THE COSTS OF CCS AND OTHER LOW-CARBON TECHNOLOGIES IN THE UNITED STATES - 2015 UPDATE

JULY 2015

Lead Author: Lawrence Irlam, Senior Adviser Policy & Economics, Global CCS Institute

ISBN
978-0-9871863-7-9

Cover image: Nagy Jozsef - Attila/Shutterstock.com

Contents

Executive Summary

Global climate change targets are ambitious. Achieving them at lowest cost will require deployment of a portfolio of emissions reduction technologies.

Carbon capture and storage (CCS) is a critical technology in the mix but it is not as well-known as other low-carbon options. While it can be cost-competitive with other emissions reduction technologies, it is more expensive than conventional choices for unabated power generation using natural gas or coal.

This paper examines costs of major low and zero emissions technologies currently available in power generation and compares them in terms of emissions reduction potential (CO_2 avoided) and costs (levelised cost of electricity). The technologies compared in this paper are fossil fuel generation (coal and gas) with CCS, wind, nuclear, solar thermal and solar photovoltaics (PV).

The analysis uses cost and performance data from several recent studies, and applies a common methodology and economic parameters to derive comparable lifetime costs per generation output and of CO_2 avoided.

Data are for the United States (US) only. Analysis and findings in this paper reflect costs specific to the US, in particular natural gas prices.

The key findings are:

- CCS is a cost competitive power sector emissions reduction tool when considered among the range of available low and zero emissions technologies. While CCS adds additional costs to traditional fossil fuel generation, the underlying coal and gas generation technology and fuel sources are relatively cheap. CCS has higher rates of utilisation than some renewables technologies.
- Nuclear generation plant as well as hydro and geothermal plant can also be cost competitive in some markets given their high utilisation rates (ie can be operated up to 80 to 90 per cent of the time). The relative costs of solar and wind generation technologies are affected by lower capacity factors (up to 40 per cent availability).
- Hydropower and onshore wind technologies are among the least-cost emissions reduction technologies identified,
- Offshore wind, solar PV and solar thermal are the highest cost technologies examined here in terms of displacing emissions from fossil fuel sources (ie CO_2 avoided), highlighting the importance of expected cost reductions and improvements in technical efficiency for these technologies.
- Significant cost reductions are also expected for CCS technologies with increased deployment. While capture technology is already widely deployed at pilot and demonstration scale in the power sector, integrated CCS at commercial scale in the power sector is still in its earliest, highest cost stage of deployment, with the world's first-of-a-kind CCS power plant at Boundary Dam, Canada, commencing operations in late 2014.
- Using data from current studies, coal-fired generators in the US with CCS capability would be on par with traditional (unabated) coal and gas generation if carbon were priced between US$48 and US$109 per tonne.
- The particular electricity generation mix consistent with a least cost, low carbon power sector will depend on the availability of resources that can be commercially exploited in the particular location. In the case of CCS, this depends on the presence of geological storage options as well as on the relative prices of coal and gas as fuel stock.

1

Introduction

This paper examines the costs and emissions intensities of low emission technologies in power generation. It uses cost data for the US from a variety of published sources and applies these in a common methodological framework, based on the levelised cost of electricity (LCOE) that allows comparisons between different technologies in terms of emission reductions. This follows the same approach we used in our 2011 study, *The costs of CCS and other low-carbon technologies*. Comparisons of this type have implications for designing policies that lead to a least-cost emissions reduction pathway.

This paper is limited to providing a range of costs for various generation technologies at a particular point in time and in the US. These are important caveats given the complexities involved in comparing generation costs across different countries where costs of construction, fuel and utilisation rates can vary considerably. This paper also does not consider revenue expectations or other investment viability considerations. It combines outputs of the LCOE framework with estimates of CO_2 emissions from various plant to compare technologies in terms of the cost of CO_2 abated.

2

Background

Global climate change emissions reduction targets are ambitious. Under the United Nations Framework for the Convention on Climate Change, the global community has committed to reducing emissions to ensure that observed increases in the global mean temperature would be limited to below 2 degrees Celsius relative to pre-industrial levels. Analysis by the Intergovernmental Panel on Climate Change (IPCC) suggests that, to achieve this target with a greater than 66 per cent probability, total anthropogenic CO_2 emissions since 1870 need to remain below about 2.9 trillion tonnes.[1] 1.9 trillion tonnes of CO_2 were already released as at 2014[2], with rapid increases in the rate of emissions in recent decades. About half of all anthropogenic CO_2 emissions have occurred in the last 40 years.[3] The overall "carbon budget" will be exceeded by 2040 under current policy settings, according to the International Energy Agency (IEA).[4]

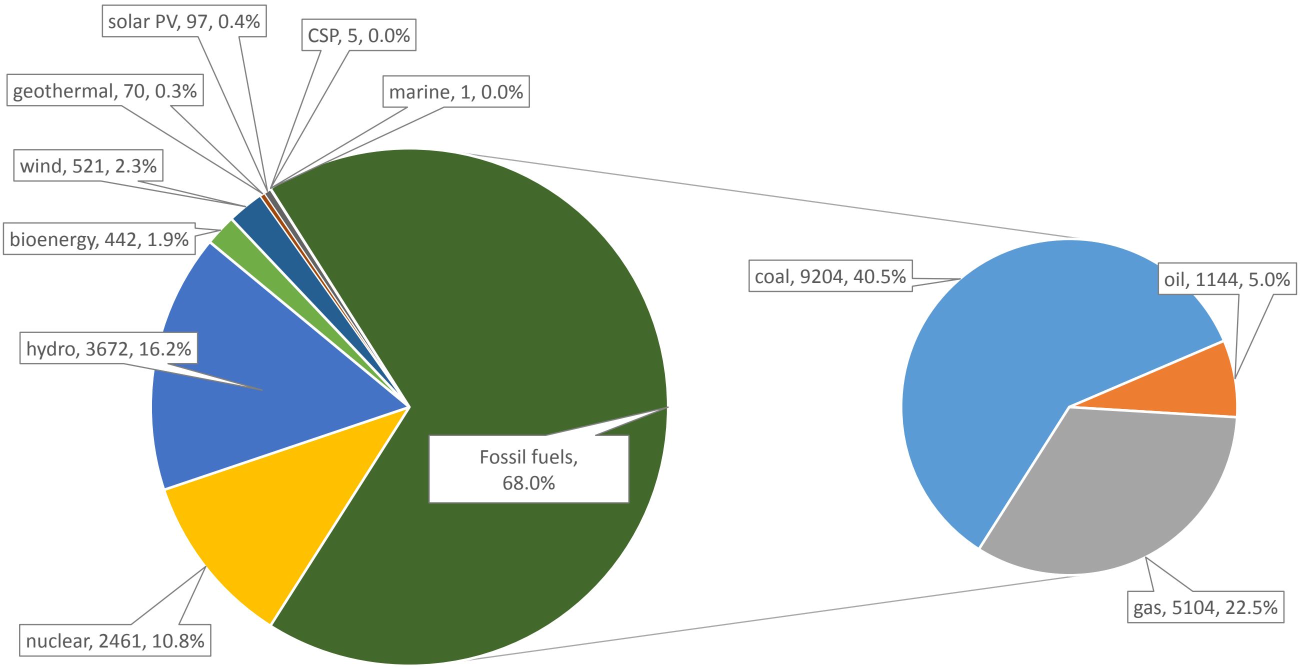
Determining how to meeting these targets in the most effective way and with the least cost to society is a key policy challenge. One solution is to impose a price on carbon that internalises the social cost of emissions into market transactions. Governments pursuing emissions reductions have chosen a mix of approaches including energy efficiency and emission standards public, funding support for low emission technologies and various other measures.

In electricity generation, which contributes about a third of global CO_2 emissions, governments have provided significant support to renewable generation sources through mandated energy targets and subsidies for wind and solar generators, including via feed-in tariffs for residential customers. A successful element of these policies has been to spur the rapid expansion of the PV industry in countries such as Germany and more recently China, with significant reductions in the cost of PV production. Investment in relatively lower cost renewable technologies in the form of geothermal and hydro generation has also taken place with somewhat less government direction or subsidies, and where suitable resources have been available. Worldwide, there has been over US$2 trillion invested in renewables technologies since 2004.[5] US$1.65 trillion of this has been on wind and solar technologies.[6]

More drastic action is, however, required to meaningfully reduce emissions in the power sector. In spite of the recent massive investment in renewable technologies, fossil fuel generators still made up 68 per cent of the world's electricity output in 2012 (see Figure 2.1), increasing from 63 per cent in 1990.[7] Technology deployment scenarios such as those developed by the IEA indicate that climate targets can only be met through a significant change in the world's electricity generation mix. In addition to the challenges posed by the large proportion of fossil fuel generation, questions remain around the role of nuclear power as a low emission alternative and the integration of large amounts of intermittent renewable generation sources. These challenges will need to be managed carefully to ensure electricity is supplied in a reliable and least cost manner, including where investment is required to meet expanding demand in developing countries like India and for continued growth in China.

1 IPCC, 2014b, p. 10.
2 IPCC, 2014b, p. 10.
3 ibid., p. 45.
4 IEA, 2014, pp. 24, 88.
5 Frankfurt School-UNEP Centre, 2015, p. 12.
6 ibid., p. 15.
7 IEA, 2014, p. 608.

FIGURE 2.1: World electricity generation by source, TWh, 2012



Source: IEA 2014, Global CCS Institute analysis

3

What is the 'levelised' cost of electricity?

The LCOE is a measure frequently used to analyse the commercial viability of particular power generation technologies.

LCOE is the present value of costs per unit of electricity generated over the life of a particular plant. It may be interpreted as the price of output the plant must receive over its lifetime to break even, expressed in a way so as to be comparable to other plants that have different lifetimes and cost profiles.

Costs include fixed capital costs as well as ongoing fuel and maintenance, in addition to a commercial rate of return paid to owners and financiers of the plant. Other parameters in the calculation of the LCOE include:

- how many hours a year the generator can run
- fuel costs and fuel efficiency
- plant life and construction time.

Values used in most LCOE calculations are assumptions or generalisations around particular plant types. Actual cost and performance characteristics depend on a variety of real life factors, for example, locational specific costs, contractual arrangements around fuel contracts (including hedging instruments) and financing arrangements.

A common issue around interpretation of LCOE data is the comparison to prices in wholesale energy markets. Comparisons like this are problematic as the LCOE is a long-run cost while market-clearing prices indicate the value of electricity generation depending on short-run demand and supply conditions. Most wholesale generation markets are also "energy only" which encourage generators to offer electricity at a price that covers short-run costs only, in particular the cost of fuel. Market-clearing prices may ultimately allow generators to recover long-run costs (reflected in the LCOE) in times of constrained capacity. The ability of generators to operate at times where the market places a high value on electricity will depend on their availability, including capability to activate or vary output at short notice to meet fluctuations in demand. This is more of an issue when comparing the value of intermittent generation sources, namely solar and wind technologies, with conventional generators that can operate whenever they are required.[8]

Studies such as that by the US Energy Information Administration have sought to engage with these complexities by assuming the market price and availability of plant at a certain times of the day and season, thus calculating comparable economic values of generation plant.[9] Other studies explore related cost issues like managing intermittent sources of electricity, transmission investment needs, the impact of government subsidies, and expected efficiency and cost improvements over time.

This paper is limited to providing a range of costs for various generation technologies at a particular point in time and in the US. These are important caveats given the complexities involved in comparing generation costs across different countries where costs of construction, fuel and utilisation rates can vary considerably. This paper also does not consider revenue expectations or other investment viability considerations. It combines outputs of the LCOE framework with estimates of CO_2 emissions from various plant to compare technologies in terms of the cost of CO_2 abated. The following section explains our data and methodology. The results, including some input sensitivities, are discussed in Section 5 and the policy implications of our analysis are contained in Section 6.

8 As pointed out by Joskow, 2010.

9 EIA, 2013a.

4

Data and methodology

A large number of power generation studies were examined (see Figure 4.1) to identify cost and performance data that met the following criteria:

- data reflective of costs and performance of generation plant in the US
- published in the last three years
- 'utility scale' plant size (a minimum value of 35 megawatts (MW) was chosen where plant capacity was identified).

Seven studies were identified that met these criteria. One exception was the IPCC (2014a) that used data sources in addition to the US. Appendix A lists the surveyed studies and generation plant types examined in each.

The following cost and technical data were drawn from from these studies:

- capital costs
- fixed and variable operational and maintenance costs
- heat rate/ thermal efficiency
- emissions intensity.

The cost data taken from the studies do not include government subsidies or decommissioning costs for any plant type. Costs for CCS technologies include CO_2 transport and storage costs however exclude cost associated with storage site location and characterisation.

As noted in the previous section, any costs associated with maintaining backup generation plant or other wholesale market management costs, as well as any required transmission network investment, are not considered. Cost information taken from each study reflects the earliest year reported for each study, including in the case of CCS-equipped plant drawn from the Electric Power Research Institute (EPRI) and the US Energy Information Agency (EIA) where the first CCS plant are assumed to be commissioned in 2025 and 2020 respectively. The cost information used has not been modified to reflect or other assumptions about technological improvements over time. All costs have been converted to December 2014 dollar terms.

For the purposes of applying a common assessment methodology, we derived averages for plant life, construction lead-time and plant capacity factors from the seven studies. Where a particular study identified several or a range of particular values, these were averaged to generate a point estimate from that study. We applied a discount rate of 8 per cent and used current fuel costs as published by the EIA (in the case of gas and coal) or assumed values in reflection of those contained in the seven studies (in the case of uranium and biomass). Appendix B contains a list of assumptions for each technology.

The results in the following section reflect the range of costs derived from this approach.

4.1

Sources examined for cost and performance data

Black and Veatch, 2012, *Cost and performance data for power generation technologies* — outdated source information.

Bloomberg New Energy Finance, 2014, H2 2014 AMER Levelised Cost of Electricity Update — full dataset is not published.

Brookings, 2014, The Net benefits of low and no-carbon electricity technologies — accepted.

Citi Group, 2014, *Evolving economics of power and alternative energy* — limited technologies covered (gas generation only).

Electric Power Research Institute (EPRI), 2013, *Program on technology innovation: integrated generation technology options 2012* — accepted.

Fraunhofer Institute for Solar Energy Systems ISE, 2014, *Up-to-date levelised cost of electricity of photovoltaics* — limited technologies covered (solar PV only).

Intergovernmental Panel on Climate Change (IPCC), 2014, 'Annex III: technology-specific cost and performance parameters' in *Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* — accepted.

International Energy Agency (IEA), 2012, *Energy technology perspectives 2012: pathways to a clean energy system* — accepted.

International Energy Agency (IEA), 2014, *Technology roadmap: energy storage* — battery storage considered but ultimately not analysed.

International Energy Agency (IEA), 2015, *Projected costs of generating electricity: 2015 update* — still awaiting publication.

International Renewable Energy Agency (IRENA), 2013, *Renewable power generation costs in 2012: an overview* — insufficient information.

International Renewable Energy Agency (IRENA), 2015, *Renewable power generation costs in 2014: an overview* — insufficient information.

Lazard, 2014, *Lazard's levelized cost of energy analysis: version 8.0* — accepted.

National Energy Technology Laboratory (NETL), various years, *Cost and performance baselines for fossil energy plants* — outdated.

National Renewable Energy Laboratory (NREL), 2014, *Annual technology baseline (ATB) spreadsheet* — accepted.

National Renewable Energy Laboratory (NREL), various years, *NREL technology and program market data* — latest data sourced in NREL's Annual Technology Baseline study.

OpenEI, *Transparent cost database* — sources from dated publications, overlap with some recent studies.

U.S. Department of Energy (DOE), 2014, *2013 Wind technologies market report* — limited technologies covered (wind only).

U.S. Energy Information Administration (EIA), 2014, *Assumptions to the Annual Energy Outlook 2014* — accepted.

U.S. Energy Information Administration (EIA), *Levelized cost and levelized avoided cost of new generation resources in the Annual Energy Outlook 2014* — already examined in EIA's Annual Energy Outlook.

5

Discussion of results

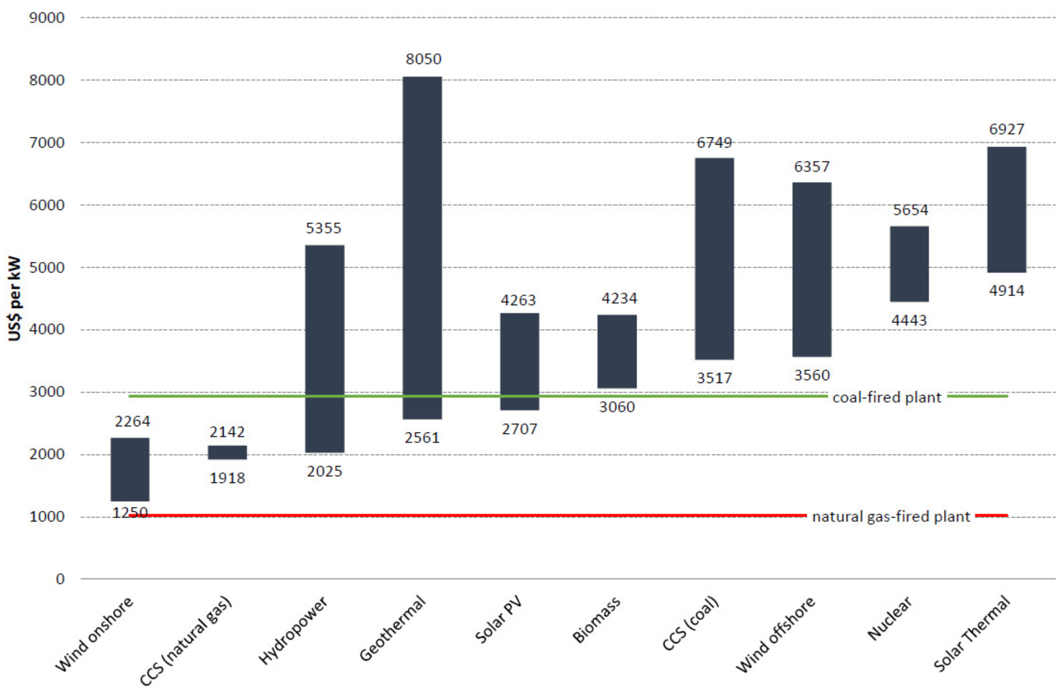
5.1

Capital Cost

This study found that:

- Capital costs per unit of installed capacity are low for onshore wind, gas-fired generation (including with CCS capability), hydro and certain geothermal plant.
- Solar PV, coal with CCS, biomass and offshore wind have higher capital costs while nuclear and solar thermal have the highest cost.
- Geothermal capital costs vary widely as some studies capture higher cost 'enhanced geothermal systems' that involve fracturing deep rock formations and are not yet commercialised.
- Costs for offshore wind also vary significantly depending on the location of wind resources over shallow or deep ocean and their distance from onshore transmission networks.
- The capital costs of CCS are significant, around double that of an unabated coal- or gas-fired generator.[10]
- The large variation in coal CCS costs reflects a combination of different coal-fired plant (IGCC and pulverised coal) as well as what appear to be higher cost estimates for IGCC plant in more recent studies.[11]

FIGURE 5.1: Capital cost for plant in the US, exclusive of interest during construction (2014 US$)



Source: Global CCS Institute analysis

10 Gas-fired generators identified in the source studies were all combined cycle with an average emissions intensity of around 370 grams of CO_2 per kilowatt-hour, while coal-fired generators included supercritical, ultra-supercritical and integrated gasification combined cycle plant ranging from 675 to 850 grams of CO_2 per kilowatt-hour.

11 See for example EIA, 2013b, page 2.

5.2

Levelised electricity costs

As explained in Section 3, the LCOE combines capital and operational costs over the life of the generation plant and expresses these in terms of the output generated by that plant. Hence the available capacity and items such as fuel costs are important factors in addition to the capital costs examined above.

Renewable hydro and geothermal generation have high capacity factors and low operational costs, hence they also have the correspondingly lowest LCOE. Onshore wind, while having a low capacity factor, also has very low operating and capital costs so has a relatively low LCOE.

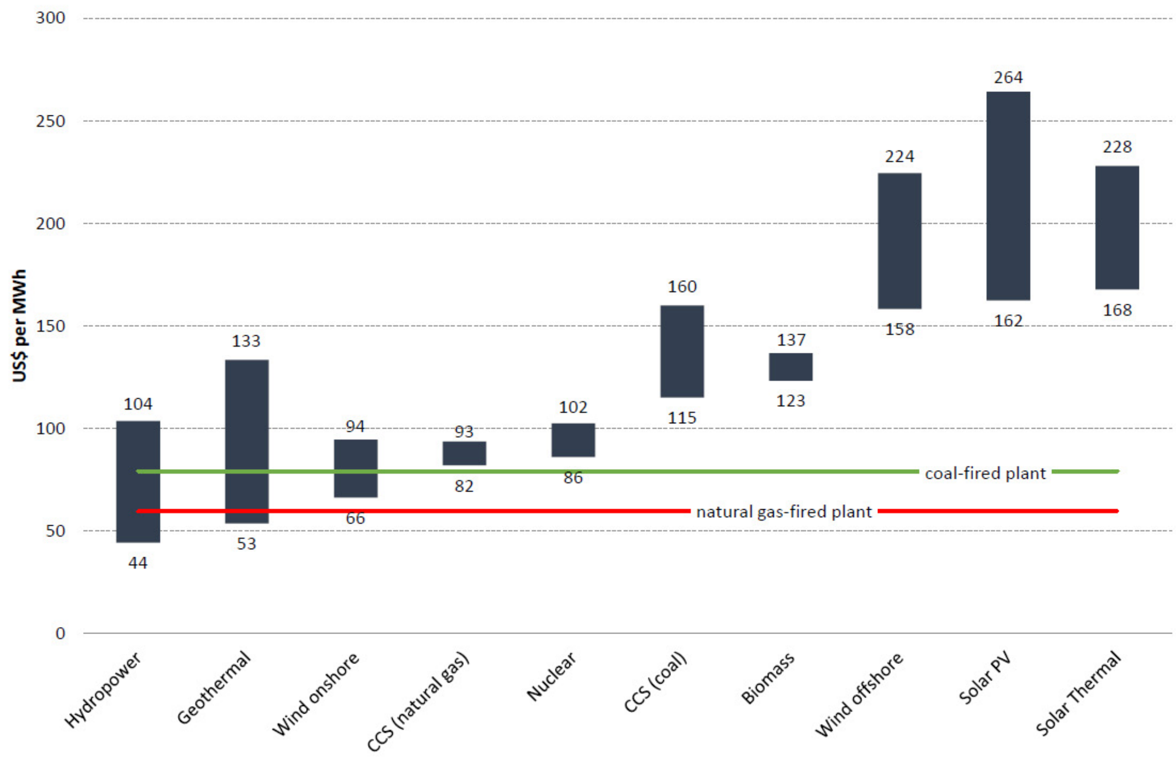
The moderate LCOE for gas plant (including with CCS) reflects high capacity factors and low capital costs. The cost of gas generation is sensitive to fuel costs, which make up approximately half of total levelised costs. The price of natural gas in the US is relatively low, historically and by international standards, reflecting the large recent expansion in shale gas production. The LCOE of nuclear plant reflects a higher capacity factor and much lower fuel costs, which offset the large capital costs involved.

LCOEs for coal with CCS and biomass reflect similar plant costs, capacity factors and fuel input costs, with the wider range for coal CCS due to variations in capital costs drawn from the studies examined.

Offshore wind generators have higher capacity factors than onshore wind, owing to sites with better wind resources, however their capacity factors are still low compared to conventional generation technologies. When these capacity factors are combined with relatively higher capital costs, the resulting LCOE for offshore wind generation is among the highest of the technologies examined. Solar thermal generators share similar characteristics.

Solar PV generators have mid-range capital costs and with very low operating costs, however have a high LCOE given they have the lowest capacity factors of all the generation technologies.

FIGURE 5.2: Levelised cost of electricity for plant in the US (2014 US$)



Source: Global CCS Institute analysis

5.3

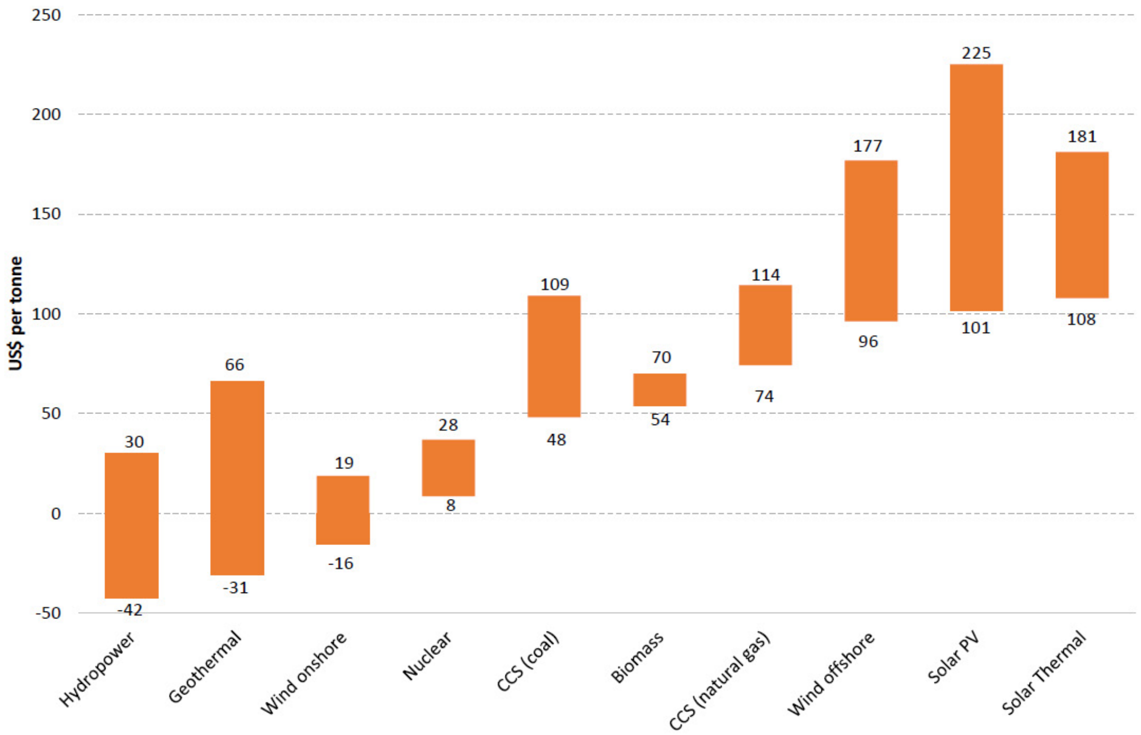
Cost per tonne of CO_2 avoided

The LCOE of a particular plant can be converted into a cost per tonne of CO_2 avoided when it is assumed that a new plant displaces the output, and associated emissions, from an existing fossil fuel generator. This is a useful metric in terms of examining changes in a generation portfolio associated with climate change policy and the incremental cost involved in such a change.

Figure 5.3 illustrates the cost of CO_2 avoided where one megawatt-hour (MWh) of output from each different generation plant is assumed to replace the same unit of output from a standard, unabated coal-fired generator (or gas generator in the case of CCS – natural gas).[12] The difference in levelised cost that results from replacing this output is divided by the amount of emissions that are avoided in doing so.

Some geothermal, hydro and onshore wind generators have a negative avoided cost given their LCOE is below that of an unabated coal plant. That is, where output from these plants displaces that of the coal plant, there would be a benefit in terms of a lower cost of electricity in addition to the amount of CO_2 emissions saved. From a climate policy perspective there is a clear case for investing in these plants. Where these resources are unavailable or already exploited, the technologies of nuclear, CCS and biomass become attractive as emissions reduction solutions. Beyond this, offshore wind and solar technologies are the highest cost technologies in terms of displacing emissions from traditional coal-fired generation.

FIGURE 5.3: Avoided cost of CO_2 for plant in the US, (2014 US$)



Source: Global CCS Institute analysis

12 The emissions intensity of the standard unabated coal generator used in this analysis is 822 grams of CO_2 per kWh, while that of the unabated gas generator is 341 grams of CO_2 per kWh

The high cost of CO_2 avoided of offshore wind and solar technologies owes mostly to their relatively small capacity factors. That is, due to the intermittency of the wind and solar energy, it would take three or four times as much solar or wind capacity (MW) to generate the same amount of energy (MWh) produced by one MW of a traditional coal plant. These higher capacity costs, when divided by the volume of CO_2 associated with coal plant output that is avoided, result in a higher cost per tonne avoided.

The avoided cost associated with gas CCS plants is higher than for coal plants. This is because gas generators have a lower carbon intensity per MWh, hence its takes more effort and cost to capture each tonne of CO_2.

Analysis of the avoided cost of CO_2 can be extended to examine the impact of imposing a price on carbon (for example in the form of traded emissions certificates or a direct price on carbon). Assuming no other policies are in place, a carbon price above US$48 per tonne would start to incentivise investment in coal plants with CCS ahead of traditional, unabated coal-fired generation in the US. Similarly, a carbon price of US$101 per tonne would equalise the costs of generation per MWh between a typical unabated coal-fired plant and the cheapest utility scale solar PV generator in the US.

5.4

Future trends and sensitivities

The following general cost trends are apparent or were identified in the cost studies examined, including beyond the US context:

- The capital costs of solar PV have reduced significantly in the last decade and are expected to decline further as the technology reaches full maturity in the coming years.
- The overall cost of hydro generation is unlikely to decrease as technologies are mature and the lowest cost/ most productive resources have already been exploited.
- Similarly, the most accessible geothermal resources have already been developed although extraction from higher cost locations may be offset by cost reductions from new technologies and techniques currently in development.
- Better wind turbine design and continuing identification of stable resources closer to load centres is likely to push wind generation costs lower.
- Nuclear technologies are generally mature with limited prospects of cost reductions, noting emerging light water and modular plant constructions.
- CCS at commercial scale in power generation is still at the first-of-a-kind stage with significant cost reductions expected. Saskpower's Boundary Dam installation is the world's first post-combustion CCS plant on a coal-fired generator, and has been in operation for less than a year.
- The cost of both gas and coal CCS generation is dependent on fuel input prices, which vary widely depending on regional and country specific market conditions:
    - Generally speaking, the price of natural gas is expected to rise over the medium term given depletion of lower cost fields. For the purposes of this paper, the expected change in gas prices from current levels in the US[13] (eg up to US$6 or even US$7 per million British thermal units (mmbtu) from the US$5 assumed in this analysis) do not materially affect our conclusions regarding gas-fired CCS generation.[14]
    - The price of thermal coal is also forecast to rise somewhat in the medium term however, as is the case with gas, prices in the US are among the lowest in the world so unabated coal-fired generation (notwithstanding climate policy measures) will remain a cost competitive generation solution in this country in the long term.
- Solar thermal technology is still in early stages of development, with higher rates of heat storage likely to improve generation capacity in combination with expected declines in costs.
- Uncertainties in these trends as well as differences in costs in particular locations need to be considered when designing policies to ensure sufficient investment in a least-cost technology mix.

13 See for example IEA, 2014, page 51.

14 This analysis reflects a gas price assumption of US$5.25 per GJ (around US$5 per mmbtu), assuming that new gas plants constructed today in the US would be able to contract or hedge in reflection of current prices. A dollar (20 per cent) increase in the gas fuel price adds around 8 dollars (or roughly 11 per cent) to the LCOE of gas-fired generation. See Appendix C for analysis of gas and coal price changes on the LCOE for CCS plant.

6

Conclusions

The key characteristic of CCS is that it can be applied to base-load or controllable fossil fuel power sources, and so it has a proportionately larger impact in terms of MWh generated and emissions reductions. While there are relatively high capital costs involved, the analysis above demonstrates that first-of-a-kind CCS technologies in the power sector are competitive in terms of the cost of CO_2 avoided compared to other low emissions technologies. This is an important finding given that meeting climate change targets will require significant investment in emissions reductions technologies in the coming years.

The role of CCS as a cost-effective low emissions technology as part of a portfolio of technologies to reduce emissions is highlighted in analysis recently published by the IPCC in its Fifth Assessment Report. The IPCC examined economy-wide modelling of the cost and likelihood of achieving global climate change targets in the absence of particular technologies. Without the deployment of CCS, the IPCC found that the cost of limiting atmospheric CO_2 concentration to less than 450 parts per million could be on average 138 per cent higher than a situation where CCS was available.[15] Furthermore, only 36 per cent of the scenarios examined by the IPCC were able to achieve this climate change target without the deployment of CCS. (Note, this modelling included CCS in combination with bio-fuels (giving rise to the possibility of net-negative power sector emissions) as well as in industrial applications like steel and cement production, where CCS is currently the only means to make significant emissions reductions).

Further modelling by the IEA in its '450 Scenario' suggests that the required investment in CCS capacity in the power sector may be relatively modest, given the significant transformation of this sector that must take place if climate change targets are to be achieved. The IEA projects that around 80GW of CCS-equipped coal and gas capacity needs to be operating by 2025 to achieve emissions reduction targets. This increases significantly by 2040, when 580GW of global coal-fired power generation would be equipped with the technology. However, with concurrent rapid expansion in renewables generation capacity, this would still amount to only 5 per cent of world power generation capacity in 2040.[16] Countries with access to relatively cheap supplies of natural gas could also avoid emissions at least cost by switching from coal to unabated gas-fired generation, potentially embedding a lower but still significant source of CO_2 emissions that will need to be addressed in the medium to long term.

What these and similar modelling exercises consistently indicate is that the optimal mix of low emissions technologies in the power sector is likely to include all those examined in this paper. The proportions of each technology deployed at any particular time and in a particular location will depend on the availability of resources, the maturity and associated cost of each technology, as well as the public perception of risk associated with particular technologies.

Governments around the world should employ stable policy that is technology neutral in order to encourage investment in those technologies that deliver a least cost energy mix. While cost is an end in itself, the transitional costs of achieving emissions reductions must be minimised in order to gain public acceptance of climate change policy. This is possible only where the costs of deploying particular solutions (such as the cost of CO_2 avoided presented in the previous section) are the primary guiding principle in policy design, rather than focusing on or excluding particular technological solutions.

This paper has examined publicly available information on various low emissions technologies to explore their relative costs, using the levelised cost of electricity as a basis of comparison. When looking at costs alone, there is a commercial and environmental incentive to invest in lower cost, low emission technologies such as traditional forms of hydro generation as well as geothermal and onshore wind. There are, however, natural limits to the ability of each individual low and zero emission technology to deliver the amount of clean generation output required to meet emissions reductions targets. While CCS currently has a higher cost than several forms of renewables technologies, CCS has clear advantages in directly reducing large amounts of emissions from fossil fuel sources and can therefore play an important role in meeting climate change targets in a least cost manner.

15 IPCC, 2014b, p. 25.

16 Based on installed generation capacity of 11,073GW. (See IEA, 2014, p. 609.)

7

References

Electric Power Research Institute, 2013, *Program on Technology Innovation: Integrated Generation Technology Options 2012*, EPRI, Palo Alto, USA.

Frankfurt School-UNEP Centre/Bloomberg New Energy Finance, 2015, *Global Trends in Renewable Energy Investment 2015,* Frankfurt School of Finance & Management, Frankfurt, Germany.

Global CCS Institute, 2011, *The costs of CCS and other low-carbon technologies,* Global CCS Institute, Canberra, Australia.

Intergovernmental Panel on Climate Change, 2014a, Annex III: Technology-specific cost and performance parameters. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change, 2014b, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* IPCC, Geneva, Switzerland.

International Energy Agency, 2012, *Energy Technology Perspectives 2012: pathways to a clean energy system*, IEA, Paris, France.

International Energy Agency, 2014, World Energy Outlook 2014, IEA, Paris, France.

Joskow, P., 2010, *Comparing the costs of intermittent and dispatchable electricity generating technologies*, MIT Centre for Energy and environmental policy research Working Paper, WP 2010-13.

Lazard, 2014, *Lazard's Levelized Cost of Energy Analysis* — Version 8.0.

National Renewable Energy Laboratory, 2015, *Annual Technology Baseline (ATB) Spreadsheet,* accessed online at http://www.nrel.gov/analysis/data_tech_baseline.html on 1 May 2015.

US Department of Commerce, Bureau of Economic Analysis, Table 1.1.9. Implicit Price Deflators for Gross Domestic Product, in *National income and product accounts tables*, U.S. DOC, Washington D.C.

US Energy Information Agency, 2013a, *Assessing the Economic Value of New Utility-Scale Electricity Generation Projects*, US Department of Energy, Washington DC, USA.

US Energy Information Agency, 2013b, *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants*, US Department of Energy, Washington DC, USA.

US Energy Information Agency, 2014, *Assumptions to the Annual Energy Outlook 2014,* US Department of Energy, Washington DC, USA.

US Energy Information Agency, 2015, *Short-term Energy and Summer Fuels Outlook April 2015*, US Department of Energy, Washington DC, USA.

Appendix A

List and coverage of studies

Source	Gas	CCS - Gas	Coal	CCS - Coal	Wind onshore	Wind offshore	Hydro	Biomass	Solar PV	Solar Thermal	Geothermal	Nuclear
Lazard 2014	☑		☑	☑	☑	☑		☑	not utility scale	includes large/ incomparable storage	☑	☑
EIA 2014	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
IPCC 2014	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Brookings 2014	☑		☑		☑		☑		☑			☑
EPRI 2013	☑	☑	☑	☑	☑	☑		☑	not utility scale	☑	☑	☑
IEA 2012	☑	☑	☑	☑	☑	☑			☑	☑		☑
NREL 2015	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑

Appendix B

Assumptions

Source	Gas	CCS - Gas	Coal	CCS - Coal	Wind onshore	Wind offshore	Hydro	Biomass	Solar PV	Solar Thermal	Geothermal	Nuclear
Discount rate (%)	8	8	8	8	8	8	8	8	8	8	8	8
Plant lifetime (years)	28	30	35	36	23	23	50	30	30	27	27	44
Construction time (years)	3	3	5	5	2	2	4	4	1	2	3	6
Capacity factor (%)	66	69	76	75	33	40	60	69	19	38	81	85
Thermal efficiency (%)	49-57	37-54	38-47	28-39	-	-	-	24-31	-	-	-	33-36
Fuel cost ($/ mmbtu)	4.98	4.98	2.36	2.36	-	-	-	3.00	-	-	-	0.71

Appendix C

Fuel price sensitivity

Gas price (US$ per mmbtu)	Average LCOE - Gas CCS (US$ per MWh)
4.98 (assumed value)	87.6
4.00	79.9
4.50	83.9
5.00	87.8
5.50	91.7
6.00	95.7
7.00	103.6
8.00	111.4
9.00	119.3
10.00	127.2
11.00	135.1
12.00	143.0
14.00	158.7
16.00	174.5

Coal price (US$ per mmbtu)	Average LCOE - Coal CCS (US$ per MWh)
2.36 (assumed value)	137.4
1.50	128.1
2.00	133.5
2.50	138.9
3.00	144.6
3.50	150.4
4.00	156.2
4.50	161.9
5.00	167.7
5.50	173.5
6.00	179.3
6.50	185.0
7.00	190.8
7.50	196.6