<sub>2</sub>, depending on the capture technology used.

In addition, unlike power stations, industrial sectors exposed to international trade face additional strains on costs due to competitiveness issues (see Box 3 in section 3.1).

### 4.3 Capital and infrastructure costs

In capital intensive infrastructure projects like CCS, the size of capital costs (or capital expenditures, CAPEX) can be a useful indicator to inform investment decisions. CAPEX typically covers the fixed costs of building a plant, such as property or equipment, while it does not include operational expenditures (OPEX) for operating and running, such as fuel costs and administration. In the case of fossil fuel plants, it can be expressed in terms of € per kilowatt (kW) installed.

On its own, CAPEX is clearly an incomplete representation of the total cost of producing electricity (Gross et al., 2013). In the case of CCS power plants, it typically represents around 55 to 70 per cent of the total LCOE (see Figure 11).

CAPEX estimates for industrial installations are very broad, as these depend on the sector as well as on the design and technologies used in the production processes, which can vary substantially. Existing estimates therefore tend to focus on power generation plants, and these will therefore be the subject of this section.

According to the studies discussed in section 4.1 (see references in Figure 7), CAPEX for coal power stations range from €2,700 to €4,500 per kW installed, with an average of €3,200/kW across the studies.

In reality, the actual costs may be larger. The first large-scale coal-fired CCS power plant, the Boundary Dam project (see Box 1), was expected to cost around €850 million (CAD 1.24) and ended up costing €1 billion (CAD 1.45 billion). With a CCS-fitted unit of 139 MW (in gross output), this corresponds to around €7,100/kW, well above theoretical estimates. Part of the cost overrun was unrelated to CCS. For example, some costs were incurred as a result of asbestos removal from the existing power station. Nevertheless, a cost premium is to be expected when building a first-of-a-kind facility. Typically, unexpected delays or problems may occur during development, and are difficult to anticipate without previous experience at building similar projects. It may also be a case of appraisal optimism, a common trend across all sectors to underestimate costs during the early stages of developing a new or nascent technology (see section 4.4).

CAPEX estimates for gas-fired CCS power stations are significantly lower than for coal, ranging from €1,300/kW to €2,000/kW (€1,600/kW on average), although there is currently no operational application to benchmark this against.

29 Original values in (Leeson et al., 2014) are in 2013 US\$. The average exchange rate used is: \$1 = €0.7532.



By comparison, the same studies indicate that capital costs of unabated power plants are between €1,600 and €2,100/kW (€1,900/kW on average) for coal-fired power plants, and between €600 and 900/kW (€700/kW on average) for gas-fired ones.

These figures are of the same order of magnitude as CAPEX for other low carbon technologies, like onshore wind (€1,700/kW), nuclear (€3,500/kW) and offshore wind (€3,600/kW) (IPCC, 2014a).

CAPEX estimates can be used to get a sense of the size of the investment needed to develop CCS in the European Union, based on the capacity envisaged in the Energy Roadmap's reference scenario: 11 gigawatts (GW) by 2030, reaching 100 GW by 2050. Using the average estimates found in the literature above<sup>30</sup> capital cost could range between €18 billion and €35 billion by 2030, and 160-€320 billion by 2050, depending on the relative share of gas-fired and coal-fired plants (in 2013 terms). Costs would likely be lower, however, as projects move along the technology learning curve and increase in scale (see section 4.4).

The same calculation could be done using the actual capital costs from the Boundary Dam, which are far higher. In this case the estimated capital cost would be €82 billion for 2030 and €740 billion for 2050 (in 2013 terms). The latter could also be seen as the upper bound cost of retrofitting the whole 100 GW of old coal power stations in the European Union, i.e. the plants that are more than 35 years old in Figure 3 (section 2.2). It is important to stress, however, that this is likely to be a significant overestimate as the Boundary Dam's figures are based on the retrofit of a 35-year-old and relatively small plant (which is likely more expensive, per kW of capacity, than larger CCS plants, due to economies of scale) and because it is a first of a kind project with large potential for cost reductions.

These are clearly ballpark estimates, but they do highlight the vast amount of funding required. They will also likely change as Member States investigate in more detail their actual investment needs for CCS. So far, however, estimates of potential capital investments on CCS are only available for the UK. The Energy Technology Institute (ETI, 2015) recommends the UK should roll out around 10 GW of CCS capacity by 2030, requiring investment of €27 – €38 billion (£22 – £31 billion)<sup>31</sup> over the period.

As for the cost of infrastructure, only one study has looked at the overall investment needs for carbon dioxide transportation in the European Union (Arup, 2010), while no estimate is available on overall potential storage infrastructure costs.

The feasibility study carried out by Arup (2010) for the European Commission estimates that cumulative costs for transport infrastructure across the European Union could range between €2.1 and €7.6 billion by 2030, and €6.8 and €12.7 billion by 2050 if both onshore and offshore storage are viable. However, it is possible that only offshore storage may be feasible, especially in case of public opposition to onshore sites. In this case costs could be 40 to 65 per cent higher, reaching €3.4 - 11.2 billion by 2030, and €9.6 - 19.8 billion by 2050. This implies that raising awareness and gaining acceptance of onshore storage could be worth up to €7 billion by 2050 (Arup, 2010).

The European Commission (2012) envisaged that about €2.5 billion will be needed in the next decade for carbon dioxide network infrastructure. This is relatively low when compared with about €200 billion needed for electricity and gas infrastructures over the same period (European Commission, 2013a). It will be important for the European Commission to assess these figures against the scale of ambition for CCS development in the European Union, and to estimate infrastructure investment in the longer term, by 2030 and 2050.

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<sup>30</sup> €3,200/kW for coal-fired CCS power plants, €1,600 for gas-fired CCS power plants.

<sup>31</sup> Average 2014 exchange rate: £1= €1.24.



#### 4.4 The evolution of CCS costs

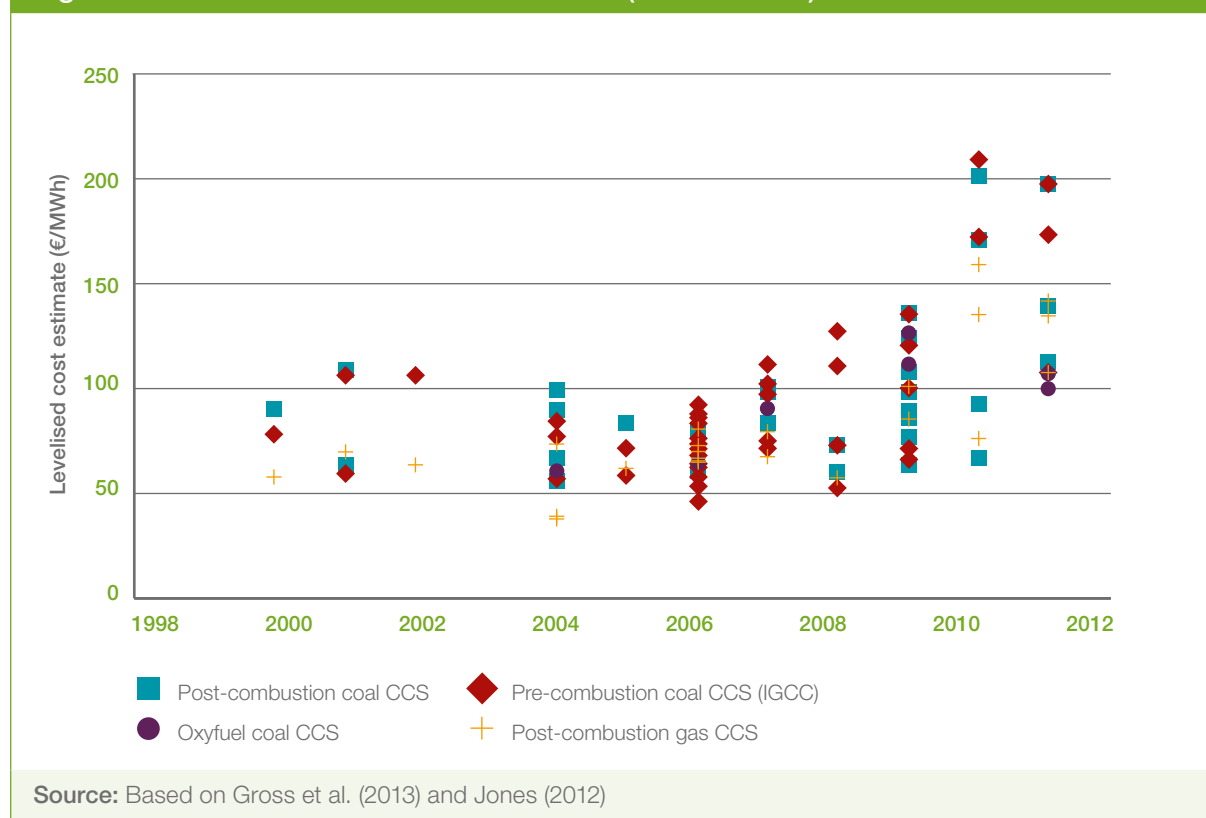
The LCOE, capital costs and costs of avoided carbon presented above are a snapshot of a particular point in time, based on first-of-a-kind projects. However, the nature of developing nascent technologies is that cost estimates will change over time and are expected to decrease in the future.

Costs are high in the early stages of technology development (largely given the small scale and short lifetime of pilot projects), and decrease with technological learning and as deployment raises experience. Cost reductions from learning, however, can be overwhelmed in the short-term by other factors, such as supply chain bottlenecks and rising material or labour costs, which may cause costs to rise temporarily. Notably, this was experienced by nuclear, combined cycle gas turbines (CCGT), offshore wind and onshore wind technologies across the 2000s (Gross et al., 2013).

This has also been the case for CCS. Some costs estimates (IEA, 2010b; NETL, 2013; WorleyParsons, 2011), for instance, have increased by 15 to 30 per cent in three years or more (GCCSI, 2011c). This upward trend is well captured by a UKERC study (Gross et al., 2013; Jones, 2012) which tracked around 50 studies on CCS costs across the world (see Figure 10).

Furthermore, CCS early-stage engineering assessment exhibited a not uncommon ‘appraisal optimism’, particularly in the form of oversimplified system design and risk underestimation. Again, this is not uncommon among new technologies. Notably, the first two examples of new-build nuclear in Europe are proving to be significantly over their anticipated budget.<sup>32</sup> This

Figure 10. CCS LCOE estimates since 2000 (€2013 values)



32 For instance, cost estimates for the Hinkley Point C, the first new generation nuclear plant to be approved in the UK, have increased from about €20 billion (€6,000/kW) in 2013 to €31 billion (€9,300/kW) in 2014, to include interest during construction and other additional costs (Financial Times, 2014).

was the case also for the CCS Boundary Dam project. Cost estimates typically improve as technologies become closer to realisation.

Looking ahead, a number of studies suggest that capital costs of CCS could decrease significantly in the next decades, for instance thanks to: larger project size, technological innovation, process integration, reduced construction times and the development of an efficient carbon transport and storage network (Al-Juaied and Whitmore, 2009; IEA, 2010c; Parsons Brinckerhoff, 2010).

The literature here reviewed suggests that, by 2030, CCS costs could decrease by 14-26 per cent (IEA, 2010b), 25-30 per cent (ECF, 2012) or even up to 40 per cent (LCICG, 2012) compared to current levels. Some studies (LCICG, 2012; CCR CRT, 2013) estimate that a 30 per cent cost reduction could be possible already in 2020.

The experience at the Boundary Dam project confirms that the potential for cost reductions is real and significant. SaskPower, the plant developer, estimates that, thanks to the knowledge gained in the course of the project, similar CCS power plants in the future could be 30 per cent cheaper (Watson, 2014).

Some phases of CCS projects are particularly promising in terms of cost reductions. The CCS Cost Reduction Taskforce (CCS CRT, 2013) suggests that half the estimated cost reduction by 2020 will be achievable through improved economies of scale and system efficiencies of transport and storage, such as oversizing transport and storage options (see section 3.2). The remaining cost improvements are expected through improved financing arrangements, such as longer-term financing or reduced cost of capital (see section 5), and through improvements to the engineering aspects of capture and reductions in the energy penalty (see section 3.1).

While future cost assessments appear encouraging, estimates should be taken with caution. In particular, cost may be higher if CCS power plants are used for part-load operation rather than for base load. This is because they may be increasingly needed as 'load-followers' to back up variable renewable sources – making up for gaps in supply, for example, when the wind does not blow (see section 2.2).

Using CCS as load-followers means CCS plants will experience lower utilisation rates, operating for between 40 and 60 per cent of the year, as opposed to 80 to 90 per cent if they were used for base-load generation. If this were the case, CCS plants would experience reduced energy sales, which will reduce profitability and raise the LCOE.

In the future, energy markets may have to take into account the overall system costs rather than focusing on the LCOE of individual installations, which do not account for the cost of the ancillary services required by some technologies, such as the need for additional balancing capacity for intermittent renewables. Until then, a higher LCOE would reduce the attractiveness of CCS power plants for investors, unless the ancillary balancing services they provide were adequately valued (for example through some form of 'capacity' market) or unless energy markets were re-designed to better account for close-to-real time forecasts of renewable energy generation (Neuhoff et al., 2011).

Overall, the large upfront investment in carbon capture equipment and on the transport and storage infrastructure required to implement the European Union Energy Roadmap appears unrealistic unless significant public and private funds are mobilised. The private sector will clearly have a role to play, but it will require clearer signals to invest. These would entail some initial support to research, development and deployment, coupled with the expectation of future (much) higher carbon prices, or the introduction of clearer targets and milestones.

## 5. Financial challenges

This chapter focuses on the key financial issues and challenges related to the lack of access to capital and to revenue uncertainty which characterise CCS projects. In particular, the chapter outlines typical sources of finance for early stage CCS projects (section 5.1) and discusses how risk plays a key role in influencing the cost of capital of these projects (section 5.2). It also highlights possible uncertainties in CCS revenue streams (section 5.3) and the sensitivity of returns to revenues, building on the example of the Boundary Dam CCS project (section 5.4). The key findings of this analysis are:

- Given the capital-intensive nature of CCS projects, investment costs are very sensitive to the delivered cost of capital.
- Perceived risks surrounding first-of-a-kind CCS projects impair access to suitable finance.
- First-of-a-kind projects may require investment by large utility developers with strong balance sheets and good access to cheaper sources of capital, and the operational experience to develop capital-intensive, complex projects. Public financing may also be necessary to alleviate other funding and risk constraints.
- The financial viability of CCS projects strongly relies on high carbon prices or other incentivising policies, such as price support mechanisms.

### 5.1 Sources of finance

Private financing sources from private actors – such as CCS project developers and energy utilities, technology providers, equity investors or commercial lenders – include equity, debt (external lending on a concessional or non-concessional basis<sup>33</sup>) and other types of participation, such as technology provision and ownership.

The high costs and associated risks of a technology that, like CCS, is not yet commercially viable tend to restrict potential sources of private finance.

Project developers need to have strong balance sheets, that is, access to large amounts of equity and/or the ability to raise additional debt, ensuring that financial resources are obtained at tolerable terms.

This is not to say that any large project developer, such as major energy utilities, will be able to invest in a technology like CCS. In the European Union, many of the world's largest utilities on asset value have suffered a severe weakening of their balance sheets in recent years because of the economic recession, and are badly constrained in what and, importantly, how much they can invest. A small number of fossil fuel companies may be in a better position to invest, thanks to stronger balance sheets. As upstream actors, they will also benefit from CCS deployment as it can extend the window of opportunity to use fossil fuels under climate change constraints.

Off-balance sheet financing structures are possible, but are unlikely to materialise at this early stage given the size of investment required, lack of experience with the technology and other associated risks.

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<sup>33</sup> A concessional or low-cost loan is one that is provided at terms (interest rates, repayment or drawdown options, or lending terms including tenor) that are better than those which can be found in the commercial capital markets.

Commercial banks are a key source of financing for many energy projects. However, many commercial banks may not be able to provide lending of the scale (likely over €1 billion for a medium-sized project) and duration (usually more than 12 years) required by CCS projects. An alternative would be to group or 'club' funding across several different banks. This is a well-established practice for large projects, but does bring with it administrative and organisational challenges, as each bank may have individual requirements and lending conditions.

Institutional investors, such as pension funds and insurance companies, could also be notable candidates for infrastructure investments like CCS. This could also be a potential hedge against unabated fossil-related assets in their portfolios. However, despite holding a vast amount of society's wealth<sup>34</sup> and being capable of lending large volumes of capital on long tenors, these institutions tend to invest in assets only when they are built and operating, in order to avoid construction and default risks, and in technologies in which they have existing expertise (Nelson and Pierpont, 2013).<sup>35</sup>

Finally, pilot and demonstration projects can be (co-) funded through public support, for instance in the form of capital grants, lending at concessional rates from state-owned financial institutions, or risk coverage commitments, such as government guarantees and insurance.<sup>36</sup>

Publicly funded support mechanisms may also be granted during the operation of CCS plants, such as feed-in tariffs with contract for difference for electricity generation. This type of public support can, in turn, help make the risk-return profile of CCS projects more attractive for institutional investors.

### 5.2 Influence of risk on the cost of capital

Different sources of finance come at a cost, which can have a significant impact on the overall profitability of a project. The cost of equity is the expected return for equity investors, while the cost of debt is the interest rate expected by lenders. The combination of these costs (sometimes adjusted for taxes) is averaged into the so called 'cost of capital'.

The cost of capital of a specific project is sensitive to the general investment climate, that is, factors such as interest rates, macro-economic and regulatory stability or conditions of financial markets (DECC, 2013a). Crucially, it is also affected by specific circumstances concerning the parties involved, such as the credit worthiness of project developers or the availability of finance from investors.

The perceived investment risk of a project is also critical. From the investor perspective, this risk can usually be translated into a cost, which in turn influences a project's cost of capital.

It is important to make a distinction between what we mean by risk in this sense. There are different risks inherent in developing new or nascent technologies. For instance, risks in the pre-construction and post-construction phases, such as construction risk or revenue risk respectively, differ greatly in concept, definition, and the tools or instruments to control them. Regardless, both sets of risks will need to be effectively dealt with or allocated and distributed to parties that are adequately prepared to manage them.

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34 Up to US\$ 80 trillion (Nelson and Pierpont, 2013).

35 There are exceptions: innovative risk sharing instruments can cover the risks in immature technologies to the extent that the investment is attractive to institutional investors (Boyd and Hervé-Mignucci, 2013; Hervé-Mignucci, 2012).

36 Strong policy support and financial incentives, such as feed-in tariffs and subsidies, can also be used to support early developing technologies, but they only indirectly improve access to finance by improving the project economics and lowering the cost of capital as discussed below. Policies to support CCS are discussed in more detail in Section 7.2.

In general, mature technologies with experienced developers are relatively low risk investments (or have adequate risk coverage) and so may enjoy lower costs of capital. On the other hand, new technologies, like CCS, tend to be beyond normal operations of project developers, or outside the experience of potential investors (Waissbein et al., 2013) and are generally perceived as riskier. Their cost of capital is typically higher than for mature technologies, as equity investors demand a higher return and/or lenders charge higher interest in order to cover for the additional risk.

Reducing the cost of capital is thus somewhat analogous to reducing the risk of investment from an investor perspective.

Information about the cost of capital for CCS is limited because the number of existing projects is small, particularly in the power sector (see section 2.3), and financial costs tend to be project-specific. Analysis carried out for the UK by the Climate Change Committee (Oxera, 2011) identified a range of discount rates used to calculate energy costs from various power generation technologies, where the discount rates reflect the cost of capital (see Table 3).

While the table is based on UK data and may reflect national conditions, it is apparent that CCS incurs a higher cost of capital than more mature technologies, reflecting higher perceived technical, regulatory, and financial risks. Oxera (2011) also make predictions of a possible evolution of the cost of capital to 2020, with an expectation that, for CCS, it will reduce by between 10 and 35 per cent from 2011.

**Table 3 Current cost of capital for selected technologies in the UK**

Category		Technology	Risk perception*	Costs of capital (2011)	Costs of capital (2020 projection)
Fossil fuels, unabated		Combined cycle gas turbines	Low	6-9%	6-9%
Low-carbon	Renewable energy sources	Hydropower (run of river)	Low	6-9%	6-9%
		Solar photovoltaic	Low	6-9%	6-9%
		Onshore wind	Low	7-10%	6-8%
		Biomass	Medium	9-13%	8-11%
		Wave (fixed)	Medium	10-14%	9-12%
		Offshore wind	Medium	10-14%	9-12%
		Tidal barrage	High	12-17%	11-15%
		Tidal stream	High	12-17%	11-15%
		Wave (floating)	High	13-18%	12-16%
	Nuclear	Nuclear (new build)	Medium	9-13%	8-11%
	CCS	Coal-fired CCS	High	12-17%	11-15%
		Gas-fired CCS	High	12-17%	11-15%

\*Note: see source for details.

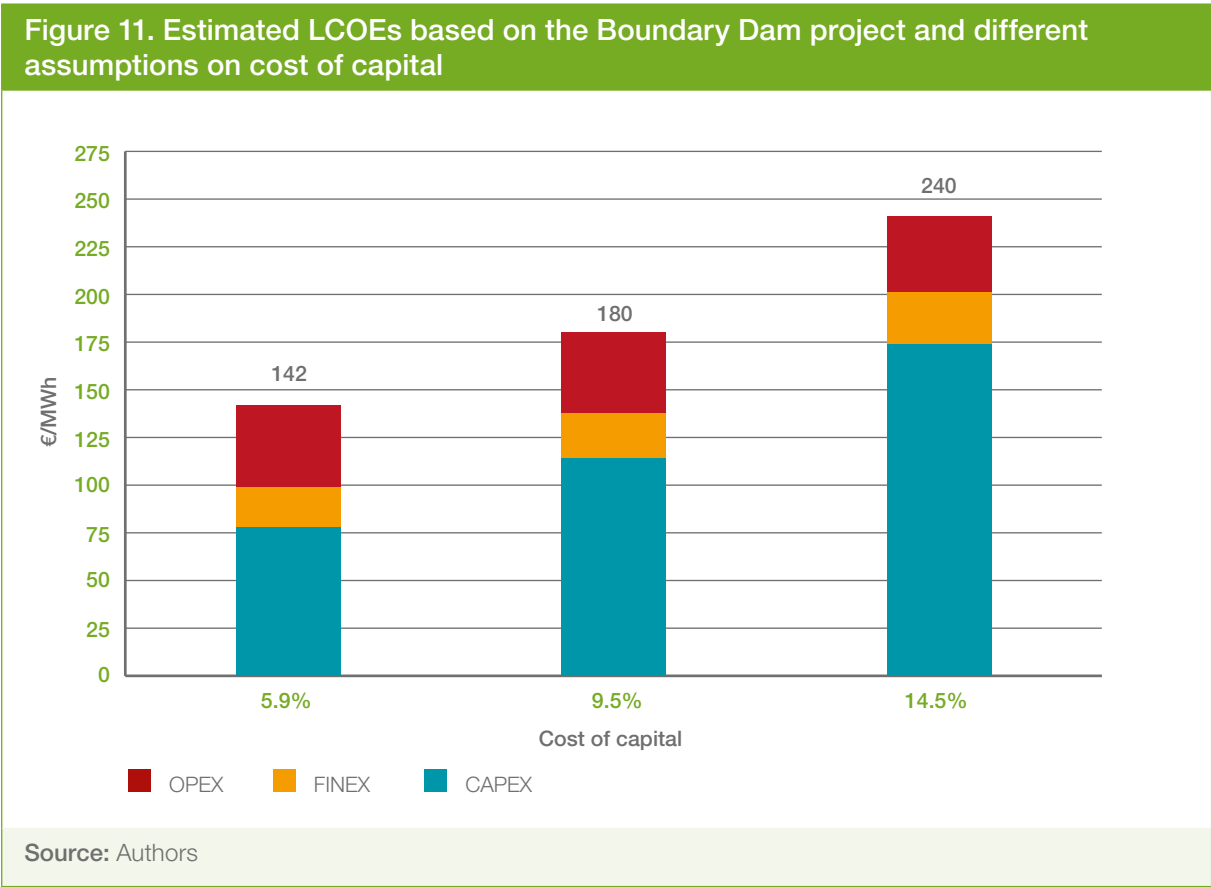
Source: Based on Oxera (2011)

The cost of capital can significantly affect the cost and profitability of a project. Notably, financial expenditures (FINEX), such as interest expenses, can be important elements of the levelised cost of electricity (LCOE). To better understand its influence, we have separated FINEX out from capital expenditures (CAPEX)<sup>37</sup> in a financial cash flow model based on the Boundary Dam CCS power plant (see Boxes 1 and 6).

The model uses a combination of actual data and theoretical assumptions from relevant literature, since full information on the financing and contracting of the project was unavailable due to confidentiality and the commercial sensitivity of the information. The cost of capital (or weighted average cost of capital, WACC) used to assess the project in our cash flow was estimated to be around 5.9 per cent. Box 6 provides for more information about the model.

A WACC of 5.9 per cent is relatively low for a new technology like CCS, and reflects the fact that Boundary Dam is a publically owned and funded project, with experienced and creditworthy developers. Projects which are privately sponsored typically face a higher WACC, particularly if operating in unregulated energy markets. LCOE estimates found in the literature (see section 4.1) use a WACC of around 9.5 per cent, but as Table 3 above suggests, the cost of capital for CCS could be higher, between 12 and 17 per cent (mid-point 14.5 per cent) (Oxera, 2011).

Figure 11 shows the estimated LCOEs when different WACCs are inputted into the cashflow model: 5.9 per cent estimated for Boundary Dam, 9.5 per cent based on the literature and a theoretical higher rate of 14.5 per cent. With a WACC of 5.9 per cent, the LCOE would be around €140/MWh, whereas with a WACC of 14.5 per cent the LCOE increases to around €240/MWh.



37 In some discussions of LCOE, FINEX is included in the CAPEX, as some combination of financing is needed before investment in capital can happen. This will typically be a combination of equity, debt or grants.



These LCOEs are in line with the literature estimates we discussed above in section 4.1. On average, FINEX accounts for a small but significant share of the LCOE; usually between 11 and 15 per cent depending on the WACC. Thus, reducing the cost of capital can reduce the LCOE significantly. CAPEX, as expected, is the largest component, accounting for between 55 and 70 per cent of the LCOE, while OPEX is between 17 and 30 per cent.

### Box 6 Case study: estimating the cost of capital of the Boundary Dam CCS power plant

Financial expenditures (FINEX) are reliant on how the project is funded. In the case of the Boundary Dam plant, the project developer, state-owned energy utility SaskPower, received a federal grant of €168 million. The rest of the project costs are financed on SaskPower's corporate balance sheet, meaning it is included in its asset base. It is possible to assume, therefore, that the project is financed according to the company leverage rating or gearing ratio (the share of equity to debt). SaskPower's (2013) Annual Report indicates the company is leveraged with 30 per cent of equity to 70 per cent of debt. In this case, it is assumed that the remaining project costs (€860 million) which are not covered by the grant are financed through €258 million in equity and €601 million in debt. The interest, at an estimated rate of 5 per cent,<sup>38</sup> would cost around €20 million per year over a 20-year tenor.

By investing on its corporate balance sheet, SaskPower would benefit from lower costs of both equity and debt, and a long track record of developing capital-intensive energy projects. Further, as a publicly-owned creditworthy entity, SaskPower will likely have access to further low-cost funding opportunities, such as bonds backed by the government.

Assuming that equity cost is 8.2 per cent (as in the company's 2013 Annual Report), and adjusting the debt interest with a tax rate of 3 per cent, gives a weighted average cost of capital (WACC) of 5.9 per cent, calculated as follow:

$$\text{WACC} = (\text{share of equity} \times \text{cost of equity}) + (\text{share of debt} \times \text{cost of debt}) = (30\% \times 8.2\%) + (70\% \times 5\% \times (100\% - 3\%))$$

For the purpose of this cashflow model, CAPEX was estimated at about €7,400/kW, based on the company's publicly available information.<sup>39</sup> OPEX was assumed to be consistent with relevant literature (see references in section 4.1) at approximately €29 million in the first year. Of these, OPEX variable costs (such as scheduled and unscheduled maintenance not provided by existing contracts) are about €0.016/MWh (€13,000 per year), fuel cost are about €20/MWh (€16.5 million per year) and transport and storage costs are around €15/MWh (€12 million per year). OPEX was assumed to grow by around 2 per cent per year to account for inflation and component degradation.

<sup>38 39</sup>

<sup>38</sup> Authors' assumption.

<sup>39</sup> The Boundary Dam CCS project capital expenditure (CAPEX) was approximately €1,027 (CAD 1,467) million, to deliver 139 MW (gross) in power capacity.

### 5.3 Potential sources of revenue

Ultimately, the business case for CCS is tied up with revenue opportunities for electricity generators, industrial sectors, and carbon dioxide network and storage operators.

A key issue is therefore whether there are enough revenue opportunities to offset CCS costs, making projects commercially viable. This can include revenues directly generated from selling captured carbon dioxide, selling the energy generated, or from policy-driven instruments, like one-off grants and long-term subsidies, or long-term price support measures such as feed-in tariffs. Carbon prices clearly strengthen the business case for CCS by making carbon-intensive processes more expensive, raising the relative competitiveness of lower-carbon technologies.

Effectively, however, the revenue opportunities that are available today through the European Union Emission Trading Scheme (EU ETS), with carbon prices substantially below €10/tCO<sub>2</sub>, are not sufficient to offset CCS costs at current levels and are unlikely to be for at least the next decade.

The captured carbon dioxide can also be sold to industrial actors to be utilised in other ways, the most widespread option being enhanced oil recovery (EOR) (see section 3.4). Returns from EOR may be sufficient to cover storage costs and potentially some of the transport costs (CS CRT, 2013). Based on experience in the US, revenues can be in the range of €29 to €32 (\$40 to \$45) per tonne of carbon dioxide in 2011 (Godec, 2011).

While there is some potential for EOR in the European Union, there are a number of challenges. CCS will have first to reach a scale sufficient to generate a steady carbon dioxide production, needed for EOR. Hence EOR may not be a viable route for financing CCS early development stages, when initial carbon dioxide flows are relatively small. There is also uncertainty about the actual value of carbon dioxide for EOR in the European Union, as this will depend on the features of each project (CCS CRT, 2013).

Other forms of carbon dioxide utilisation can have significant returns. For instance, the price for pure carbon dioxide generally used in the food industry can be above €100/tCO<sub>2</sub>.<sup>40</sup> However, several applications are still expensive and under investigation (see section 3.4). Furthermore, the current demand for carbon dioxide is not large compared to the volumes that could be produced if CCS becomes commercially viable (Mac Dowell, forthcoming) and the markets could quickly saturate. Utilisation is therefore unlikely to be a game changer for CCS development, unless breakthrough applications are developed in the longer run. However, it has the potential to provide a moderate revenue stream for some CCS projects in some favourable location (GCCSI and Parsons Brinkerhoff, 2011).

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40 Personal communication with Paula Carey, Managing Director of Carbon8 Systems Ltd.

## 5.4 Sensitivity of returns to revenues

The expected revenue stream will ultimately affect the returns that companies will be able to make on CCS and therefore justify (or not) investment.

Through a simple cashflow model, introduced in chapter 5.2, it is possible to make a preliminary estimate of the revenues from an actual project – the Boundary Dam CCS power plant – both from sales of captured carbon and from energy generated. It is also interesting to observe how sensitive a project's internal rate of return (IRR) is to changing revenues.

In the case of the Boundary Dam, the entire tonnage of carbon dioxide – approximately one million tonnes per year – will be sold for enhanced oil recovery (EOR). The price of carbon dioxide that this specific power plant receives is not publicly available, but we assume it is priced around €40/tCO<sub>2</sub> based on available literature (Godec, 2011).<sup>41</sup> In general, the price for captured carbon dioxide tends to differ from project to project depending on the prevailing market conditions, including local demand for the carbon dioxide and availability of transport options. For energy prices, we use the average consumer electricity price of €63/MWh, as highlighted in the 2013 annual report of SaskPower. In the first year of operation, therefore, we assume the project earns about €93 million.<sup>42</sup>

In this case, we estimate that the project internal rate of return (IRR) would be around 7.6 per cent before taxes. This is relatively low, as private sector developers typically require higher IRR before undertaking an investment (sometimes called the hurdle rate of return). For instance, an 'appealing' IRR could be in the region of 10 per cent, but this could be even higher.<sup>43</sup> However, a low pre-tax IRR for the Boundary Dam project is not surprising given the public nature of the investment (see Box 6 in section 5.2).

Figure 12 shows the project IRR (pre-tax) against the combined annual revenues from both carbon and energy sales. The chart indicates how, by increasing total annual revenues from €93 million (in the reference case) to approximately €125 million, the project IRR would rise to reach 10 per cent – the theoretical level which, as we mentioned, would be more appealing for private investors.

41 In the absence of a global or regional market price of carbon, we refer here only to a possible carbon price that the developer could earn on the project-level by selling on the captured carbon dioxide. This is based on estimates by Godec (2011) of \$40-45/tCO<sub>2</sub> in 2011, and adjusted for inflation. It should be noted that the carbon dioxide price used for EOR is strongly affected by oil prices. Our value of €40/tCO<sub>2</sub> should be seen as an upper bound, as Godec's (2011) estimates relied on oil prices above \$100/bbl, while these were below \$60/bbl in January 2014 (Nasdaq, 2015).

42 We assume that the energy and carbon prices rise on an annual basis to account for market trends and inflation. While it is likely the prices in the Boundary Dam project have been agreed on a contract (fixing the prices for perhaps some years ahead), this information is unavailable. We have thus assumed that the carbon price will grow by around 4 per cent per year, and energy by 3 per cent per year.

43 In the UK, the Department of Energy and Climate Change (DECC) estimate the pre-tax hurdle rate of return for CCS as 13.5-13.8% depending on the technology (DECC, 2013a).

**Figure 12. Sensitivity of IRR to combined annual revenues from electricity and carbon dioxide sales**



Clearly, project revenues can be increased by raising electricity prices, carbon prices, or a combination of the two, throughout the life of the project (analogous to moving right along the red line in Figure 12). In more detail, by letting the first year energy price vary but fixing the carbon price at three levels (current level €40/tCO<sub>2</sub>, €0/tCO<sub>2</sub> and €100/tCO<sub>2</sub>) it is possible to observe three IRR 'trajectories' (see Figure 13).

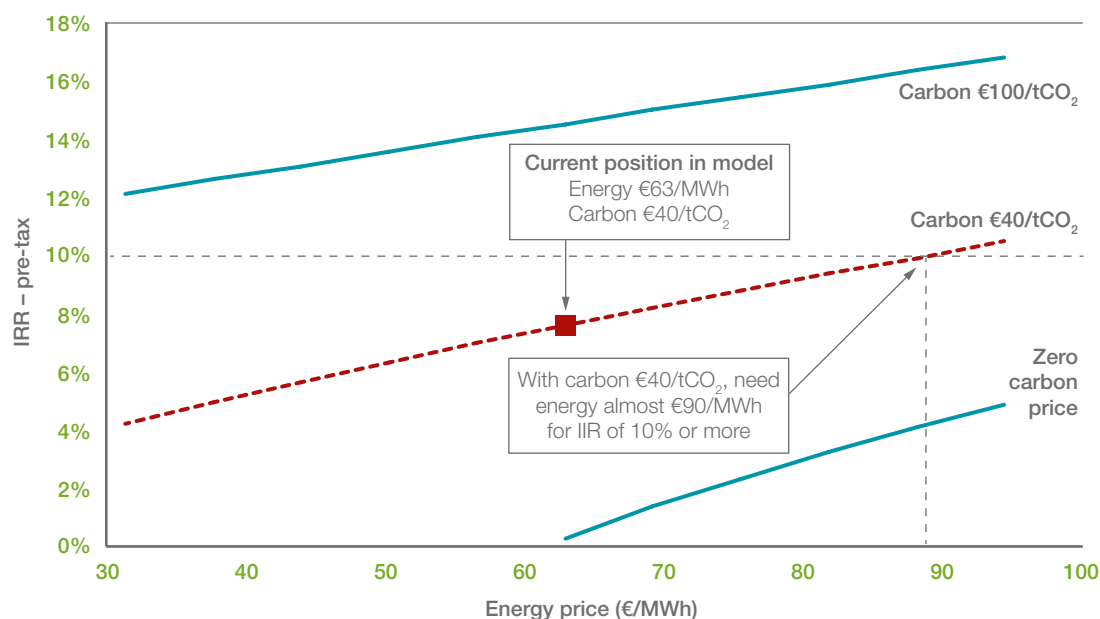
This suggests that, for a project like the Boundary Dam, a high carbon price in the order of €100/tCO<sub>2</sub> would lead to a project IRR always above 10 per cent. On the other hand, in the absence of a carbon price, the project would never earn more than approximately 4 per cent IRR. At the €40/tCO<sub>2</sub> level assumed for the Boundary Dam, electricity prices should be around €90/MWh to ensure the IRR reaches the 10 per cent threshold.

In the European Union, the year-ahead wholesale power price in 2014, for instance, ranged from about €40 to €60/MWh (Argus, 2014). In other words (and with all else being equal), a pre-tax IRR of approximately 10 per cent can be reached by either increasing the carbon price by €20/tCO<sub>2</sub> or the energy price by €30/MWh.

As discussed above, additional revenues are possible from other by-products. The Boundary Dam CCS project, for instance, not only sells the captured carbon dioxide for EOR, but also sells a number of other chemicals, such as sulphuric acid and coal ash, to local industry sectors. Early results from the project suggest the carbon dioxide captured is of such a high purity level (over 99.99 per cent) that it could be used in other industries, such as for food and drinks.

While it was not possible to model these additional revenues, due to a lack of information, it is likely that the economics of CCS projects can be bolstered or improved if the project developers are able to take advantage of local demand from any by-products.

Figure 13. Sensitivity of IRR to fixed carbon dioxide prices and variable electricity prices



Source: Authors

Ultimately the profitability of CCS projects will depend on the price of carbon (sold or traded) as well as on the price of electricity. The model shows that, in the absence of a carbon price, electricity prices will have to be higher than market prices for a CCS project to be financially viable. Alternatively, if a CCS power plant were to rely on market prices, it would require significantly higher carbon prices than today's. Most likely, a combination of price support mechanisms and carbon pricing will be needed to generate adequate returns. Policy instruments will therefore be essential during the operational phase of CCS projects to ensure their viability. This is discussed in the following section.

## 6. Regulatory and policy challenges in the European Union

In this section we examine the policies which are aimed at promoting CCS research, development and deployment, including financial incentives (section 6.1) and carbon pricing (section 6.2), as well as the legal provisions enabling CCS (section 6.3), notably the legislative architecture of the CCS Directive (2009/31/EC) and other key regulations affecting CCS and international transport. The key findings of this analysis are:

- Current instruments and policies have proved insufficient support to the uptake of CCS, and the Council of the European Union's (2007) ambition of having up to 12 CCS demonstration projects operating by 2015 has not been met.
- Carbon prices would have to increase substantially to make CCS power plants competitive with unabated fossil fuel ones. Studies suggest these should be around €35 - €60/tCO<sub>2</sub> to stimulate coal CCS plants, and €90 - €105/tCO<sub>2</sub> for gas-fired ones. The price of carbon in the European Union Emissions Trading System (EU ETS) is unlikely to be at this level for at least the next decade.
- The existing regulation imposes significant costs and liabilities on carbon dioxide storage site operators, which discourage investment.

### 6.1 European Union policies to support CCS

The European Union has ambitious climate change targets. In the long term, it is committed to reduce its greenhouse gas emission by 80 to 95 per cent by 2050 compared to its 1990 levels (European Council, 2009, 2011). Intermediate targets include emissions reductions by 20 per cent by 2020 (European Commission, 2008) and by 40 per cent by 2030 compared to 1990 levels (European Council, 2014).

According to the 2011 'Roadmap for moving to a competitive low carbon economy in 2050' (European Commission, 2011a) by 2050 emissions in the industrial sector should be 83 to 87 per cent below 1990 levels, while the power sector should be almost fully decarbonised. As noted in section 2.1, the 2050 Energy Roadmap, investigating emission reduction pathways for the energy sector, envisages that CCS will play a significant role.

In order to support the development and uptake of CCS, a number of European and national policies have been introduced to support CCS research, development and deployment through direct subsidies or other market-based instruments. Further to this, while no explicit target has ever been set, the European Council stated an aspirational objective of having up to 12 CCS demonstration projects operating by 2015 (Council of the European Union, 2007).

The European Union Emissions Trading System (EU ETS) is commonly seen as a critical driver to mobilise private sector investment in a wide range of low carbon technologies, including CCS (see, for example, European Commission, 2011a). However, several factors, including the recent economic downturn and the interaction of the EU ETS with national and European low carbon policies, have depressed the prices of European Union allowances (EUAs). EUAs have traded below €20/tCO<sub>2</sub> in the past five years, and stagnated between €3-6/tCO<sub>2</sub> in 2013 and 2014, providing no incentive for large investments of the scale required for CCS.



Public funding programmes have also been set up to support CCS. At European level, two key initiatives have been the European Energy Programme for Recovery (EEPR) and the New Entrant Reserve (NER) 300. These too, however, did not deliver strong results.

The EEPR allocated €1 billion to finance six CCS demonstration plants, which were due to be scaled up to commercial level in 2015. To date, only one pilot project reached completion (the Compostilla plant in Spain), but project developers decided not to proceed with a commercial scale demonstration plant. Three projects have been terminated prematurely (in Poland, Italy and Germany), purportedly due to finance, legal and/or public acceptance issues. Two projects are still ongoing (the ROAD project in the Netherlands and Don Valley in the UK), but their completion is dependent on their ability to secure additional funding (European Commission, 2014c).

The NER 300 was initially aimed at pre-commercial CCS projects only, although it was eventually extended to innovative renewable energy sources. The funding was raised from the ring fencing of revenues from the sale of 300 million allowances from the EU ETS's New Entrant Reserve (NER).<sup>44</sup> In the first phase of the programme, which concluded in September 2012, 13 CCS projects were submitted but none were awarded as Member States were not able to confirm backing to their projects (IEA, 2014a). In the second phase, nine CCS projects were initially announced, but only one applied, the White Rose project in the UK. The project received a grant of €300 million in July 2014.

One reason for the lack of success of these funding programmes is the unforeseen drop in the EUA price at the time of projects application, which heavily affected their business case and eventually led to the several withdrawals. Furthermore, since the NER 300 funding base depended on the value of EUAs, a drop in prices also meant that the funds available were significantly lower than expected.

The recently agreed 2030 Climate and Energy Policy Framework has mandated the creation of the NER 400 (also known as 'Innovation Fund'). This funding mechanism is similar to the NER 300, but with a larger endowment of 400 million EU ETS allowances and a broader scope encompassing also low carbon innovation in industrial sectors (European Council, 2014). Further opportunities for CCS may materialise via the new 'Modernisation Fund', also included in the 2030 package. This will consist of a reserve of around 300 million EU ETS allowances set aside to improve energy efficiency and 'modernise the energy systems' in low income Member States.<sup>45</sup> Both funds will come into play after 2020.

Additional financial resources may be available through the new European Fund for Strategic Investment (European Commission, 2014d), which will become operational by mid-2015. An initial allocation of €21 billion in public funding is expected to trigger €315 billion worth of investment up to 2018. Targeted areas include energy infrastructures, research and innovation, although it is yet unclear whether and to what extent CCS projects will receive funding.

Furthermore, some of the €450 billion available under the 2014-2020 European Structural and Investment Funds<sup>46</sup> are also meant to support 'the shift towards a low-carbon economy' (European Parliament and Council, 2013).

However, as the scope of these funds is much broader than CCS, it is yet unclear if and to what extent CCS projects will be financed. Experience with the NER300 suggests that less costly

44 The New Entrants Reserve is a set aside of EU ETS allowances reserved for new operators or existing operators who have significantly increased capacity.

45 With a GDP per capita below 60 per cent of the European Union average.

46 These include: the European Regional Development Fund (ERDF); the European Social Fund (ESF); the Cohesion Fund (CF); the European Agricultural Fund for Rural Development (EAFRD); and the European Maritime & Fisheries Fund (EMFF).

technologies may end up attracting most of the funding. More clarity is therefore needed on the size of resources available for the first CCS projects.

At Member State level, to date only the UK is in the process of finalising a policy package that can support CCS deployment, as part of its Electricity Market Reform process. This includes: feed-in tariffs combined with contracts for difference (CfDs); an emission performance standard which will prevent new coal plants to be built without CCS; and, a carbon floor price underpinning the EU ETS carbon price.

The UK government also made £1 billion (€1.2 billion)<sup>47</sup> available for CCS large-scale development through the UK CCS Commercialisation Programme. Four projects applied and, in 2013, two were awarded funding: the Peterhead gas-fired CCS power plant and the White Rose coal-fired CCS power plant (the latter also co-funded through the NER 300). Final investment decisions on these projects will be made in late 2015. The UK government is also discussing support for additional projects (such as the Don Valley project), although this will be limited to issuing CfDs.

European and Member States policy and funding so far has focused primarily on power applications, rather than on the industrial sector. Only the UK has allocated some £1 million (€1.2 million)<sup>48</sup> to an industrial project, the Tees Valley City Deal, which includes a feasibility study on industrial CCS (GCCSI, 2014c).

Poor support and guidance on industrial applications means industries in the European Union have had very little incentive to invest in CCS, even if the relative cost of capture for some sectors (especially those which already capture carbon dioxide in their production process) would be lower than for power stations (see section 4.1). Some of the challenges specific to the industrial sector (see Box 3 in section 3.1) would require tailor made policies.

As for CCS research and development, investment has been relatively small in the European Union. The IEA (IEA, 2014d) estimated that public investment on CCS research and development in 19 Member States<sup>49</sup> was about €125 million in 2012. This is of a similar scale as publicly funded CCS research and development in the US, which stood at €133 million in the same year.

This level of expenditure is relatively small when compared to public support for research and development on other energy technologies. In the European Union, renewable resources received about €800 million, and nuclear energy and energy efficiency received around €1 billion each.

At Member States level, the largest investors in 2012 were France (€34 million), the UK (€32 million), Italy (€24 million) and Germany (€17 million). Most Member States dedicate less than 5 per cent of their overall energy research and development budget<sup>50</sup> to CCS, or slightly more in Italy (6 per cent) and the UK (9 per cent).

Private investment in CCS research and development is more difficult to track, but data on patents can give an idea of the scale of both public and private investment in innovative CCS technologies (see Figure 14).

Overall, efforts on CCS research and development as well as on deployment by Member States vary significantly in size and are largely uncoordinated. European policies have mostly relied on public subsidies, and their size has been largely inadequate to support widespread investment. As a

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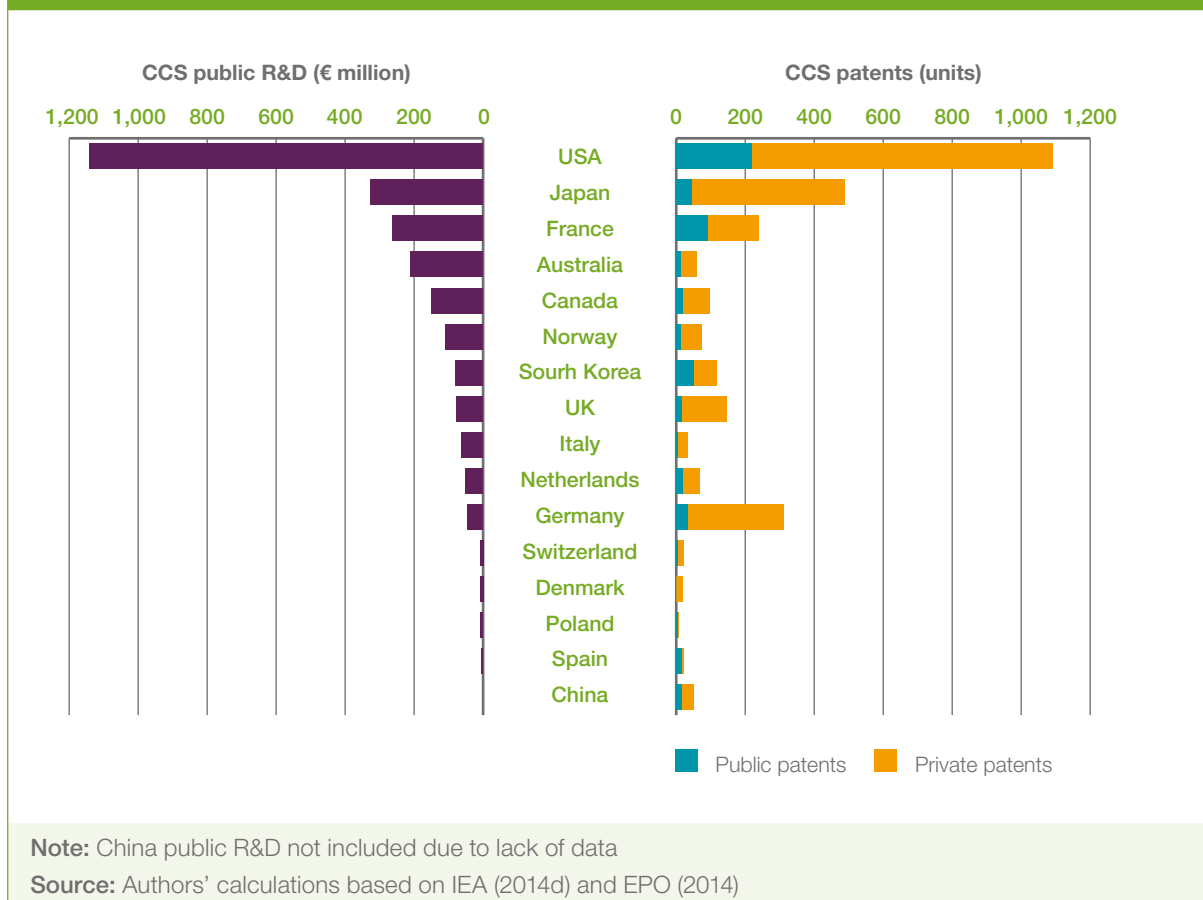
<sup>47</sup> Average exchange rate in 2013 was £1= €1.178.

<sup>48</sup>

<sup>49</sup>

<sup>50</sup>

**Figure 14. Public CCS R&D spending and public/private CCS patents, cumulative 2000-2011**



result, the expectations by the European Council of having 12 CCS demonstration projects by 2015 have not been met.

The IEA (IEA, 2013b) emphasised that, globally, the principal reason for slow pace in CCS deployment is the absence of comprehensive and adequate financial support for demonstration and deployment from government. The European Union is no exception.

New and bolder policies will be needed to prove the feasibility of CCS and deploy it to the levels envisaged in the European Energy Roadmap (European Commission, 2011). Incentives should be provided not only in the form of public subsidies, but also by stimulating private investment. This will require adequate market signals, for instance through a stronger market price or through regulatory targets, like emission performance standards. The European Commission has been reluctant to enforce new mandatory targets besides those on emission reduction, but it is something that may have to be reconsidered if the private sector fails to act.

The recent launch of the European Energy Union offers new prospects for the European Commission to play a steering role. However, CCS does not feature strongly in the Communication outlining the objectives of the Energy Union (European Commission, 2015). While the Communication highlights the importance of energy efficiency, renewables deployment, energy demand management and stronger interconnection, CCS is only briefly referred to as an 'additional research priority'. This was a missed opportunity to re-create momentum around CCS. A more comprehensive coordination of CCS policies and actions at European and Member State level is arguably needed to stimulate investment, and would require a stronger, forward looking European strategy.

### 6.2 The role of carbon prices and electricity price support measures

European funding so far has focused mostly on capital grants for the construction of CCS installations. However, as noted in section 5.4, support will also be needed during their operational phase to make projects financially viable.

Unlike the Boundary Dam project, the first early-stage CCS projects in the European Union are unlikely to benefit from enhanced oil recovery (EOR) opportunities (see section 3.4). However, the carbon price embedded in the price of allowances of the European Union Emission Trade System (EU ETS) would, in principle, act as a similar driver for projects' profitability, provided its level is sustained and credible over the long run.

While the price of EU ETS allowances is currently relatively low (ranging between €4 and €5/tCO<sub>2</sub> in 2013<sup>51</sup>), some Member States have or are implementing additional carbon price measures, such as the carbon price floor in the UK. However, not even these additional measures have been sufficient to stimulate investment in CCS. For example, our cashflow model analysis of the Boundary Dam CCS project shows that, to get to a 10 per cent pre-tax internal rate of return (IRR), total revenues from electricity and carbon dioxide sales have to increase by around 35 per cent compared to estimated 'current' revenues.<sup>52</sup> This can be achieved either with an increased EU ETS carbon price or increased electricity price. With a fixed wholesale electricity price of €63/MWh (which is comparable to wholesale prices in the European Union) for instance, the carbon price would have to be in the order of €60/tCO<sub>2</sub> (see section 5.4).

This would be consistent with analysis by the UK Energy Technology Institute (ETI, 2014), which suggests carbon prices should be of the order of €60/tCO<sub>2</sub> (£45) for new base-load CCS coal power plants. A study by Zero Emission Platform (ZEP, 2011) suggests that coal and lignite CCS plants could become competitive with conventional plants should the EU ETS price reach around €35/tCO<sub>2</sub>, although this would apply to more mature projects.<sup>53</sup>

Higher prices would be required to make gas-fired CCS power plants competitive: up to 105/tCO<sub>2</sub> (£85/tCO<sub>2</sub>)<sup>54</sup> according to ETI (2014), or around €90/tCO<sub>2</sub> for more mature projects according to ZEP (2011).

Bioenergy CCS (BECCS) is likely to be even more expensive. According to Akgul et al. (2014), the price required to incentivise the generation of carbon negative electricity is in the region of €150 to €215 /tCO<sub>2</sub> (£120 to £175/tCO<sub>2</sub>).<sup>55</sup>

51 Based on ICE ECX daily prices of EUA futures with maturity December 2014.

52 Based on current available data from Boundary Dam and our own assumptions.

53 Commissioned after the first full-size plants have been in operation, likely around 2025.

54 Average 2014 exchange rate: £1= €1.24.

55 Average 2014 exchange rate: £1= €1.24.

Carbon prices could increase after 2020, when the EU ETS is expected to be reformed and 2030 climate targets will be formalised. But there is large uncertainty on the future price of allowances, and in the next decade or so it is difficult to foresee that their price will reach the levels needed to make CCS compete with unabated fossil fuel technologies.

In the absence of a sufficiently high carbon price, or of profitable uses of captured carbon dioxide (for example through enhanced oil recovery), CCS will simply not be commercially viable, especially in the first development phases when the cost of technology is particularly high.

Furthermore, as CCS plants are likely to be used as ‘load-followers’ (see section 4.4), their profitability will be further negatively affected. As an example, reducing the ‘availability’ (a measure of the amount of time a plant is in operation over a certain period) in our cashflow model from the assumed 85 per cent to 50 per cent, reduces the pre-tax IRR by around 50 per cent.

Ultimately, to ensure that CCS power plants are profitable and attractive from an investor perspective, additional incentives will be needed. Such policies will likely have to differ across countries and/or regions, depending on the specific role played by CCS within the market it operates.

To date, the UK is the only Member State which is defining an explicit incentive mechanism for CCS, through feed-in tariffs with contracts for difference (CfDs). The CfDs are still under negotiation, and pressures on reducing electricity costs and on keeping energy policy budget within a certain ceiling (the ‘levy control framework’) means there is large uncertainty on the final price that will be granted to electricity from CCS plants.

Indeed, from our financial cashflow model results (Figure 11 in section 5.4), in order to reach a pre-tax IRRs of above 13.5 per cent, which the UK Department for Energy and Climate Change (DECC) estimates as an attractive level for coal CCS investors (DECC 2013, table 16), the combined annual modelled revenues of both carbon and energy sales would have to increase by around 65 per cent.<sup>56</sup> This could be achieved through the EU ETS, through electricity price incentive measures (like the CfDs), or both.

Devising incentives for industrial applications is even more challenging, as the cost of CCS would be ultimately embedded in the price of final products, like steel or cement, potentially affecting their competitiveness. Currently no policy instrument has been implemented, either at European or national level, to offset CCS costs in industrial sectors over the long run. This is something that will require careful consideration.

### 6.3 The regulatory framework concerning transport and storage of carbon dioxide

The main legislation regulating CCS activities is Directive 2009/31/EC on the geological storage of carbon dioxide, known as the ‘CCS Directive’ (European Parliament and Council, 2009a), and the four Guidance Documents which provide additional details on its implementation (European Commission, 2011c, 2011d, 2011e, 2011f).

Introduced as part of the 2020 Climate and Energy Package, the Directive establishes general principles and rules for the environmentally safe geological storage of carbon dioxide that Member States need to comply with, while leaving some degree of freedom in the way it is implemented. It also contains provisions on the capture and transport components of CCS, though these activities are covered mainly by existing environmental legislation, such as the Environmental Impact

<sup>56</sup> Noting that the results from our cashflow model are specific to the CCS project we studied and geographically dependent upon the policy regime in which it operates, as discussed in chapter 5.

Assessment Directive (2014/52/EU) and the Industrial Emissions Directive (2010/75/EU), which were partially amended following the introduction of the CCS Directive.

While the CCS Directive is a useful common denominator for CCS regulation in the European Union, there are a number of issues, especially some key aspects of finance and liability, which lack clarity, leaving project developers exposed to a significant degree of uncertainty (GCCSI, 2013).

In particular, in the directive there is a mismatch between the risk management powers that are exclusively available to national regulators, and the significant costs and liabilities which are to be borne by storage site operators. Notably, operators are expected to bear all environmental and related financial liabilities, and to purchase emission allowances to cover leakage events which may occur during the lifetime of a storage site.

The directive does provide the possibility to transfer storage sites (and the liabilities associated to them) from private storage operators to a Member State's control in the long term. However, that can only occur once the competent authority has been assured that no leakage is likely to occur, that is when:

- All available evidence indicates that the carbon dioxide will be completely contained for the indefinite future (article 18).
- A minimum period, to be determined by the competent authority and no shorter than 20 years since closure, has elapsed (article 18).
- A financial contribution for the post-transfer period, covering at least the costs for monitoring for 30 years, has been made by the operator (article 20).
- The site has been sealed and the injection facilities have been removed (article 18).

The directive suggests that site operator liabilities and financial obligations end within approximately 20 years after storage site closure (article 18). However, this is only a minimum period, and the language in Article 18.1-2 leaves some uncertainty as to when effectively responsibilities will be passed on to Member States. For instance, the directive requires evidence that the stored carbon dioxide 'will be completely and permanently contained' (18-1(a)), and that 'the storage site is evolving towards a situation of long-term stability' (18-2(b)). However, these conditions may not be fully proven by that time.

As such, the directive leaves an open door to deny the transfer of responsibility from the storage site operator to the competent authority at the 20-year threshold. Experience from analogous environmental law fields, for instance, suggest that regulators may not accept such a transfer of responsibility – notably this happened in relation to waste management facilities and contaminated land sites in Canada and the US (Makuch and Pereira, 2012). Transfers could therefore be indefinitely stalled by competent authorities, for example through requests for more monitoring data. This issue ought to be considered by industry when operating under particularly risk-averse governments. Furthermore, operators could also face additional liabilities if authorities were to close a site earlier than expected (which it is in their powers under certain circumstances, according to article 11). In such cases, set-up and operational costs might not be fully recovered at the time of closure.

Lack of clarity also affects the regulation of third party access. Access to storage and access to transport infrastructure are jointly regulated under article 21, although they actually entail different risks which should arguably be dealt with separately. Concerns have also been raised on the inability of storage operators to refuse access, and on the arrangements for the sharing of liability



(Triple E et al., 2014). This could potentially disincentivise first movers if the additional risk of offering access to second movers is not adequately regulated and compensated for.

The requirements for financial security can also be problematic. Under article 19, operators are required to set aside a certain amount of funds, in the form of cash, securities, bonds, insurances or loan facilities, when applying for a storage permit – including after closure for at least 20 years. This financial security must include coverage for the cost of compensation in case of carbon dioxide leakage. This is linked to the price of allowances in the European Union Emission Trading Scheme (EU ETS). The uncertainty over the amount of carbon dioxide that could leak and the future EU ETS carbon price make this liability potentially open-ended. Furthermore, environmental damage from carbon dioxide leakage would also fall under the Environmental Liability Directive (2004/35/EC), with the potential risk that site-operators may have to pay for the same damage two times over, once through the EU ETS and once through the Environmental Liability Directive.

The development of CCS in the European Union is also affected by the European provisions on national state aid. The 2008 Guidelines on State Aid for Environmental Protection have been a reason for concern for project developers. State subsidies for CCS demonstration projects had to go through a relatively lengthy process before clearance, although eventually all proposals were approved. The 2014 Community Guidelines on State Aid for Environmental Protection and Energy (European Commission, 2014a), however, have broadened the scope of aid projects, including, for the first time, detailed rules for the energy sector. State aid for CCS demonstration projects is now legally permissible, provided that there is appropriate prior notification to the European Commission.

Another key regulation affecting CCS is the 1972 International Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Convention). This is a global agreement regulating the disposal of wastes and other matters from land-based sources at sea, including the trans-boundary transport and storage of carbon dioxide,<sup>57</sup> which applies when storage takes place outside a country's internal waters.

The 1972 Convention permitted dumping of wastes at sea, except for those materials on a banned list. This was followed by the 1996 Protocol to the London Convention, which entered into force on March 2006. In contrast to the Convention, the Protocol prohibited dumping, except for materials on an approved list. At first the list did not include carbon dioxide, resulting in a potential barrier for offshore storage in the context of CCS operations.

Storage of carbon dioxide under the seabed was eventually allowed through an amendment introduced in 2007. This has created a basis for regulating CCS in sub-seabed geological formations in international environmental law, and would apply to large point sources of carbon dioxide emissions, including power plants, steel and cement works.

However, the Convention in its current form still prohibits the export of carbon dioxide from one country to another. An amendment was proposed to address this problem, but it has not yet been ratified, and concerns have been expressed that implementation may take a long time (Evar et al., 2012).

57 The operative provisions of the London Dumping Convention which pertain to CCS are included in articles 3, 4, 6, 10 and 12.

## 7. Policy recommendations

Meeting the European Union's objective of reducing greenhouse gas emissions by 80 to 95 per cent by 2050 will require a radical transformation of its energy system. By then, the power sector will need to be almost fully decarbonised. The industrial sector will also have to contribute significantly, curbing its emissions by more than 80 per cent from its current levels. Whatever the choice of technologies and energy sources, the scale of the investment required to decarbonise the economy is considerable.

In this regard, the European Commission has high ambitions for the role that CCS could play in reducing emissions and keeping costs to a minimum. In the Energy Roadmap 2050 (European Commission, 2011b) all of the energy scenarios presented envisage CCS as part of the European energy system to some degree from 2030 onwards.

However, in the past ten years, European and Member State policies supporting CCS have been too weak to stimulate significant investment. While a few projects are under development, to date there are no commercial CCS installations operating in the European Union. Interest seems also to have cooled somewhat in European institutions. Notably, CCS does not appear to feature strongly among the objectives of the newly established Energy Union.

The slow pace of CCS development in the European Union reveals a mismatch between ambition and reality. To meet Europe's emissions targets, more certainty is needed on which energy technologies to invest in. This makes it important to determine, as soon as possible, whether CCS is a viable technology in the European Union.

Several of the barriers identified in this policy brief point to the need for a concerted effort between the public and private sectors. The European Council's (2009) view that 'without bold funding decisions by the companies... complementary public funding may not be triggered' appears to have understated the scale of investment needed and the challenges that companies face. In reality, waiting for the private sector to make the first move has so far proven unsuccessful, and companies largely unwilling or unable to bear the risks of CCS alone. As noted by the IEA (IEA, 2014a), the absence of strong policy means that there is currently no clear business case for private investment in CCS.

The appointment of the new European Commissioners in late 2014 and the creation of a European Energy Union offer the opportunity to take stock of these experiences and consider why the policies so far implemented have had such a limited effect. The European Commission and the Member States should devise new policy tools that can incentivise the development and testing of CCS, to find out once and for all whether CCS is economically viable in the European Union.

This analysis reviews the latest and most authoritative evidence on the barriers to CCS investment in the European Union and how they could be overcome. Alongside desk research, the authors have consulted with selected experts and stakeholders from across Europe. This analysis points to the need for a shared strategy that enables coordination across Member States efforts and improves CCS policy and legislation. The European Council should endorse a European CCS strategy that increases the ambition and accelerates the development of CCS by prompting urgent action in three critical areas: stronger policies to incentivise investment in CCS (section 7.1), stronger coordination of Member States' efforts (section 7.2), and better legislation (section 7.3).

Some of the barriers hampering investment require relatively straightforward policy fixes which could be addressed in the coming five to six years. Others are challenging and will ultimately require additional resources, bold decisions and fundamental changes to operational mind-sets, both from the public and the private sector. These may take a longer timeline to implement. A summary timeline of policy intervention, based on these recommendations, is shown in Table 4.

**Table 4 Timeline for possible European Union and national policies**

<div>Short term (2015-2020)</div> <div>Medium term (2020-2030)</div> <div>Long term (2030-2050)</div>			
Policy	R&D support		
	Funds to early deployment	NER 400 and additional funds	
	Leverage through development banks (e.g. EIB/EBRD)		
	European Structural and Investment Funds		
	Private sector fund		
	EU ETS	Reformed EU ETS	
		Price incentives or certificates	
		Targets	
Coordination	EU CCS strategy		
	Identify national potential		
	Encourage storage exploration		
	Set milestones	Revise milestones	
	Infrastructure planning and development		
	Shared learning		
	Encourage coherence across Member States policies		Further harmonisation
Regulation	Remediation cost under Environmental Liability Directive		Consider reverting to EU ETS
	Liability cap	Revise cap	
	Financial mechanism for damage remediation		Revise mechanisms
	Special treatment for demonstration projects		
	CCS Directive	Full revision of CCS Directive	
Source: Authors			

The actions recommended include the strengthening of existing tools and legislation, but also involve the allocation of additional, and potentially significant, public resources, at least in the earlier stages of CCS development. The private sector, including large utilities, fossil fuel companies and institutional investors, will also have a role to play. It will be unlikely to act, however, unless adequate policy signals are provided, for instance through carbon pricing and emission performance standards or other regulatory targets.

Increasing the use of public resources to fund CCS could be unpopular, especially as several Member States continue to struggle with their recovery from the ongoing economic and financial crisis. On the other hand, targets or standards to mobilise private investment can also be politically sensitive. There is no easy solution, and this may explain why it has been so difficult to speed up CCS and, arguably, other low carbon investment.

To meet Europe's emissions targets more certainty is needed on the energy technologies the European Union should invest in. If the policies required to encourage investment in CCS will be considered politically unviable, either because they are too burdensome on the public finances or on the private sector, the expectations around CCS must be revised in a timely manner and alternative options (and their cost) should be explored.

Above all, the European Union and its Member States must show much greater urgency and determination to develop and deploy CCS, otherwise it will not be able to contribute towards the demanding targets for reducing emissions of greenhouse gases, perhaps making them significantly more difficult and/or expensive to achieve.

### 7.1 Incentivising CCS through stronger policy

High costs and complex infrastructure planning are key barriers to CCS (see section 4). Given the relatively low carbon price currently embedded in the European Union Emission Trading System (EU ETS), the market alone is not sufficient to justify investment. Different policies will be needed at different phases of CCS development to improve its business case.

Some of these policies have been repeatedly suggested by influential bodies, associations and government agencies (see, for example, EASAC, 2013; IEA, 2014b). Relying on just one or two of them – like the carbon price at its current levels and a weak subsidy scheme – has proven unsuccessful. Clearly a more ambitious package of measures is needed.

- **Early development: developing new funding mechanisms to finance early stage development projects**

Financial support will be needed in the first phase of development, until CCS proves to be economically feasible in the European Union or is eventually abandoned and replaced by other technologies. A time-bound credible support programme will give much-needed policy certainty to the private sector, while a clear timeline, with periodic revision points and an exit strategy, will keep public financial resources in check.

First, **additional support to research and development** is needed to address the market failures that typically affect innovation, such as spillovers from research and development and economies of scale. Current public expenditures have proven too modest, and close to zero in some Member States (see section 6.1). Significant public support is necessary to improve existing technologies and identify new opportunities to reduce cost and enhance CCS performance. Priority areas for research and development support should be identified by the European Commission and the Member States, in consultation with relevant stakeholders. Focus should fall on those areas that can best deliver reduced costs at lower environmental impacts. Key areas could include, for instance: biomass Energy with CCS (BECCS); carbon dioxide utilisation (especially EOR, but also other niche

applications); whole systems modelling and simulation; specific industrial applications; next generation capture technologies such as post-combustion carbonate looping and chemical looping; and, innovative applications (such as ship-based CCS).

Second, **direct funding** may be needed to **bridge the ‘valley of death’** between research and development, and full deployment. A number of demonstration projects will be needed to achieve and consolidate cost and technology discoveries. Some instruments have already been envisaged, such as a new round of funding under the New Entrant Reserve (NER 400) and the potential to use of Structural and Investment Funds for 2021-2027. While these initiatives are helpful, they come with limitations and, alone, are likely to be insufficient.

The NER 400 will likely suffer from the same weaknesses of the previous NER 300 programme, namely an uncertain budget (depending on the future price of EU ETS allowances) and insufficient focus on CCS. As with NER 300, CCS will have to compete with other low carbon technologies for funding. Under NER 300 only one project out of the 39 funded was CCS.

As for the European Structural and Investment Funds, it remains to be seen whether Member States will be incentivised to include CCS among their national Operational Programmes, and if funding will be sufficient to make CCS projects appealing to the private sector. Overall, it will be crucial to assess the potential of these measures to stimulate CCS, and consider expanding public support at European Union and/or national level, especially targeting regions that would most benefit from CCS (for example, those which rely heavily on domestic fossil fuels).

Third, as CCS is very sensitive to the cost of financing resources (see section 5.2), instruments are needed to reduce risks of projects, and thus reduce the cost of capital, as much as realistically possible in the near future. Until then the first large scale CCS projects are likely to be hampered by prohibitively high costs of capital.

The cost of capital could be lower though if **projects are undertaken by project developers with strong balance sheets**, such as upstream fossil fuel companies or downstream large power utilities, rather than niche developers on a project finance basis. Large, incumbent energy utilities could be well-placed to develop these first CCS projects as they have the size, experience and capacity to undertake diversified, large-scale and complex investments at the same time as minimising many of the barriers and inherent risks to CCS projects. Furthermore, those utilities operating within a regime of regulated returns based on their asset bases could further benefit from reducing investment risks by stabilising long-term revenues and reassuring investment decisions.

This is not to say that large-scale energy utilities in the European Union will find it easy to invest in CCS, since in the current economic and political setting they are facing significant funding constraints. Furthermore, CCS project financing has a different risk profile to traditional capital intensive energy infrastructure projects and needs to be managed or handled differently. In particular the risks associated with construction are very different from the risks associated with the operation of the installation. Different investors may be able to absorb one or the other, but there will still be enduring risks that can only be minimised or managed to a certain degree.

These complexities suggests a **role for public financial institutions**, such as the European Investment Bank (EIB) or the European Bank for Reconstruction and Development (EBRD) which can provide (limited) funding and, more significantly, convening power and know-how that can ultimately crowd-in additional private financing sources. National financial institutions, like the German KfW bank and the UK Green Investment Bank, also have the potential to contribute. However, given the overall constraint on public financing in Europe, development banks should act as leaders and syndicators, rather than sole providers of finance.

Finally, private or public owners of fossil fuel reserves can benefit from CCS because it could allow for a larger, though limited, share of fossil fuel reserves to be exploited in compliance with climate change targets<sup>58</sup> (McGlade and Ekins, 2015). Fossil fuel companies may oppose an additional tax on their activities or assets to fund CCS development. However, there is a case for **encouraging the creation of a private sector fund**, which could contribute to lowering the costs of sequestration technologies.

- **Mature projects: carbon pricing, price support and/or targets**

Even if significant cost reductions can be achieved in more mature projects, CCS may still struggle to compete with unabated fossil fuel power plants unless the carbon price rises significantly and existing fossil fuel subsidies are removed.

**A carbon price** is crucial to help level the playing field between high and low carbon technologies and stimulate private investment. The European Union already has a uniform carbon price through the European Union Emission Trading System (EU ETS). At present this is relatively low, but proposed reform to the EU ETS can help move towards a stronger and more predictable carbon price. This will also affect the size of funding available through the NER 400 programme. However, the large investment required to deploy CCS and its related infrastructure would require a carbon price level that may be unreachable within the EU ETS, at least in the coming five to ten years. For example, estimates suggest this should be above €40-60/tCO<sub>2</sub> for CCS coal power plants, and above €100/tCO<sub>2</sub> for gas power plants (see section 6.2). Therefore, carbon prices will likely be too low to make CCS bankable in the absence of other policies.

In the case of electricity, the cashflow analysis illustrated in Figure 12 in section 5.4 shows that both carbon prices and energy prices have a substantial impact on project viability and investment attractiveness. Carbon pricing can therefore be complemented by **price support mechanisms**, such as those introduced for renewable power generation, to guarantee sufficient returns to CCS plants operators and make projects bankable. Possible policies include feed-in tariffs with contract for difference, along the lines of those recently introduced in the UK. Under these contracts low-carbon generators sell their electricity at an agreed strike price, set at a level sufficient to cover their long-run costs, and which will remain fixed for a given number of years (for example, 15 years in the UK). While strike price for CCS projects have not yet been determined, initial estimates by the UK Energy Technology Institute (ETI, 2015) suggest that these could be around €140-190/MWh<sup>59</sup> (for coal and gas CCS respectively) in the early 2020s, decreasing to €110/MWh (for both coal and gas) in the late 2020s. These are not dissimilar to the strike prices that the UK government is granting to offshore wind installations, which are around €190/MWh in 2014/15 (DECC, 2013b).

Another option would be to invite private sector generators to bid for a rate of return on the basis of their budgeted capital operating and fuel costs, with bids evaluated on the basis of the least long term cost to consumers. The initial wholesale price should be set so as to deliver the rate of return of the successful bidder, and allowed to vary so that no more and no less than the agreed return is guaranteed. This would prevent any 'super profit' as well as act as a downside protection for the generators. Similar systems are in place in the US.

58 Within a 2°C scenario, energy modelling suggests that the amount of coal and gas global reserves that could be utilised before 2050 would be, respectively, 6 and 2 per cent higher if CCS becomes available as from 2025 (McGlade and Ekins, 2015).

59 The average exchange rate used in this paragraph is: £1 = €1.241 in 2014.



Overall, price support mechanisms can provide certainty over the total project revenue stream and the rate of return a developer can achieve, bringing down the associated investment risk. This could also help make CCS projects more palatable to institutional investors.

The **industrial sector** will require more targeted policies. For those facilities for which carbon capture is already part of their production process, like the refining and petrochemicals industry, the cost of CCS can be relatively small. These are more likely to endorse CCS in response to an increase of the carbon price, although they may still have little appetite to develop carbon dioxide transport infrastructure (see section 3.2).

For other sectors, such as steel and cement production, it will be more difficult to incentivise CCS. Higher carbon prices will be needed to trigger a switch in technology and these could have significant impact on the competitiveness of some of the most energy-intensive and trade-exposed industries. This could partially be mitigated by appropriate trade measures, like sectoral agreements or border adjustments. However, these have proven politically difficult to initiate. The development of the most expensive CCS industrial applications, therefore, may be delayed. CCS in these sectors may need to follow successful implementation in the power sector, in order to enable cost reductions, in particular through infrastructure sharing and clustering.

In order to further stimulate action by the private sector, **mandatory targets** could be introduced in the medium-long term, either as an alternative to price support mechanisms, or as an additional driver of change. They could be in the form of carbon intensity targets, or emission standards, for example limiting emissions from coal power plants so that only coal with CCS could be built.

Alternatively **quantity-based instruments** could be introduced, such as tradable certificates for carbon dioxide sequestration. These would require industries to store an increasing percentage of their carbon dioxide emissions (for example starting from one per cent in the first year) or buy a certain number of 'CCS certificates' in a dedicated market, similar to the EU ETS. A full description can be found in Allen et al. (2009).

Whatever the instrument(s) used in addition to carbon pricing, it will be important that the EU ETS cap is adjusted to take into account the increase in CCS uptake. This will help prevent the price signal from the EU ETS being weakened by the increasing amount of carbon dioxide sequestered by CCS plants. The market stability reserve could be a useful mechanism in this respect.

Ultimately, the balance between public subsidies and other instruments, like carbon prices or mandatory targets, will have a strong impact on how costs are shared between the public and private sector.

### 7.2 Improving coordination across Member States

At present, the approach to demonstrating and deploying CCS significantly differs across Member States. Only one Member State, the UK, has a national framework for supporting CCS. Others are trying but struggling to stimulate projects, and some have effectively no plan for CCS development (see section 2.3 and 6.1).

There is also little understanding of which Member States may lack sufficient storage space, or may need CCS the most, for example those who rely more heavily on domestic fossil fuels for energy generation and/or that have limited low-carbon alternatives. There is also limited understanding of which type of applications (gas or coal power plants, other industrial sectors) and infrastructures may be appropriate and where.

While recognising that Member States will each have different ambitions, opportunities and barriers to the development of CCS, a Europe-wide strategy should provide more coordination across Member States' approaches to ensure CCS is developed in a coherent way, and consistently with European climate change targets. Key areas that will benefit from stronger coordination include the following:

- **Identifying the potential for CCS in each member state.** To date there is limited understanding of Member States' potential and appetite (or lack of) for CCS. This, however, would be essential to establish CCS feasibility and acceptability. It would also help tailoring future policies to actual needs, for example on infrastructure (including by identifying storage supply and demand) and on funding allocations. This could consist of a bottom-up analysis carried out by the Member States themselves, with guidance from the European Commission. It could focus on relevant national features, such as the reliance on domestic fossil fuel sources, the location and size of potential capture installation (in the power and industrial sector), the geology of potential storage sites (onshore and offshore), transport infrastructure options, and so on. Although outside the scope of this policy brief, the social acceptability of CCS is also an important issue for the future of CCS. Reasons for opposition tend to reflect concerns about risks to the environment and safety (especially due to potential leakages from storage sites), and about conflicting allocation of financial resources (as CCS could divert funds from other mitigation alternatives, like renewables and energy efficiency) (Shackley et al., 2007). These concerns deserve to be further investigated and addressed by Member States and the European Commission. Member States should also identify valid alternative routes for emission reduction up to 2050, with and without CCS, providing at least a preliminary indication of costs. This would be important to determine how Member States' choices concerning CCS feed into their long-term plans for decarbonisation. The interest and collaboration of Member States will clearly be essential to kick start such process. In case only a sub-set of countries were effectively willing to engage, the European Commission may consider coordinating CCS funding and initiatives across a 'coalition of the willing', rather than at EU-wide level.

- Ensuring coherence across national and European policies.** Coordination and cooperation between Member States within a common European framework is one of the main ambitions of the new Energy Union (European Commission, 2015). Although CCS appears to be marginal in the Energy Union strategy, it is a perfect example of where such a coordinated approach is badly needed. Few Member States have provided funding and support to research and development and/or to potential pilot and demonstration projects, and almost none has a domestic strategy on CCS. The European Commission could stimulate action by recommending a portfolio of viable instruments that could complement the carbon price, such as those outlined in section 7.1. While these would not need to be prescriptive, they could provide guidance to those Member States interested in CCS and in need of assistance, as well as provide a benchmark to measure progress and compare domestic policies.
- Enabling shared learning and innovation.** A European CCS strategy should set solid basis for collaboration between the public and private sectors (including CCS developers and financial institutions), encouraging the showcasing of technologies, lessons learned and examples of best practices, knowledge sharing and communication between stakeholders, taking stock of spillovers from technology developments. Keeping track of new cost discoveries and innovation will also help update CCS-related policies, for example to assess the need for supporting certain applications or to revise targets and milestones, should these be adopted. The design an organisation of knowledge sharing platform should take into account potential intellectual property concerns by the private sector, especially as CCS technologies get closer to full deployment. Lessons on possible forms of collaboration can be drawn from existing examples, such as the IEA's Greenhouse Gas Research and Development Programme (IEAGHG) and the World Intellectual Property Organisation (WIPO) Green Database.
- Defining milestones against which progress can be measured.** The possibility of introducing mandatory European targets (such as on carbon intensity, emission standards or specific CCS goals) should be taken into account, at least in the medium-long term, in a Europe-wide strategy (see section 7.1). In the short run, indicative milestones could be introduced (for example, in terms of amount of carbon captured on number of CCS installations by a given date) to help measure the pace of progress. In the event that CCS fails to progress at the speed or scale needed to avoid dangerous climate change, contingencies should be in place to avoid the lock-in of fossil fuel technologies (Aghion et al., 2014).
- Supporting and coordinating action on infrastructure development.** The transport of carbon dioxide from capture plants to storage sites may require extended, cross-border pipeline networks. Furthermore, the infrastructure for early demonstration projects may need to be oversized and clustered to host future potential CCS plants (see section 3.2). The private sector will have little incentive to invest on infrastructures that are beyond their needs. These may also be hampered by potential delays in permitting if infrastructures are at odds with national or local planning. Only a constructive collaboration between public and private actors would help a coherent and strategic development of the CCS infrastructure. This would require some degree of strategic planning and facilitation by the European Commission, including: promoting (and potentially co-financing) the oversizing of infrastructures to accommodate future larger fluxes of carbon dioxide from multiple sources; clustering pipelines, for example around industrial areas with significant CCS potential and/or around 'anchor' projects by large power plants; and, identifying possible investment and operational needs for trans-boundary transportation.

- **Encouraging storage exploration, characterisation and development.** The appraisal of potential carbon dioxide storage sites is critical to the design and operation of CCS components, from capture through to storage (see section 3.3). But while the cost of storage characterisation is relatively small compared to the cost of the whole CCS chain, this is one of the most lengthy and risky phases, especially if sites prove unsuitable. Returns from carbon dioxide storage are also uncertain. High risk and low profitability means storage can be a bottleneck for CCS investment. The European Commission should have a role in channelling targeted support and de-risking storage, either at European or national level.

Lastly, CCS will be part of a broader transition out of the existing energy system, which will likely require a transformation of the electricity market and increased interrelation between Member States' energy demand and supply. The implications of such transition go beyond the scope of this paper, and further research is needed in this area. However, in the context of future coordination, it is advisable that the European Commissions, and in particular the newly established Energy Union, start investigating opportunities for further harmonising Member States' energy policies and markets.

### 7.3 Improving liability rules through better legislation

Some risks associated with CCS operations are essentially uninsurable, especially around post-operational storage sites and potential future leakage of carbon dioxide (see section 6.3). This may be further exacerbated by the fact that different operators, within and across Member States, may need access to shared infrastructure and storage.

The potential risk of large losses, especially in the case of carbon dioxide leakage, not only raises the cost of capital (section 5.2), but can deter investment altogether. Ultimately, neither insurers nor storage operators will be able to bear unlimited liabilities. In these cases, innovative insurance instruments, coupled with some level of risk sharing with governments, will be required.

The review of the CCS Directive offers the opportunity to tackle some of these shortcomings early on. Recent analysis supporting the review of the directive (Triple E et al., 2014) identifies the main weaknesses in the legislation, including issues related to the financial securities needed for transferring storage sites from operators to public authorities, and the legal meaning of 'capture readiness' for new power plants. It also suggests that, given the lack of practical experience, it would not be appropriate to reopen the directive for significant changes until the first demonstration projects are rolled out, while revision should focus on the non-binding guidance documents.

While it is ultimately for the European Commission, together with the Member States, to decide when and to what extent the directive should be amended, there are a number of issues which would require attention sooner rather than later, in particular around the liability and insurability concerning the risk of carbon dioxide leakage. This policy brief identifies some priority areas of intervention, which will need to be addressed as soon as possible to allow the first demonstration projects to be developed in a timely manner and to create the right conditions for future investment.

- **Clarifying the size of remediation costs.** Currently, in the event of carbon dioxide leakage, a storage operator will need to buy EU ETS allowances equivalent to the amount of carbon dioxide released. At the same time, damages would also have to be dealt under the Environmental Liability Directive. Effectively, operators may end up paying twice for the same damage. Furthermore, the size of the remediation costs associated with the EU ETS are highly uncertain, given the difficulty to forecast future carbon prices at the time the leakage may occur. To avoid double penalties and reduce uncertainty, remediation cost for carbon leakage may be better dealt with under the Environmental Liability Directive, rather than also through the purchase of allowances within the EU ETS. The concept of the ‘polluter pays principle’ is already well established in the Environmental Liability Directive and, if properly applied, already provides competent authorities with the means of punishing and remediating leak-based damage, including climate-related damage. Only if the EU ETS market become more stable and carbon price more predictable, the EU ETS may become a more suitable basis for estimating emission allowance purchases required to account for a leakage event.
- **Capping long-term liability.** Experience from the nuclear sector reveals that the existence of a cap on liability, in addition to insurance, may be the minimum basis for encouraging private sector participation. Similarly, CCS regulation should facilitate the existence of such mechanism if the private sector is to become more engaged. The initial size of the cap will ultimately have to be negotiated between the European Commission and the Member States, in consultation with relevant stakeholders. Building on experience from the nuclear sector, we suggest the cap should not be lower than €60 million.<sup>60</sup>

To incentivise cutting edge CCS technology development and to provide for the best storage sites, the cap for each site could be subject to periodic review, for instance every five years. Such adjustments should be based on specific criteria, such as: storage site characteristics, technical competence of the operator and the financial capacity of the operator to address CCS risk. Revisions should also take into account developments in the private insurance sector (see below).

Greater regulatory certainty should be established by specifying a maximum period of time after which there should be a full transfer of responsibility for a closed storage site to a competent authority. A period somewhere between 20 and 30 years would be reasonable and could be accommodated without the amendment of the CCS Directive.

- **Establishing clear financial mechanism for damage remediation.** The weight and nature of risk management opportunities available to the regulator, combined with the commensurate risk management standards, procedures and financial and related liability requirements placed upon the storage site operators, suggests that a ‘cooperation’ or ‘partnership’ approach to risk management and long-term liability for leakage is necessary. Claims up to the above-mentioned liability cap should be covered by site operators, while claims over the limit should be absorbed by a public insurance mechanism or another form of public guaranty. In case of transboundary transport and storage of carbon dioxide, remediation costs could be shared proportionally between Member States. Possible financial mechanisms for the private sectors could include:

<sup>60</sup> Nuclear Liability Acts in Canada and India set a cap of, respectively CA\$75 million (around €50 million) and INR5 billion (around €60 million) per nuclear plant operator, while the US Price Andersen Act sets a similar cap of US\$120 million (around €90 million). Acknowledging that the US features higher costs and damages awards for environmental liability, and that nuclear accidents are generally more damaging than one might foresee for a carbon dioxide leak, an estimated CCS liability cap of €60 million would appear to be sufficiently high to anticipate CCS remediation cost to be borne by the private sector. Personal communication between the authors and potential industry participants suggest this threshold may be acceptable, in principle, by site operators.

- **Site-operators' liability fund:** All site operators should jointly and mutually be required to set up a negotiable financial instrument (for example in the form of guaranteed bonds, agreements to pay, etc.) that would act as security to cover the remediation costs that may arise in case of carbon dioxide leakage. This is not an entirely new concept. A similar fund, for instance, exists for oil and gas spills at sea (the 1992 Oil Pollution Compensation Fund). Any financial security under the CCS Directive could count towards the financial requirements of this fund.
- **Private insurance products:** The setting of a clear cap on liability and the creation of a liability fund may stimulate the creation of a private insurance market for CCS. In such case, the provision of contracts of insurance for carbon dioxide leakage for the operational life of a storage site could replace or be an alternative to liability funds. As the insurance market for post-operational leakage evolves, the liability cap could be revised upwards in proportion to the willingness of private insurers to insure additional risks.
- **Special treatment of demonstration projects.** In order to help first movers absorb the risk associated with CCS operations, a public liability scheme should be set up to cover potential leakage associated to the first demonstration projects. Similar support was provided, for instance, to CCS demonstration projects in Norway. Public indemnification should be granted provided that site operators are fully compliant with permit requirements and can demonstrate no fault or negligence in their operations. A duty to apply best available techniques in the demonstration phase along the lines of Industrial Emissions Directive would also be advisable.



# References

- Aghion, P., Hepburn, C., Teytelboym, A., and Zenghelis, D., 2014. *Path-dependency, innovation and the economics of climate change*. Supporting paper for New Climate Economy. [pdf] London: Centre for Climate Change Economics and Policy Grantham Research Institute on Climate Change and the Environment. Available at: <http://www.lse.ac.uk/GranthamInstitute/publication/path-dependence-innovation-and-the-economics-of-climate-change/>
- Akgul, O., Mac Dowell, N., Papageorgiou, L. G., and Shah, N., 2014. A mixed integer nonlinear programming (MINLP) supply chain optimisation framework for carbon negative electricity generation using biomass to energy with CCS (BECCS) in the UK. *International Journal of Greenhouse Gas Control*, 28, pp.189–202.
- Al-Juaied, M., and Whitmore, A., 2009. *Realistic Costs of Carbon Capture*. Discussion Paper 2009-08. [pdf] Cambridge (MA): Harvard Kennedy School, Harvard University. Available at: [http://belfercenter.ksg.harvard.edu/files/2009\\_AlJuaied\\_Whitmore\\_Realistic\\_Costs\\_of\\_Carbon\\_Capture\\_web.pdf](http://belfercenter.ksg.harvard.edu/files/2009_AlJuaied_Whitmore_Realistic_Costs_of_Carbon_Capture_web.pdf)
- Allen, M. R., Frame, D. J., and Mason, C. F., 2009. The case for mandatory sequestration. *Nature Geoscience*, 2(12), pp.813–814.
- Argus, 2014. *European Electricity – daily electricity market prices, news and analysis*. Issue 14-152 Friday 1 August 2014. [pdf] London: Argus. Available at: <http://www.argusmedia.com/~media/Files/PDFs/Samples/Argus-European-Electricity.pdf?la=en>
- Arup, 2010. *Feasibility Study for Europe-Wide CO<sub>2</sub> infrastructure*. [pdf] Leeds (UK): Arup. Available at: [http://ec.europa.eu/energy/coal/studies/doc/2010\\_10\\_co2\\_infrastructures.pdf](http://ec.europa.eu/energy/coal/studies/doc/2010_10_co2_infrastructures.pdf)
- Aycaguer, A.C., Lev-On, M., and Winer, A.M., 2001. Reducing Carbon Dioxide Emissions with Enhanced Oil Recovery Projects: A Life Cycle Assessment Approach. *Energy & Fuels*, 2001, 15(2), pp.303–308.
- Hong, B.D. and Slatick, E. R., 1994. Carbon Dioxide *Emission Factors for Coal*. Quarterly Coal Report, January-April 1994, DOE/EIA-0121(94/Q1). [html] Cambridge (UK): CMCL Innovations. Available at: [http://www.eia.gov/coal/production/quarterly/co2\\_article/co2.html](http://www.eia.gov/coal/production/quarterly/co2_article/co2.html)
- Benton, D., 2015. *Decarbonising British industry: why industrial CCS clusters are the answer*. [pdf] London: Green Alliance. Available at: [http://www.green-alliance.org.uk/decarbonising\\_british\\_industry.php](http://www.green-alliance.org.uk/decarbonising_british_industry.php)
- Bhave, A. 2012. *Techno-Economic Study of Biomass to Power with CO<sub>2</sub> Capture*. Presentation for the 12 APGTF Workshop ‘CCS – Can UK maintain a leadership role?’ [pdf] Available at: <http://www.apgtf-uk.com/files/workshops/12thWorkshop2012/10AmitBhave.pdf>
- Blackford, J., Stahl, H., Bull, J. M., Bergès, B. J. P., Cevatoglu, M., Lichtschlag, A., Connelly, D., James, R.H., Kita, J., Long, D., Naylor, M., Shitashima, K., Smith, D., Taylor, P., Wright, I., Akhurst, M., Chen, B., Gernon, T.M., Hauton, C., Hayashi, M., Kaieda, H., Leighton, T.G., Sato, T., Sayer, M.D.J., Suzumura, M., Tait, K., Vardy, M.E., White, P.R., and Widdicombe, S., 2014. Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage. *Nature Climate Change* 4, pp.1011–1016.
- Blunt, M., 2010. *Carbon dioxide storage*. [pdf] London: Imperial College. Available at: [https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing Papers/Briefing Paper 4.pdf](https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Briefing%20Paper%204.pdf)
- Bowen, A., 2011. *The case for carbon pricing*. [pdf] London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science. Available at: [http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/02/PB\\_case-carbon-pricing\\_Bowen.pdf](http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/02/PB_case-carbon-pricing_Bowen.pdf)
- Boyd, R. and Hervé-Mignucci, M., 2013. San Giorgio Group Case Study: Jädraås Onshore Windfarm. [pdf] San Francisco (CA): Climate Policy Initiative. Available at: <http://climatepolicyinitiative.org/wp-content/uploads/2012/08/Jadraas-Onshore-Windfarm-Case-Study.pdf>
- BP, 2014. *BP Statistical Review of World Energy* June 2014. [pdf] London: BP. Available at: <http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BP-statistical-review-of-world-energy-2014-full-report.pdf>
- Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., Fernandez, J.R., Ferrari, M.-C., Gross, R., Hallett, J.P., Haszeldine, R.S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R.T.J., Pourkashanian, M., Rochelle, G.T., Shah, N., Yao, J.G. and Fennell, P. S., 2014. Carbon capture and storage update. *Energy & Environmental Science*, 7(1), pp.130–189.



- Carbon Capture & Storage Association (CCSA), 2011. *A Strategy for CCS in the UK and Beyond*. [pdf] London: CCSA. Available at: [http://www.ccsassociation.org/index.php/download\\_file/view/251/76/](http://www.ccsassociation.org/index.php/download_file/view/251/76/)
- CCS Cost Reduction Taskforce (CCS CRT), 2013. *The potential for reducing the costs of CCS in the UK – Final Report*. [pdf] London: CCS CRT. Available at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/201021/CCS\\_Cost\\_Reduction\\_Taskforce\\_-\\_Final\\_Report\\_-\\_May\\_2013.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/201021/CCS_Cost_Reduction_Taskforce_-_Final_Report_-_May_2013.pdf)
- Committee on Climate Change (CCC), 2008. *Building a low-carbon economy – the UK's contribution to tackling climate change*. [pdf] London: CCC. Available at: <http://www.theccc.org.uk/publication/building-a-low-carbon-economy-the-uks-contribution-to-tackling-climate-change-2/>
- Committee on Climate Change (CCC), 2010. *The Fourth Carbon Budget Reducing emissions through the 2020s*. [pdf] London: CCC. Available at: [http://downloads.theccc.org.uk.s3.amazonaws.com/4th Budget/CCC-4th-Budget-Book\\_with-hypers.pdf](http://downloads.theccc.org.uk.s3.amazonaws.com/4th%20Budget/CCC-4th-Budget-Book_with-hypers.pdf)
- Council of the European Union, 2007. *Presidency Conclusions – Brussels European Council 8/9 March 2007*. [pdf] Brussels: Council of the European Union. Available at: [http://www.consilium.europa.eu/ueDocs/cms\\_Data/docs/pressData/en/ec/93135.pdf](http://www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/ec/93135.pdf)
- Daverne, D., 2013. Integrated Carbon Capture & Storage Demonstration Boundary Dam Power Station. In *Proceedings from the 2012 CCS Cost Workshop*, 25-26 April 2012 California US. [pdf] Canberra (AU): GCCSI. Available at: [http://sequestration.mit.edu/pdf/2012\\_Costs\\_Workshop\\_Proceedings.pdf](http://sequestration.mit.edu/pdf/2012_Costs_Workshop_Proceedings.pdf)
- Davis, C. B., Chmieliauskas, A., Dijkema, G. P. J., and Nikolic, I., 2014. *Enipedia*. [html] Delft (NL): Energy & Industry Group, Faculty of Technology, Policy and Management, TU Delft. Available at: <http://enipedia.tudelft.nl>
- Department of Energy and Climate Change (DECC), 2013a. *Electricity Generation Costs 2013*. [pdf] London: DECC. Available at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/223940/DECC\\_Electricity\\_Generation\\_Costs\\_for\\_publication\\_-\\_24\\_07\\_13.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223940/DECC_Electricity_Generation_Costs_for_publication_-_24_07_13.pdf)
- Department of Energy and Climate Change (DECC), 2013b. *Investing in renewable technologies – CfD contract terms and strike prices*. [pdf] London: DECC. Available at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/263937/Final\\_Document\\_-\\_Investing\\_in\\_renewable\\_technologies\\_-\\_CfD\\_contract\\_terms\\_and\\_strike\\_prices\\_UPDATED\\_6\\_DEC.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263937/Final_Document_-_Investing_in_renewable_technologies_-_CfD_contract_terms_and_strike_prices_UPDATED_6_DEC.pdf)
- Department of Energy and Climate Change (DECC), 2015. *Energy Trends – March 2015*. [pdf] London: DECC. Available at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/415976/ET\\_Mar\\_15.PDF](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/415976/ET_Mar_15.PDF)
- De Nationale Geologische Onderzoekingen voor Danmark og Grønland (GEUS), 2008. *EU GeoCapacity – Assessing European Capacity for Geological Storage of Carbon Dioxide*. Publishable Final Activity Report. [pdf] Copenhagen: GEUS. Available at: [http://ec.europa.eu/clima/events/docs/0028/geocapacity\\_en.pdf](http://ec.europa.eu/clima/events/docs/0028/geocapacity_en.pdf)
- Dessens, O., Anandarajah, G., and Gambhir, A., 2014. *Review of existing emissions pathways and evaluation of decarbonisation rates*. AVOID 2 WPC1. [pdf] London: Imperial College. Available at: <https://workspace.imperial.ac.uk/grantham/Public/AVOID/Review-of-existing-emissions-pathways-and-evaluation-of-decarbonisation-rates-WPC1.pdf>
- Drax, 2015. Preliminary results for the year ended 31 December 2014 – Delivering Europe's largest decarbonisation project, on time and on budget, whilst producing 8% of the UK's electricity. [pdf] Selby (UK): Drax Group plc. Available at: <http://www.drax.com/media/56579/preliminary-results-for-the-year-ended-31-december-2014.pdf>
- Energy Technologies Institute (ETI), 2014. *Potential for CCS in the UK*. [pdf] Loughborough (UK): ETI. Available at: [http://www.eti.co.uk/wp-content/uploads/2014/03/ETI\\_CCS\\_Insights\\_Report.pdf](http://www.eti.co.uk/wp-content/uploads/2014/03/ETI_CCS_Insights_Report.pdf)
- Energy Technologies Institute (ETI), 2015. *Building the UK carbon capture and storage sector by 2030 – Scenarios and actions*. [pdf] Loughborough (UK): ETI. Available at: <http://www.eti.co.uk/carbon-capture-and-storage-building-the-uk-carbon-capture-and-storage-sector-by-2030/>
- European Academies Science Advisory Council (EASAC), 2013. *Carbon capture and storage in Europe*. [pdf] Halle (Germany): EASAC. Available at: [http://www.easac.eu/fileadmin/Reports/Easac\\_13\\_CCS\\_Web\\_Complete.pdf](http://www.easac.eu/fileadmin/Reports/Easac_13_CCS_Web_Complete.pdf)
- European Climate Foundation (ECF), 2012. *Roadmap 2050: a practical guide to a prosperous, low-carbon Europe. Volume I: technical and economic assessment*. [pdf] The Hague: ECF. Available at: <http://www.roadmap2050.eu/reports>

European Commission, 2008. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions- 20 20 by 2020 Europe's climate change opportunity*. [pdf] Brussels: European Commission. Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52008DC0030&from=EN>

European Commission, 2011a. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – A Roadmap for moving to a competitive low carbon economy in 2050*. [pdf] Brussels: European Commission. Available at: [http://eur-lex.europa.eu/resource.html?uri=cellar:5db26ecc-ba4e-4de2-ae08-dba649109d18.0002.03/DOC\\_1&format=PDF](http://eur-lex.europa.eu/resource.html?uri=cellar:5db26ecc-ba4e-4de2-ae08-dba649109d18.0002.03/DOC_1&format=PDF)

European Commission, 2011b. *Impact Assessment accompanying the document Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions – Energy Roadmap 2050*. Commission Staff Working Paper. SEC(2011) 1565/2 Part 1/2. [pdf] Brussels: European Commission. Available at: [https://ec.europa.eu/energy/sites/ener/files/documents/sec\\_2011\\_1565\\_part1.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part1.pdf)

European Commission, 2011c. *Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide – Guidance Document 1 CO<sub>2</sub> Storage Life Cycle Risk Management Framework*. [pdf] Brussels: European Commission. Available at: [http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd1\\_en.pdf](http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd1_en.pdf)

European Commission, 2011d. *Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide – Guidance Document 2 Characterisation of the Storage Complex, CO<sub>2</sub> Stream Composition, Monitoring and Corrective Measures*. [pdf] Brussels: European Commission. Available at: [http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd2\\_en.pdf](http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd2_en.pdf)

European Commission, 2011e. *Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide – Guidance Document 3 Criteria for Transfer of Responsibility to the Competent Authority*. [pdf] Brussels: European Commission. Available at: [http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd3\\_en.pdf](http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd3_en.pdf)

European Commission, 2011f. *Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide – Guidance Document 4 Article 19 Financial Security and Article 20 Financial Mechanism*. [pdf] Brussels: European Commission. Available at: [http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd4\\_en.pdf](http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd4_en.pdf)

European Commission, 2012. *Connecting Europe – The energy infrastructure for tomorrow*. Brussels: European Commission.

European Commission, 2013a. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – Long term infrastructure vision for Europe and beyond*. Brussels, 14.10.2013COM(2013) 711 final. [pdf] Brussels: European Commission. Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013DC0711&from=EN>

European Commission, 2013b. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Future of Carbon Capture and Storage in Europe*. [pdf] Brussels: European Commission. Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0180:FIN:EN:PDF>

European Commission, 2014a. *Communication from the Commission – Guidelines on State aid for environmental protection and energy 2014-2020*. OJ, C 200/1, 2. [pdf] Brussels: European Commission. Available at: [http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014XC0628\(01\)&from=EN](http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014XC0628(01)&from=EN)

European Commission, 2014b. *EU Energy in Figures – Statistical Pocketbook 2014*. [pdf] Luxembourg: Publications Office of the European Union. Available at: [http://ec.europa.eu/energy/sites/ener/files/documents/2014\\_pocketbook.pdf](http://ec.europa.eu/energy/sites/ener/files/documents/2014_pocketbook.pdf)

European Commission, 2014c. *Report from the Commission to the European Parliament and the Council on the implementation of the European Energy Programme for Recovery*. [pdf] Brussels: European Commission. Available at: [http://ec.europa.eu/energy/eepr/doc/2014\\_cswd\\_council\\_final.pdf](http://ec.europa.eu/energy/eepr/doc/2014_cswd_council_final.pdf)

European Commission 2014d. *Communication from the Commission to The European Parliament, the Council, the European Central Bank, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank – An Investment Plan for Europe*. Brussels, 26.11.2014 COM(2014) 903 final. [pdf] Brussels: European Commission. Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0903&from=EN>

- European Commission, 2015. *Energy Union Package – Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*. Brussels, 25.2.2015, COM(2015) 80 final. [pdf] Brussels: European Commission. Available at: [http://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC\\_1&format=PDF](http://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC_1&format=PDF)
- European Council, 2009. *Brussels European Council 29/30 October 2009 – Presidency Conclusions*. [pdf] Brussels: European Council. Available at: <http://register.consilium.europa.eu/doc/srv?l=EN&f=ST%2015265%202009%20INIT>
- European Council, 2011. *European Council 4 February 2011 – Conclusions*. [pdf] Brussels: European Council. Available at: [http://www.consilium.europa.eu/uedocs/cms\\_data/docs/pressdata/en/ec/119175.pdf](http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/119175.pdf)
- European Council, 2014. *European Council (23 and 24 October 2014) – Conclusions. 2030 Climate and Energy Policy Framework*. [pdf] Brussels: European Council. Available at: [http://www.consilium.europa.eu/uedocs/cms\\_data/docs/pressdata/en/ec/145397.pdf](http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf)
- European Parliament and Council, 2013. *Regulation (EU) no 1303/2013 of the European Parliament and of the Council of 17 December 2013 laying down common provisions on the European Regional Development Fund, the European Social Fund, the Cohesion Fund, the European Agricultural Fund for Rural Development and the European Maritime and Fisheries Fund and laying down general provisions on the European Regional Development Fund, the European Social Fund, the Cohesion Fund and the European Maritime and Fisheries Fund and repealing Council Regulation (EC) No 1083/2006*. OJ L 347/320, 20.12.2013. [pdf] Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R1303&from=EN>
- Eurostat, 2014a. *Supply, transformation, consumption – all products – annual data [nrg\_100a] Last update: 30-07-2014*. [html] Luxembourg: Eurostat. Available at: [http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg\\_100a&lang=en](http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_100a&lang=en)
- Eurostat, 2014b. *Supply, transformation, consumption – electricity – annual data*. [html] Luxembourg: Eurostat. Available at: [http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg\\_105a&lang=en](http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_105a&lang=en)
- Evar, B., Armeni, C., and Scott, V., 2012. An introduction to key developments and concepts in CCS. In Markusson, N., Shackley, S., and Evar, B., (Eds.), *The social dynamics of carbon capture and storage*. Abingdon (UK): Routledge, Taylor and Francis.
- Financial Times, 2014. *Brussels backs Hinkley Point C as cost forecasts soar* – October 8, 2014. [html] Available at: <http://www.ft.com/cms/s/0/372216e6-4ec0-11e4-b205-00144feab7de.html#axzz3Q1F2K5UN>
- Frisari, G., Hervé-Mignucci, M., Micale, V., & Mazza, F., 2013. *Risk Gaps: Executive Summary*. [pdf] San Francisco (CA): Climate Policy Initiative. Available at: <http://climatepolicyinitiative.org/wp-content/uploads/2013/01/Risk-Gaps-Executive-Summary.pdf>
- Gammer, D., 2014. *CCS Infrastructure Development – All Energy 2014*. [pdf] Loughborough (UK): Energy Technologies Institute (ETI). Available at: <http://www.eti.co.uk/wp-content/uploads/2014/05/CCS-Infrastructure-Development-All-Energy-2014ff-Den-Gammer.pdf>
- Global Energy Assessment (GEA), 2012. *Global Energy Assessment – Toward a Sustainable Future*. [pdf] Cambridge (UK), New York (USA) and Laxenburg (AT): Global Energy Assessment and International Institute for Applied Systems Analysis. Available at: <http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA-Summary-web.pdf>
- Global CCS Institute (GCCSI), 2009. *Strategic analysis of the global status of carbon capture and storage. Report 5 (Synthesis report)*. [pdf] Canberra (AU): GCCSI. Available at: <http://www.globalccsinstitute.com/publications/strategic-analysis-global-status-carbon-capture-storage-Report-5>
- Global CCS Institute (GCCSI), 2011a. *The cost of CCS and other low-carbon technologies – Issues Brief 2011, No. 2*. [pdf] Canberra (AU): GCCSI. Available at: <http://cdn.globalccsinstitute.com/sites/default/files/publications/24202/costs-ccs-and-other-low-carbon-technologies.pdf>
- Global CCS Institute (GCCSI), 2011b. *The global status of CCS 2011*. [pdf] Canberra (AU): GCCSI. Available at: <http://cdn.globalccsinstitute.com/sites/default/files/publications/22562/global-status-ccs-2011.pdf>
- Global CCS Institute (GCCSI), 2011c. *The Global Status of CCS: 2010*. [pdf] Canberra (AU): GCCSI. Available at: <http://cdn.globalccsinstitute.com/sites/default/files/publications/12776/global-status-ccs-2010.pdf>
- Global CCS Institute (GCCSI), 2012. *The Global Status of CCS 2012*. [pdf] Canberra (AU): GCCSI. Available at: <http://cdn.globalccsinstitute.com/sites/default/files/publications/47936/global-status-ccs-2012.pdf>

- Global CCS Institute (GCCSI), 2013. *The experience of CCS demonstration projects in the European Union with the transposition of the CCS Directive*. [pdf] Canberra (AU): GCCSI. Available at: <http://www.globalccsinstitute.com/publications/experience-ccs-demonstration-projects-eu-transposition-ccs-directive>
- Global CCS Institute (GCCSI), 2014a. *Large Scale CCS Projects*. [pdf] Canberra (AU): GCCSI. Available at: <http://www.globalccsinstitute.com/projects/large-scale-ccs-projects>
- Global CCS Institute (GCCSI), 2014b. *Status of CCS Project Database – 7 October 2014*. [html] Canberra (AU): GCCSI. Available at: <http://www.globalccsinstitute.com/projects/status-ccs-project-database>
- Global CCS Institute (GCCSI), 2014c. *The Global Status of CCS 2014*. [pdf] Canberra (AU): GCCSI. Available at: <http://www.globalccsinstitute.com/publications/global-status-ccs-2014>
- Global CCS Institute (GCCSI) & Parsons Brinkerhoff, 2011. *Accelerating the uptake of CCS: Industrial use of captured carbon dioxide*. [pdf] Canberra (AU): GCCSI. Available at: <http://decarboni.se/sites/default/files/publications/14026/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide.pdf>
- Godec, M. L., 2011. *Global technology roadmap for CCS in industry – Sectoral Assessment CO<sub>2</sub> Enhanced Oil Recovery*. [pdf] Arlington (VA) USA. Available at: [http://www.unido.org/fileadmin/user\\_media/Services/Energy\\_and\\_Climate\\_Change/Energy\\_Efficiency/CCS/EOR.pdf](http://www.unido.org/fileadmin/user_media/Services/Energy_and_Climate_Change/Energy_Efficiency/CCS/EOR.pdf)
- Gross, R., Heptonstall, P., Greenacre, P., Candelise, C., Jones, F., & Castillo, A. C., 2013. *Presenting the Future – An assessment of future costs estimation methodologies in the electricity generation sector*. [pdf] London: UKERC. Available at: <http://www.ukerc.ac.uk/publications/presenting-the-future-electricity-generation-cost-estimation-methodologies.html>
- Her Majesty's Government (HMG), 2011. *The Carbon Plan: Delivering Our Low Carbon Future*. [pdf] London: HMG. Available at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf)
- Hervé-Mignucci, M., 2012. *San Giorgio Group Case Study: Walney Offshore Windfarms*. [pdf] San Francisco (CA): Climate Policy Initiative. Available at: <http://climatepolicyinitiative.org/wp-content/uploads/2013/02/Walney-Offshore-Windfarms.pdf>
- Honoré, A., 2014. *The Outlook for Natural Gas Demand in Europe*. [pdf] Oxford (UK): Oxford Institute for Energy Studies. Available at: <http://www.oxfordenergy.org/wpcms/wp-content/uploads/2014/06/NG-87.pdf>
- International Energy Agency (IEA), 2009. *Technology Roadmap: Carbon Capture and Storage 2009*. [pdf] Paris: IEA. Available at: <http://www.iea.org/publications/freepublications/publication/CCSRoadmap2009.pdf>
- International Energy Agency (IEA), 2010a. *Power Generation from Coal – Measuring and Reporting Efficiency Performance and CO<sub>2</sub> Emissions*. [pdf] Paris: IEA. Available at: [http://www.iea.org/ciab/papers/power\\_generation\\_from\\_coal.pdf](http://www.iea.org/ciab/papers/power_generation_from_coal.pdf)
- International Energy Agency (IEA), 2010b. *Projected Costs of Generating Electricity – 2010 Edition*. [pdf] Paris: IEA. Available at: [http://www.iea.org/publications/freepublications/publication/projected\\_costs.pdf](http://www.iea.org/publications/freepublications/publication/projected_costs.pdf)
- International Energy Agency (IEA), 2010c. *World Energy Outlook 2010*. [pdf] Paris: IEA. Available at: <http://www.worldenergyoutlook.org/media/weo2010.pdf>
- International Energy Agency (IEA), 2011a. *Combining Bioenergy with CCS Reporting and Accounting for Negative Emissions under UNFCCC and the Kyoto Protocol*. [pdf] Paris: IEA. Available at: [http://www.iea.org/publications/freepublications/publication/bioenergy\\_ccs.pdf](http://www.iea.org/publications/freepublications/publication/bioenergy_ccs.pdf)
- International Energy Agency (IEA), 2011b. *Cost and Performance of Carbon Dioxide Capture from Power Generation*. [pdf] Paris: IEA. Available at: [http://www.iea.org/publications/freepublications/publication/costperf\\_ccs\\_powergen.pdf](http://www.iea.org/publications/freepublications/publication/costperf_ccs_powergen.pdf)
- International Energy Agency (IEA), 2012. *Energy Technology Perspectives (ETP) 2012 – Pathways to a Clean Energy System*. [pdf] Paris: IEA. Available at: [http://www.iea.org/publications/freepublications/publication/ETP2012\\_free.pdf](http://www.iea.org/publications/freepublications/publication/ETP2012_free.pdf)
- International Energy Agency (IEA), 2013a. *Technology Roadmap – Carbon Capture and Storage. 2013 Edition*. [pdf] Paris: IEA. Available at: <https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf>
- International Energy Agency (IEA), 2013b. *Tracking Clean Energy Progress: IEA Input to the Clean Energy Ministerial*. [pdf] Paris: IEA. Available at: [http://www.iea.org/publications/tcep\\_web.pdf](http://www.iea.org/publications/tcep_web.pdf)
- International Energy Agency (IEA), 2013c. *World Energy Outlook 2013*. Paris: IEA.



- International Energy Agency (IEA), 2014a. *Carbon Capture and Storage: Legal and Regulatory Review – Edition 4*. [pdf] Paris: IEA. Available at: [http://www.iea.org/publications/insights/insightpublications/CCSReview\\_4thEd\\_FINAL.pdf](http://www.iea.org/publications/insights/insightpublications/CCSReview_4thEd_FINAL.pdf)
- International Energy Agency (IEA), 2014b. *CCS 2014 – What lies in store for CCS?* [pdf] Paris: IEA. Available at: [https://www.iea.org/publications/insights/insightpublications/Insight\\_CCS2014\\_FINAL.pdf](https://www.iea.org/publications/insights/insightpublications/Insight_CCS2014_FINAL.pdf)
- International Energy Agency (IEA), 2014c. *World Energy Outlook 2014*. Paris: IEA.
- International Energy Agency (IEA), 2014d. *Energy Technology RD&D Statistics*. Paris: IEA.
- International Energy Agency (IEA) Greenhouse Gas (GHG) R&D Programme, 2009. *CO<sub>2</sub> Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery. 2009/12, December 2009*. [pdf] Paris: IEA. Available at: [http://ieaghg.org/docs/General\\_Docs/Reports/2009-12.pdf](http://ieaghg.org/docs/General_Docs/Reports/2009-12.pdf)
- Intergovernmental Panel on Climate Change (IPCC), 2014a. Annex III: Technology Specific cost and performance parameters. In S. Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani (Ed.), *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [pdf] Cambridge (UK) and New York (NY, USA): IPCC. Available at: [http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc\\_wg3\\_ar5\\_final-draft\\_postplenary\\_annex-iii.pdf](http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_annex-iii.pdf)
- Intergovernmental Panel on Climate Change (IPCC), 2014b. Summary for Policymakers In S. Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani (Ed.), *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [pdf] Cambridge (UK) and New York (NY, USA): IPCC. Available at: [http://report.mitigation2014.org/spm/ipcc\\_wg3\\_ar5\\_summary-for-policymakers\\_approved.pdf](http://report.mitigation2014.org/spm/ipcc_wg3_ar5_summary-for-policymakers_approved.pdf)
- Jones, F., 2012. *UKERC Technology and Policy Assessment Cost Methodologies Project: CCS Case Study*. UKERC Report UKERC/WP/TPA/2013/004. [pdf] London: UKERC. Available at: [http://www.ukerc.ac.uk/support/tiki-download\\_file.php?fileId=3207](http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=3207)
- Joskow, P. L., 2011. Comparing the costs of intermittent and dispatchable electricity generating technologies. *The American Economic Review*, 101(3), pp.238–241.
- Knopf, B., Chen, Y.-H. H., De Cian, E., Förster, H., Kanudia, A., Karkatsouli, I., Keppo, I., Koljonen, T., Schumacher, K. & Van Vuuren, D. P., 2013. Beyond 2020 — Strategies and Costs For Transforming The European Energy System. *Climate Change Economics*, 4 (Suppl. 01).
- Krey, V., Luderer, G., Clarke, L., & Kriegler, E., 2013. Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, pp.1–14.
- Léandri, J.F., Paelinck, P., Skea, A., & Bohtz, C., 2011. *Cost assessment of fossil power plants equipped with CCS under typical scenarios*. [pdf] Levallois-Perret Cedex (FR): Alstom Power. Available at: <http://www.zeroemissionsplatform.eu/library/publication/181-cost-assessment-of-fossil-power-plants-equipped-with-ccs-under-typical-scenarios.html>
- Leeson, D., Fairclough, J., Petit, C., & Fennell, P., 2014. *A Systematic Review of Current Technology and Cost for Industrial Carbon Capture*. [pdf] London: Imperial College. Available at: <http://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/institute-reports-and-analytical-notes/A-Systematic-Review-of-Industrial-CCS---GR7.pdf>
- Low Carbon Innovation Coordination Group (LCICG), 2012. *Technology Innovation Needs Assessment (TINA) – Carbon Capture & Storage in the Power Sector. Summary report*. [pdf] London: Ecofys Consulting. Available at: <http://www.lowcarboninnovation.co.uk/document.php?o=5>
- MacDowell, N., Florin, N., Buchard, A., Hallett, J., Galindo, A., Jackson, G., Adjiman, C.S., Williams, C.K., Shah, N. & Fennell, P., 2010. An overview of CO<sub>2</sub> capture technologies. *Energy & Environmental Science*, 3(11), pp.1645–1669.
- Mac Dowell, N., Fennell, P. S., Shah, N. and Maitland, G. C., Forthcoming. *Carbon Capture Utilisation: A beguiling opportunity or dangerous distraction?*
- Makuch, K & Pereira, R., 2012. *Environmental and Energy Law*. Chichester (UK): Wiley-Blackwell.
- Massachusetts Institute of Technology (MIT), 2013. *Carbon Capture and Sequestration Project Database*. [html] Available at: [http://sequestration.mit.edu/tools/projects/index\\_capture.html](http://sequestration.mit.edu/tools/projects/index_capture.html)
- McGlade, C., and Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, 517(7533), pp.187–190.

- McGlashan, N. R., Workman, M. H. W., Caldecott, B., and Shah, N., 2012. *Negative Emissions Technologies*. Grantham Institute for Climate Change Briefing Paper No.8. [pdf] London: Imperial College. Available at: [https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing Papers/Briefing Paper 8.pdf](https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Briefing%20Paper%208.pdf)
- Morbee, J., Serpa, J., and Tzimas, E., 2010. *The Evolution of the Extent and the Investment Requirements of a Trans-European CO<sub>2</sub> Transport Network*. [pdf] Luxembourg: Publications Office of the European Union. Available at: <http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/15100/1/Idna24565enn.pdf>
- Nasdaq, 2015. *End of day Commodity Futures Price Quotes for Crude Oil Brent*. [html] Retrieved January 23, 2015. Available at: <http://www.nasdaq.com/markets/crude-oil-brent.aspx>
- National Energy Technology Laboratory (NETL), 2013. *The Cost and Performance Baseline for Fossil Energy Power Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity*. [pdf] Washington, DC: NETL, US Department of Energy. Available at: [http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/OE/BitBase\\_FinRep\\_Rev2a-3\\_20130919\\_1.pdf](http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/OE/BitBase_FinRep_Rev2a-3_20130919_1.pdf)
- Nelson, D., and Pierpont, B., 2013. *The Challenge of Institutional Investment in Renewable Energy*. [pdf] San Francisco (CA): Climate Policy Initiative. Available at: <http://climatepolicyinitiative.org/wp-content/uploads/2013/03/The-Challenge-of-Institutional-Investment-in-Renewable-Energy.pdf>
- Neuhoff, K., Boyd, R., Grau, T., Hobbs, B., Newbery, D., Borggrefe, F., Barquin, J., Echavarren, F., Bialek, J., Dent, C., von Hirschhausen, C., Kunz, F., Weigt, H., Nabe, C., Papaefthymiou, G., Weber, C., 2011. *Consistency with other EU policies, System and Market integration: A Smart Power Market at the Centre of a Smart Grid*. [pdf] Karlsruhe (DE). Available at: [http://www.reshaping-res-policy.eu/downloads/D20-A Smart-Power-Market-at-the-Centre-of-a-Smart-Grid.pdf](http://www.reshaping-res-policy.eu/downloads/D20-A%20Smart-Power-Market-at-the-Centre-of-a-Smart-Grid.pdf)
- Oxera, 2011. *Discount rates for low-carbon and renewable generation technologies* – Prepared for the Committee on Climate Change. [pdf] Oxford: Oxera. Available at: <http://www.oxera.com/Oxera/media/Oxera/downloads/reports/Oxera-report-on-low-carbon-discount-rates.pdf?ext=.pdf>
- Parsons Brinckerhoff, 2010. *Powering the Nation Update 2010*. [pdf] London: Parsons Brinckerhoff. Available at: [https://www.pbworld.com/pdfs/regional/uk\\_europe/pb\\_ptn\\_update2010.pdf](https://www.pbworld.com/pdfs/regional/uk_europe/pb_ptn_update2010.pdf)
- PBL Netherlands Environmental Assessment Agency and European Commission Joint Research Centre (JRC), 2012. *Trends in global CO<sub>2</sub> emissions – 2012 report*. [pdf] The Hague: PBL. Available at: [http://www.pbl.nl/sites/default/files/cms/publicaties/PBL\\_2012\\_Trends\\_in\\_global\\_CO<sub>2</sub>\\_emissions\\_500114022.pdf](http://www.pbl.nl/sites/default/files/cms/publicaties/PBL_2012_Trends_in_global_CO2_emissions_500114022.pdf)
- Pembina Institute, 2015. *Climate Impacts*. [html] Calgary (CA): Pembina Institute. Available at: [http://www.pembina.org/oil-sands/os101/climate#footnote1\\_bkgw9yf](http://www.pembina.org/oil-sands/os101/climate#footnote1_bkgw9yf)
- Platts, 2012. *PowerVision*. [html] New York (NY): Platts. Available at: <http://www.platts.com/products/powervision>
- Platts, 2013. *World Electric Power Plants Database*. [html] New York (NY): Platts. Available at: <http://www.platts.com/products/world-electric-power-plants-database>
- Rochelle, G. T., 2009. Amine Scrubbing for CO<sub>2</sub> Capture. *Science*, 325(5948), pp.1652–1654.
- Rhodes J. and Keith D., 2008. Biomass with capture: negative emissions within social and environmental constraints: an editorial comment. *Climatic Change*. 87(2008), pp.321–8.
- SaskPower, 2013. *SaskPower Annual Report 2013 – It takes power to grow*. [pdf] Regina, Saskatchewan (CA): SaskPower. Available at: [http://www.saskpower.com/wp-content/uploads/2013\\_saskpower\\_annual\\_report.pdf](http://www.saskpower.com/wp-content/uploads/2013_saskpower_annual_report.pdf)
- Saskpower, 2014. *Boundary Dam CCS Project*. [html] Regina, Saskatchewan (CA): SaskPower. Available at: <http://saskpowerccs.com/ccs-projects/boundary-dam-carbon-capture-project/>
- SaskPower, 2015a. *Building on the success at Boundary Dam*. UKCCSRC Cranfield Biannual 21-22 April 2015. [html] Regina, Saskatchewan (CA): SaskPower. Available at: <http://www.slideshare.net/UKCCSRC/max-ball-saskpowerchoosing-researchdirectionsforccsranfieldbiannual2122april>
- SaskPower, 2015b. *CCS performance data exceeding expectations at world-first Boundary Dam Power Station Unit #3*. Press Release 11 February 2015. [html] Regina, Saskatchewan (CA): SaskPower. Available at: <http://www.saskpower.com/about-us/media-information/news-releases/ccs-performance-data-exceeding-expectations-at-world-first-boundary-dam-power-station-unit-3/>

- Shackley, S., Waterman, H., Godfroij, P., Reiner, D., Anderson, J., Draxlbauer, K., de Conick, H., Groenenberg, H., Flach, T., and Sigurtorsson, G., 2007. *Stakeholder Perceptions of CO<sub>2</sub> Capture and Storage in Europe: Results from the EU-funded ACCSEPT Survey Deliverable D3.1 from ACCSEPT – Main Report*. Available at: [http://www.accsept.org/outputs/main\\_survey\\_report.pdf](http://www.accsept.org/outputs/main_survey_report.pdf)
- Triple E, Ricardo AEA and TNO, 2014. *Support to the review of Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive)*. [pdf] Brussels: European Commission. Available at: <http://www.ccs-directive-evaluation.eu/assets/CCS-Directive-evaluation-final-report-tasks-2-and-3-27-1-15-new-cover.pdf>
- UK Energy Research Centre (UKERC), 2013. *The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios*. [pdf] London: UKERC. Available at: [http://www.ukerc.ac.uk/support/tiki-download\\_file.php?fileId=2976](http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2976)
- Utrecht University, 2014. *LIMITS Low climate IMPact scenarios and the Implications of required Tight emission control Strategies – DELIVERABLE No D3.1 Report on the comparison of model runs, based on the global and national IAMs*. [pdf] Utrecht (NL): Utrecht University. Available at: [http://www.feem-project.net/limits/docs/limits\\_d3-1\\_uu.pdf](http://www.feem-project.net/limits/docs/limits_d3-1_uu.pdf)
- Waissbein, O., Glemarec, Y., Bayraktar, H., and Schmidt, T.S., 2013. *Derisking Renewable Energy Investment. A Framework to Support Policymakers in Selecting Public Instruments to Promote Renewable Energy Investment in Developing Countries*. [pdf] New York: UNDP. Available at: [http://www.undp.org/content/undp/en/home/librarypage/environment-energy/low\\_emission\\_climateresilientdevelopment/derisking-renewable-energy-investment/](http://www.undp.org/content/undp/en/home/librarypage/environment-energy/low_emission_climateresilientdevelopment/derisking-renewable-energy-investment/)
- Watson, R., 2014. CCS Technology Powering the Future in Saskatchewan, Canada. *Hitachi Review*, 63(7). [pdf] Available at: [http://www.hitachi.com/rev/pdf/2014/r2014\\_07\\_expert\\_01.pdf](http://www.hitachi.com/rev/pdf/2014/r2014_07_expert_01.pdf)
- WorleyParsons, 2011. *Economic Assessment of Carbon Capture and Storage Technologies – 2011 update*. [pdf] Canberra (AU): GCCSI. Available at: <http://cdn.globalccsinstitute.com/sites/default/files/publications/12786/economic-assessment-carbon-capture-and-storage-technologies-2011-update.pdf>
- Zero Emission Platform (ZEP), 2011. *The Cost of CO<sub>2</sub> Capture, Transport and Storage – Post demonstration CCS in the EU*. [pdf] Available at: <http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html>



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