GLOBAL CCS INSTITUTE

# THE COSTS OF CCS AND OTHER LOW-CARBON TECHNOLOGIES — ISSUES BRIEF 2011, NO. 2

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## KEY POINTS

Managing the risks of climate change requires the development and adoption of a wide range of low-carbon technologies across many industrial sectors.

It is likely that the stringent targets of 450ppm can only be achieved efficiently with a portfolio of technologies that include options that have the potential for removing carbon dioxide ($CO_2$) from the atmosphere, as well as negating $CO_2$ emissions from industrial sources, such as carbon capture and storage (CCS) technologies.

This paper focuses on the electric power generation industry, and examines the costs of different technologies that are expected to play a part in reducing $CO_2$ emissions to the atmosphere.

The Global CCS Institute has been tracking and reporting on the latest cost studies of various CCS technologies for the past two years. Drawing on recent studies into other low-carbon technologies, the costs for a range of technologies are derived using a consistent methodology and underlying economic assumptions. The technologies compared in this paper include CCS, wind, nuclear, solar thermal and solar photovoltaics.

The key findings are:

- CCS is a competitive power sector emissions abatement tool when compared to other low-carbon technologies.
- Hydropower and onshore wind technologies are among the least-cost technologies identified for reducing emissions from the power sector.
- Once these relatively low-cost technology options are fully exploited – because of limits in their availability – or in countries where these technologies are not an option, CCS becomes very competitive.
- The cost of mitigating or avoiding $CO_2$ emissions for a coal-fired power plant fitted with current CCS technology ranges from US$23-92 per tonne of $CO_2$ and is a little higher for natural gas-fired power plants. This is compared to an avoided cost of US$90-176/tonne for offshore wind, US$139-201/tonne for solar thermal, and even more for solar PV.
- It is important to note that the costs of new technologies that have not yet reached full maturity, such as CCS amongst others, will become lower in the future.
- These findings are in line with International Energy Agency (IEA) estimates that identify that without CCS, abatement costs in the electricity sector could be higher by more than 70 per cent.


Combating climate change requires urgent action. In the Copenhagen Accord, the international community set a target to keep greenhouse gas (GHG) concentrations in the atmosphere at a level such that global temperature increases will be below 2°C (UNFCCC 2009). This atmospheric GHG concentration target, estimated at around 450 parts per million (ppm) of carbon dioxide-equivalent, requires deep cuts in global emissions by 50 to 85 per cent compared to 2000 levels by 2050 (IPCC 2007).

To achieve significant reductions in national and global emissions in an efficient manner means that adjustments in some economic sectors will occur faster and go further than others – as the costs of abating, or reducing, emissions varies across sectors. The electricity and heat generation sector is a candidate for complete decarbonisation as it accounts for a large share, more than 40 per cent, of global energy-related $CO_2$ emissions (Figure 1), and it is likely that decarbonisation can be achieved at a lower cost than in other sectors such as agriculture.

To meet the growing demand for electricity, decarbonising electricity production requires moving away from uncaptured or unabated fossil fuel generation and deploying low-carbon or zero-carbon generation technologies, such as renewables, nuclear, and CCS. It is possible that stringent targets of 450ppm can only be achieved efficiently with technologies considered as having the potential for negative carbon emissions (removing $CO_2$ from the atmosphere as well as negating $CO_2$ emissions), such as CCS deployed with biomass-based fuel resources (Ecofys 2011; IPCC 2011). At present, these negative emissions technologies are still in their early stages of development.

To assess the technological challenges and opportunities, models of climate change mitigation have examined what changes would be required in the power sector to achieve GHG concentration targets of 450-550 ppm by 2050. One example is the 'Blue Map' scenario developed by the IEA that examines what technologies could be deployed and their rate of deployment to halve energy-related $CO_2$ emissions by 2050. The scenario considers an energy future where there is widespread deployment of existing and new low-carbon generation technologies in the least-cost way possible (IEA 2010b).

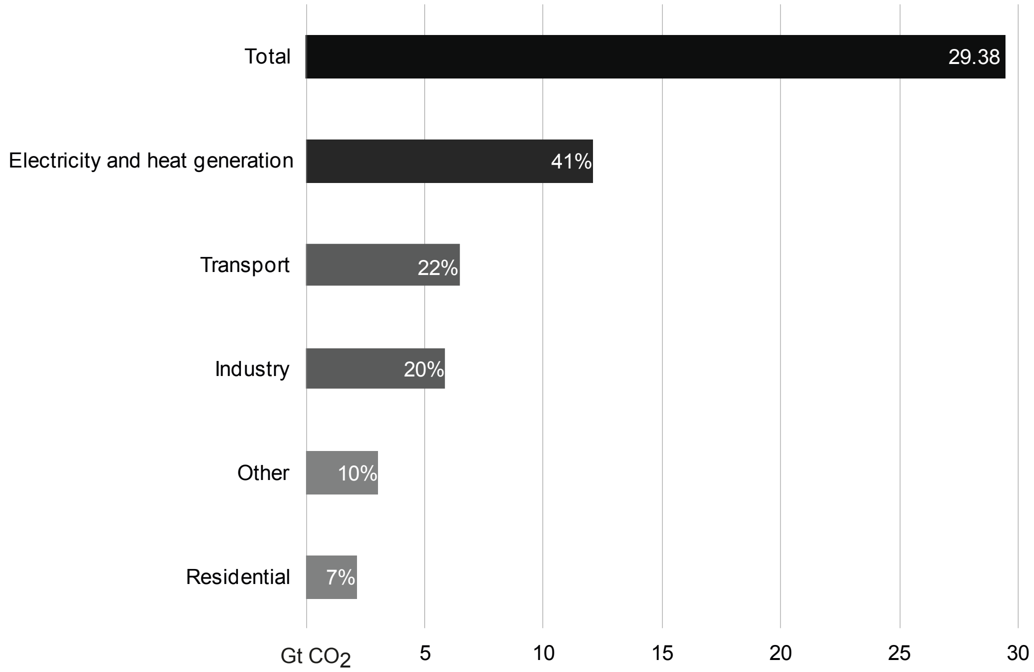
In addition to taking advantage of effective energy efficiency opportunities to slow the growth in demand, the Blue Map scenario identifies early deployment roles for relatively low-cost renewable technologies such as wind (and increased role for hydropower) through to 2020s. However, as wind and water resources become fully exploited, other more expensive technologies such as CCS, nuclear and high-cost renewables such as solar thermal and photovoltaic technologies are required to meet demand and reduce emissions. By 2050, more efficient power plants, CCS, nuclear and renewable technologies have the potential to contribute to annual power sector $CO_2$ emissions reductions of up to 16, 31, 19 and 34 per cent, respectively (Figure 2).

The rate of technology development and availability of resources such as wind or solar energy will influence the costs of the technology and the rate at which they are deployed. The rate of technology development will be influenced by both industry and public sector efforts in research, development and demonstration activities – with major demonstration programs underway for CCS and large-scale solar thermal and photovoltaic technologies. Ultimately, the global deployment path of generation technologies to manage the risks of climate change will differ from any particular model scenario, including the Blue Map, and will be almost solely determined by the cost and commercial availability of the technology to meet demand.

Since 2009, the Institute has been tracking and reporting on the latest cost studies of various CCS technologies (see WorleyParsons et al. 2009; Global CCS Institute 2011a and 2011b; and WorleyParsons 2011). These studies contain detailed cost and performance data for CCS technologies. Over the same period, cost and performance studies for renewable and nuclear technologies have also been released by a range of agencies with expertise in those technologies.

This paper presents a comparison of the current costs of low-carbon technologies based on the most recently available studies in order to assess the relative rankings of the differing technologies anticipated to meet most of the future demand for electricity. The comparison is undertaken on an equivalent basis using cost metrics such as the levelised cost of electricity (LCOE) and the cost of $CO_2$ avoided, derived using a common methodology and standardised technology and economic assumptions where appropriate.

**Figure 1 Global energy-related carbon dioxide emissions by sector in 2008**




Source: $CO_2$ Emissions from Fuel Combustion Highlights (IEA 2010a).

## COST METRICS

### Levelised cost of electricity

The levelised cost of electricity is a metric used to represent the average cost of generating electricity for the duration of the power plant's economic lifetime. Simply put, LCOE is the average price that an electricity generating plant would need to receive for each and every hour of operation in order for project proponents to recover all capital and operating costs, including receiving a competitive return on invested capital. It is defined here in terms of the net output in US dollars per megawatt hour (US$/MWh). LCOE computations include:

- investment cost (or installed capital cost);
- operating costs; and
- fuel costs.

Investment cost, often accounting for the largest share in the cost of production, includes items such as engineering, procurement, construction as well as site-specific costs (also known as owner's costs) together with contingencies to manage uncertainties and risks related to project development and construction. Added together in present-value terms, these items represent the 'overnight cost' of the plant: the lump sum cost that would have to be paid up front to completely fund its immediate construction. As project development and construction take several years, the total investment, or installed, cost of a plant includes the present value of the financing costs incurred during this period together with the overnight cost.

Operating costs, fixed and variable, relate to expenses necessary to operate and maintain the plant, once it is constructed. Fuel costs are specific operating costs that take into account feedstock or fuel requirements of a generating plant, and depend on the price of fuels such as coal, natural gas, uranium, energy crops, or other feedstock materials.

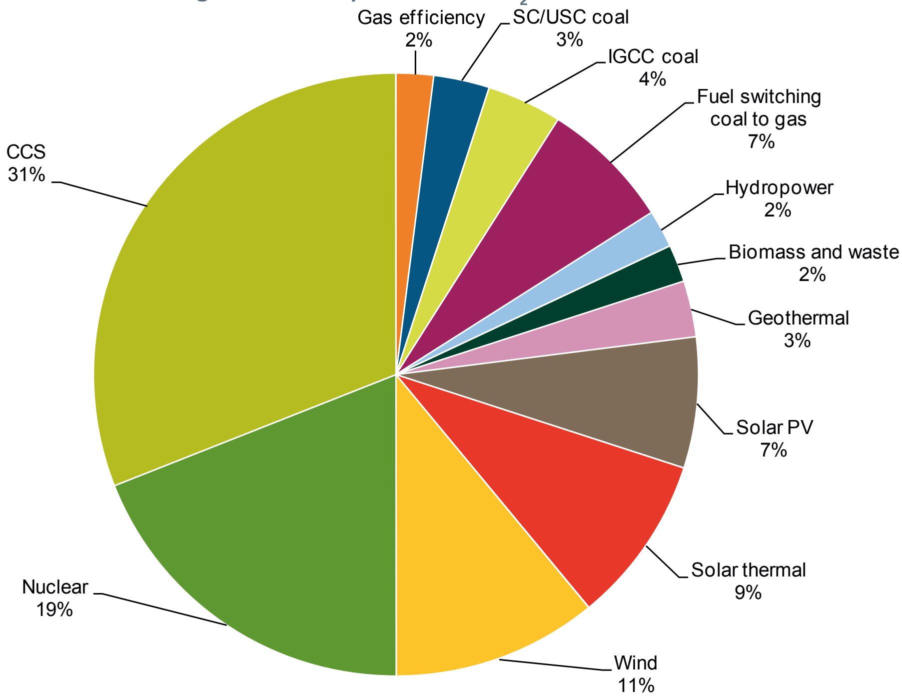
Other significant techno-economic parameters that go into LCOE computations are:

- plant lifetime;
- lead time for construction;
- thermal efficiency;
- capacity factor; and
- discount rate.

### Avoided cost of carbon dioxide

Mitigating $CO_2$ is the only reason for undertaking CCS investments, and as the aim of climate change policy is the abatement of $CO_2$ (and other GHGs), the appropriate metric to compare technologies is the cost of avoiding $CO_2$. The cost of $CO_2$ avoided identifies the cost of reducing emissions through the displacement of unabated fossil-fuel production, expressed in dollars per tonne of $CO_2$. The reduction in $CO_2$ emissions to the atmosphere depends on the type of fossil fuel plant displaced or retired as a result of investment in the low-carbon technology. Estimating the cost of $CO_2$ avoided requires information on $CO_2$ emissions intensity of the plants under evaluation, as well as their levelised costs.

**Figure 2 Contribution of technologies to reduce power sector $CO_2$ emissions**




Source: Energy Technology Perspectives 2010: Scenarios and Strategies to 2050 (IEA 2010b).

Efficiently managing the risks of climate change implies that the marginal cost of abatement incurred in each sector of the economy is the same. If the cost of abating an additional tonne of $CO_2$ differed across economic activities or inputs, savings to reach a particular emissions reduction target could be achieved by increasing abatement in the lower cost activity and reducing abatement in the more expensive activity. Similarly, placing a price on carbon will encourage the use of all those generating technologies that have a lower cost of abatement than the price (including consideration of future price paths and cost potential). More expensive abatement opportunities will only be selected if mandated through regulation as they will be unable to recover their costs from the electricity and carbon markets combined.

## COSTS: DATA AND APPROACH

This cost review focuses on low-carbon technologies applied to stationary power generation, which include CCS, nuclear and renewable technologies. CCS is subdivided into CCS-coal and CCS-natural gas; and renewable technologies into biomass (or bio-energy), conventional geothermal, hydropower, solar photovoltaic (PV), solar thermal (or concentrating solar power – CSP), wind offshore and wind onshore. Annex A provides a brief description of each low-carbon technology.

**Targeting emission reductions means the appropriate metric to compare technologies is the cost of avoiding $CO_2$ emissions.**

To obtain the cost data for this study, the Institute conducted an extensive review of publicly available studies for new-build, low- and zero-carbon electric power generation plants. Comparing the costs from different studies on an equivalent basis poses several challenges. For instance, the levelised cost estimates from various studies are not usually directly comparable because different cost methodologies are used as well as different economic assumptions such as plant lifetimes, discount rates or capacity factors.

To construct comparable levelised costs, the underlying cost and performance characteristics of the generating technologies are required. However, these data are often not directly comparable. They can be denominated in different currencies or different nominal (year) terms. The costs of plants constructed and operated in different geographical regions will also vary as a result of differing economic conditions leading to location-sensitive costs for labour and capital, as well as location-sensitive performance factors, such as wind and solar resources. Another challenge is that several studies do not completely specify the underlying economic and technical assumptions, or differ in the boundary conditions between stages within the same generating plant. This lack of transparency limits opportunities for testing, verification and further adjustment of underlying data.

To ensure that the studies can be compared on the same basis, studies were screened according to the following criteria. Cost studies by organisations that generated and analysed their own cost and performance data were considered or preferred. This criterion excluded those studies that drew on data generated by other studies, however exceptions were made with the recent IEA and OECD NEA (2010) and IPCC (2011) studies, which analysed cost and performance data gathered from a variety of sources including other techno-economic studies. To reduce the variability in labour and construction costs or quality of resource due to regionalisation, only studies with cost and performance information of low-carbon generating plants found in the United States were considered. Exceptions were the IEA and OECD NEA (2010) and IPCC (2011) studies, from which OECD and world mean values of techno-economic data were also used. To ensure that cost values were current, only publications with cost and performance data of the past two years (since 2010) were evaluated.

Based on the criteria above, the following cost studies were included in this study:

- *Cost and Performance Assumptions for Modelling Electricity Generation Technologies 2010* - United States Department of Energy National Renewable Energy Laboratory .
- *Cost and Performance Baseline for Fossil Energy Power Plants Study, Vol. 1, 2010* - United States Department of Energy National Energy Technology Laboratory.
- *Economic Assessment of Carbon Capture and Storage Technologies: 2011 Update* - WorleyParsons.
- *Projected Costs of Generating Electricity 2010* - International Energy Agency and Organisation for Economic Co-operation and Development Nuclear Energy Agency.
- *Special Report on Renewable Energy Sources 2011* - Intergovernmental Panel on Climate Change.
- *Annual Energy Outlook: 2011* - United States Energy Information Administration.

From these relevant cost studies, the cost and performance data were adjusted to 2010 US dollar levels. The underlying techno-economic assumptions such as capacity factor, efficiency, plant lifetime and lead time were derived by taking the average of the data from the studies identified. Further, the study only considered the cost and performance data of generating plants with the size or capacity of 50 MW or higher (Table 1).

**Table 1 Indicative plant capacities**

| Technology | Capacity (MW, net) |
|---|---|
| Hydropower | 500 - 10,000 |
| Nuclear | 1350 - 2240 |
| CCS-coal | 475 - 550 |
| CCS-natural gas | 400 - 485 |
| Offshore wind | 70 - 400 |
| Solar thermal | 100 - 150 |
| Onshore wind | 50 - 155 |
| Solar PV | 50 - 150 |
| Biomass | 50 - 80 |
| Geothermal | 50 - 55 |

Using the average technology and economic assumptions and a common discount rate (see Annex B), a standard methodology was applied to calculate the LCOE and cost of $CO_2$ avoided.

## RESULTS

### Investment cost

Both the level of the investment cost and the share that investment costs account for in the total costs (that is, the capital intensity) are important factors in selecting a generation technology in a world with uncertainty and multiple possible paths and outcomes going forward. The larger the level of investment required, the more capital that is at risk. The higher the capital intensity, the more exposed the investment is to future variations in electricity prices, and is also difficult to fully hedge. In real investment decisions, this risk is accounted for through varying the rate of return required to appropriately adjust for the expected level of risk that is being incurred. However, in levelised cost studies, this is often abstracted away through assuming a constant discount rate across all technologies. Nonetheless, the estimated installed investment cost reflects the level of capital that may be 'at risk' for each technology.

Technologies that have high investment costs relative to conventional (coal-fired) plant include CCS-coal, biomass, solar PV, offshore wind, nuclear, and solar thermal (Figure 3). Those that have the same level of investment costs or lower than a conventional plant include CCS-natural gas, hydropower, geothermal and onshore wind.

CCS technologies have higher investment costs relative to coal- and natural gas-fired plants because the capital costs associated with capturing, transporting and storing carbon dioxide are added to a conventional plant. Figure 3 shows that investment cost for CCS-natural gas is lower than a conventional coal-fired plant (see orange line in Figure 3), although still higher than a conventional gas-fired plant.

### Levelised cost of electricity

After extracting the underlying capital and operating costs that reflect the performance characteristics of each technology, levelised costs were calculated using a common set of assumptions on plant lifetime, capacity factor, lead time for construction, owner's costs, contingencies and thermal efficiency (where applicable) for the individual technologies (see Annex B), a common discount rate, and a common costing methodology.

Compared to conventional coal-fired plants, low-carbon technologies that have relatively low LCOEs include conventional geothermal (US$43-61/MWh) and hydropower (US$52-60/MWh) (Figure 4).

Technologies that sit in the 'middle range' of the LCOE distribution are onshore wind (US$67-86/MWh), nuclear (US$68-94/MWh), biomass (US$81-113/MWh), CCS-natural gas (US$107-119/MWh) and CCS-coal (US$89-139/MWh).

Offshore wind (US$146-215/MWh) and both solar PV and solar thermal technologies (at least US$185/MWh) have some of the highest LCOEs.

### Intermittent technologies

Care must be taken in drawing conclusions when comparing LCOE estimates for intermittent technologies like solar and wind with those for dispatchable technologies like fossil fuel generators and nuclear. The economic value of electricity consumed varies with the level of demand and time of day – whether in a market-based system or regulated cost-of-service system. Consequently, the value of any given technology to meet that demand will also vary. It will only have positive economic value if its costs of operation are less than the value consumers are paying – or in a regulated system, lead to the total system costs being minimised. Levelised costs, which are calculated on an average basis, may not fully account for this measure of value without further adjustment. For example, the average LCOE estimate for onshore wind is US$76/MWh. If this energy is generated in an off-peak period, wind is not necessarily adding economic value to the system – especially if electricity prices are negative. That is, the use of LCOE as a metric overvalues wind technologies relative to dispatchable technologies (Joskow 2010).

Due to this effect, it is not uncommon for wind farms to be limited in operation at periods of low prices because their operation only depresses market prices further – undermining the investment case for all technologies in the system – including the wind farm itself (Parkinson 2011). Similarly for solar technologies that operate only during daylight hours – when electricity is usually more valuable – LCOE calculations undervalue solar technologies relative to wind technologies.

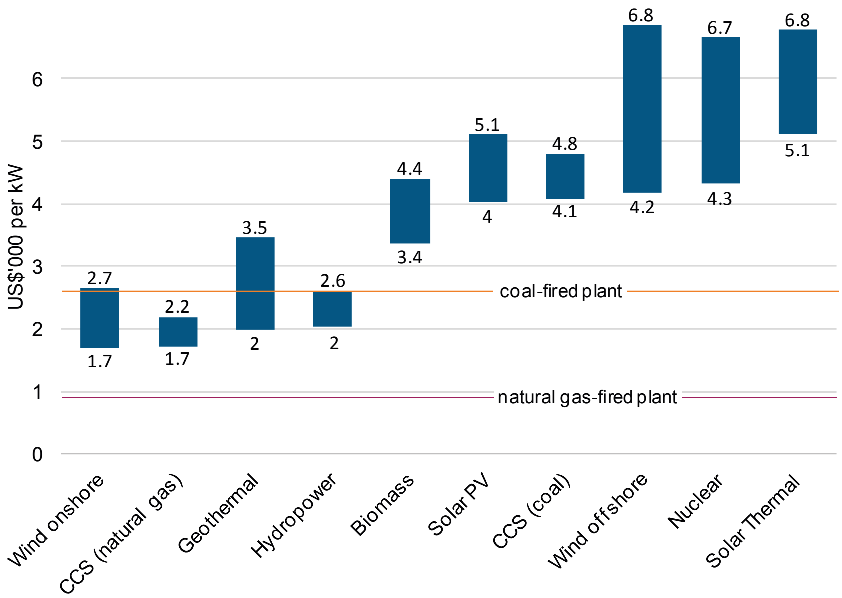
The effect of 'intermittency' on total system costs could be accounted for in LCOE calculations through adjustments to the capacity factor to better match the time profile when they make a positive economic contribution to the electricity network. This is not done here and care should be exercised when making inferences where levelised costs are similar. For example, the levelised cost of some onshore wind plants is equivalent to, and even lower than, the levelised cost of a conventional (natural gas-fired) plant (Figure 4).

### Technological maturity

Low-carbon technologies are at varying stages of technological development and often straddle one or more development stages as new designs and configurations are developed. For example, nuclear electricity generation is a mature technology that has been in use for more than 50 years (IEA 2010c). Several low-carbon technologies are proven technically, but still have some cost or regulatory barriers to overcome before they are broadly taken up. These technologies include solar (PV and thermal), onshore wind and biomass (IEA 2010b) – however, few of these technologies operate at a scale commensurate with fossil fuel plants.

Technologies that are still undergoing testing and demonstration are CCS, deep offshore wind technologies and solar thermal with storage to extend the hours of operation. CCS is already proven at pilot scale in power generation applications and will soon be demonstrated at large scale with two power plants in construction and several more anticipated to make investment decisions in the next 12-24 months (Global CCS Institute 2011b). Offshore wind technologies at water depths greater than 60 metres, particularly those using floating subsurface structures, are still being tested. Solar thermal technologies are being demonstrated to provide base load power with the use of thermal storage options such as molten salts (IEA 2010b).The state of maturity of low-carbon generation technologies may give an indication of the future trajectory of their generation costs. Their generation costs fall as they are developed, improved, proven at scale and deployed commercially.

**Figure 3 Installed capital cost of low-carbon technologies and conventional power generation**



For mature technologies, the ongoing reduction in costs is not expected to be as dramatic as for less mature or emerging technologies.

### Avoided costs of carbon dioxide

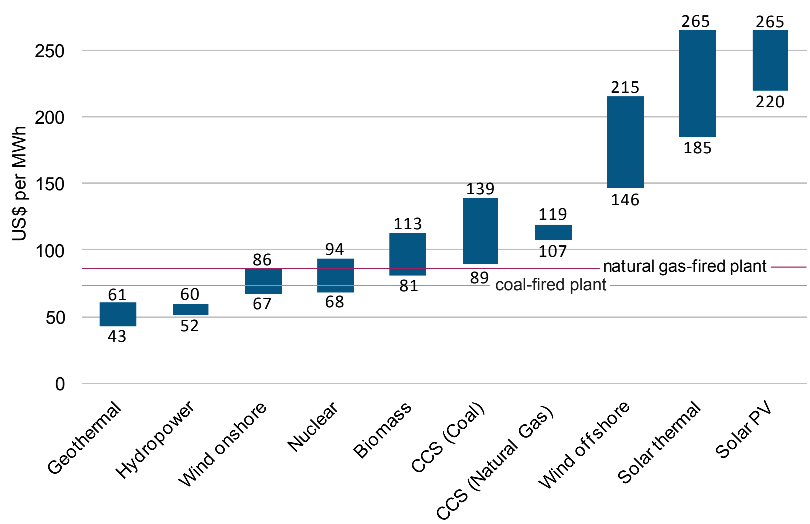
Each megawatt hour of generation from technologies that displace fossil fuelled generation displaces most, if not all, emissions associated with that generation. However, the avoided cost calculations here exclude emissions from any backup generation requirements needed when deploying intermittent technologies such as wind and solar. For CCS technologies, the level of avoided emissions is less than 100 per cent because capture is less than 100 per cent and because capture and storage consume additional energy. Unlike the abatement cost calculations for the intermittent technologies, the less than 100 per cent capture of $CO_2$ by CCS technologies is explicitly accounted for in cost calculations for these technologies.

There are technologies that have zero or negative avoided costs, such as conventional geothermal and hydropower plants amongst others (Figure 5). This occurs because the levelised costs for these two technologies are lower than the non-abated coal plant they are compared with in order to calculate the avoided cost of carbon. This means that if it were possible to increase the output from plants using these technologies or construct new plants and reduce or replace output from coal-fired electricity, the total cost of reducing $CO_2$ emissions would fall. There remains significant potential for additional hydro and traditional geothermal based plants in non-OECD countries (IEA 2010d), but only relatively small opportunities in OECD countries. The relatively low cost of these resources generally means they have often been fully exploited during the development of a country's energy system. Nonetheless, the potential for cost savings indicates that opportunities should be actively pursued to the extent the resources are available in developing or existing power systems in any country.

Compared to the cost estimates for first-of-a-kind CCS plants, the mature technologies of onshore wind power and nuclear have lower costs of mitigating emissions but are limited in availability due to resource constraints (onshore wind) or challenges with managing radioactive waste. The current costs of solar PV and solar thermal systems range from US$182-239/tonne and US$139-203/tonne respectively, a cost two to three times larger than coal-fired CCS plants (US$23-92/tonne) to mitigate $CO_2$ emissions.

A subtle but important change in the mitigation costs when compared to generation costs is the increase in gas-fired CCS plant costs relative to coal-fired CCS plants and offshore wind. That is, the carbon price required to implement CCS for a gas-fired power plant could be higher than that of a coal-fired plant and there is significant overlap with offshore wind. While the assumed capture rate for the CCS technologies in the cost calculation is the same (approximately 90 per cent), the amount of $CO_2$ captured from a gas-fired plant is lower due to the lower emissions intensity of the unabated gas power plant. As a result, there are more tonnes of $CO_2$ abated by CCS applied to coal-fired plants than by CCS applied to gas-fired plants. This leads to the avoided costs for a CCS coal-fired plant often being lower than that for a CCS gas-fired plant.

**Figure 4 Levelised cost of electricity of low-carbon technologies and conventional power generation**



## POLICY IMPLICATIONS

### Cost-competitiveness and deployment

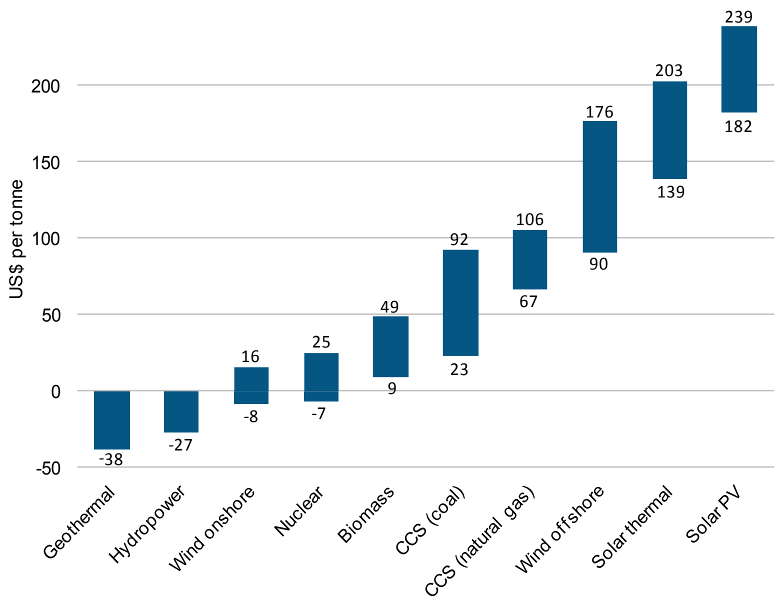
Compared to existing conventional plants, most of the low-carbon technologies that the IEA projects will provide abatement in the power sector have relatively higher costs as of today (Figure 5). There are mature technology options such as conventional geothermal, hydropower, and onshore wind that offer relatively low (or negative) cost options for early deployment. These low-cost options are rapidly taken up in the early phase of reducing emissions under the IEA Blue Map (Figure 6). The rate of up-take in that scenario for renewables increases globally post 2020 as more countries are projected to commit to reducing emissions. However, the limited availability of wind and hydro resources limits their role in meeting emission targets and requires higher cost options of CCS and solar thermal technologies. Despite the increased use of solar technologies over the latter part of the projection period, the annual increase in mitigation by renewable technologies declines slightly post 2030. In contrast, the rate of uptake of CCS technologies (in both power and industrial sectors) increases sharply post 2030, reflecting the anticipated cost competitiveness relative to other technologies in decarbonising the energy sector.

Estimates of marginal abatement costs by technology also provide a guide to policy-makers implementing policies designed to reduce GHG emissions. Pricing emissions explicitly with just one price ensures achieving emission reductions as efficiently as possible if all opportunities for emission reductions that cost less than the price are taken up. However, policies to reduce emissions are being implemented with a variety of approaches beyond carbon pricing – often on a sectoral or technology basis. In this context, policy makers should be constantly checking estimated marginal abatement costs to ensure that these costs are approximately similar across all areas of emission reduction in order to reduce the costs of meeting GHG targets (Stern 2009). For example, the estimates of the cost of CCS used in this paper recognise the cost of CCS is higher than it was believed to be only two to three years ago (Global CCS Institute 2010a). Yet avoided $CO_2$ cost estimates presented here for first-of-a-kind CCS plants are less than half those of a solar PV plant – a technology that has experienced a cost decline by more than a factor of 10 over the past 30 years (IPCC 2011). Within the consideration of local circumstances and resource availability, estimates of marginal abatement costs offer a strong guide to policy-makers on efficiently managing the costs of abatement.

### Innovation and research, development and demonstration

Continuing innovation through further Research, Development and Demonstration (RD&D) will help in addressing the cost-competitiveness issue of some of the low-carbon technologies. Improvements in the technologies (for example, in their design or in their processes or operations) that lead to better performance can lead to cost savings. Further, as a number of low-carbon technologies are still being demonstrated at scale, there are opportunities to improve them further and reduce costs.

**Figure 5 Cost of $CO_2$ avoided[1]**



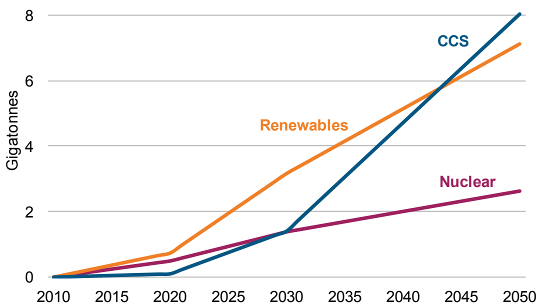

[1] For all technologies except gas-fired CCS plants, the amount of $CO_2$ avoided is relative to the emissions of a supercritical pulverised coal plant. For gas-fired CCS, the reference plant is an unabated combined cycle plant.

As mentioned above, however, the innovations and improvements for any technology, as well as the possible cost reductions they bring, tend to be less for mature technologies than for immature ones.

### Portfolio approach for overall mitigation

The use of all these technologies, when commercially available and consistent with local energy resource conditions, is required to manage the risks of climate change in the most cost-effective manner. Excluding any one technology will increase total costs of power generation and GHG abatement. For example, the IEA has estimated that excluding CCS will lead to increases in abatement costs by more than 70 per cent if energy-related emissions are to be halved by 2050 (IEA 2010b). Consistent with the IEA analysis, the (average) generation costs in the present study would be higher if clean generation options like CCS were excluded.

**Figure 6 $CO_2$ abatement by technology grouping in the IEA Blue Map Scenario**




## CONCLUSION

Decarbonising the power sector is necessary to stabilise GHG concentrations in the atmosphere to limit global temperature rise to below 2ºC. The transition from heavy reliance on fossil fuel power generation to broad deployment of low-carbon generation technologies is not an easy process and will take many different pathways. The deployment of low-carbon generation technologies requires many issues to be taken into account, but foremost of which is consideration of the costs surrounding these technologies. In this study, employing the most widely used metrics, current generation costs and current mitigation costs of various low-carbon technologies, were considered and compared to understand how deployment may be done in a low-cost (if not least-cost) manner.

Comparing the levelised costs of intermittent renewable technologies such as wind and solar with dispatchable technologies cannot be done easily given the variability and unpredictability of electricity production of solar and wind plants, which, in turn, affects their true economic value and profitability.

The spread of levelised generation costs and avoided costs for low-carbon generation technologies present onshore wind and hydropower as low-cost options that could be broadly deployed now. The rest of the low-carbon generation technologies are relatively more expensive with global deployment some time off.

**Taking the least-cost path to decarbonising the power sector requires a diversified mix of low-carbon technologies. Excluding CCS will increase total abatement costs.**

Far from being static, the costs of low-carbon technologies that are more expensive now compared to conventional power generation are expected to decrease over time as more innovations and improvements are made, particularly for immature technologies.

On the whole, taking the least-cost path to decarbonising the power sector requires the deployment of all low-carbon technologies. Excluding technologies from the energy mix, CCS in particular, will lead to more expensive abatement costs.

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## ANNEX A LOW-CARBON TECHNOLOGIES – A BRIEF DESCRIPTION

**1. Carbon capture and storage.** As a mitigation option, CCS involves an integrated process of capturing carbon dioxide from fossil fuels either before or after combustion, transporting through pipeline or other means, and permanently storing it in deep geologic formations like depleted oil and gas fields, saline formations and unmineable coal seams.

**a. CCS-coal** – pertains to CCS technology applied to coal-fired (base load) power plants where around 90 per cent of $CO_2$ is removed using either post-combustion, precombustion or oxy-fuel technologies.

**b. CCS-natural gas** – pertains to CCS technology applied to natural gas-fired (base load) power plants where around 90 per cent of $CO_2$ is removed using post-combustion capture.

**2. Nuclear power.** The process of nuclear power generation begins with nuclear fission, or the splitting of (uranium) atoms, releasing heat energy that boils water in the core of a nuclear reactor. The heated water from the core goes to, and heats up a set of pipes filled with water that produce steam. The steam then goes to a steam turbine to generate (base load) electricity with no emissions.

**3. Renewable technologies:**

**a. Biomass.** Biomass or bio-energy refers to the conversion of feedstocks (for example, oil crops, sugar and starch crops, lignocellulosic biomass, and biodegradable MWS or municipal solid wastes) through combustion, pyrolysis, gasification or anaerobic digestion to produce heat, or biogas, which is used in steam turbines and engines to generate electricity. It is considered carbon neutral since the $CO_2$ produced during the combustion is approximately the same quantity consumed during biomass growth (IEAGHG 2011).

**b. Geothermal power.** Conventional geothermal power that uses subsurface heat provided through steam or hot water to turn turbines that generate (base load) electricity with virtually no emissions.

**c. Hydropower.** Hydropower generation uses the force of moving water (created from the release of dammed water in controlled amounts) to move a series of turbines to produce electricity with no emissions.

**d. Solar Power:**

**i. Solar photovoltaic (PV)** – pertains to systems using a semiconductor device called a PV cell that converts solar energy into direct current (DC) electricity.

**ii. Solar thermal (concentrating solar power or CSP)** – pertains to concentrating energy from the sun's rays to heat a receiver to high temperatures and the heat produced is used to power a turbine or engine that generates electricity with very low levels of emissions.

**e. Wind power.** Wind power generation harnesses the force of moving air to turn large turbines to generate electricity with no emissions. This generation technology depends on the quality of wind resources and is considered intermittent technology for having variable power production profile.

**i. Offshore wind power** – pertains to construction of wind farms in bodies of water to generate electricity from the wind. 'Offshore', as a description of this technology, is not limited to its typical usage in the maritime sector, but offshore wind may include water areas like lakes, fjords and coastal areas.

**ii. Onshore wind power** – pertains to electricity generation from large turbines located on land. Onshore wind power technologies are already manufactured and deployed on large scale.

## ANNEX B TECHNO-ECONOMIC ASSUMPTIONS

| Technology | | Biomass | CCS-coal | CCS-natural gas | Geothermal | Hydropower | Nuclear | Solar PV | Solar thermal | Onshore wind | Offshore wind |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Discount rate/IDC[1] rate | % | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| Plant lifetime | years | 26 | 32 | 30 | 28 | 45 | 60 | 27 | 28 | 24 | 24 |
| Capacity factor | % | 80 | 84 | 84 | 86 | 49 | 88 | 21 | 28 | 37 | 39 |
| Lead time | years | 3 | 4 | 4 | 3 | 4 | 6 | 2 | 2 | 2 | 3 |
| Owner's cost | % | 5 | 15 | 15 | 5 | 5 | 15 | 5 | 5 | 5 | 5 |
| Thermal efficiency | % | 27 | 30 | 42 | - | - | 33 | - | - | - | - |

[1] Interest during construction.